2021 Doctoral Thesis

Development of Regionalized Life Cycle Impact Assessment Method for African Countries

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Abbreviations

BCOC Black Carbon or Organic Carbon

CO_2 Carbon dioxide

CTM Chemical Transport Models

DALY Disability-adjusted life year

ERTR Environmentally related tax revenue

FAO Food and Agriculture Organization of the United Nations

IEA International Energy Agency

ISO International Organization for Standardization

LCA Life Cycle Assessment

LCI Life Cycle Inventory

LCIA Life Cycle Impact Assessment

NH_3 Ammonia

NO_x Nitrogen Oxide

PM Particulate Matter

SO_2 Sulfur Dioxide

UNEP United Nations Environment Programme

VOC Volatile Organic Compounds

WHO World Health Organization

Chapter 1: Introduction

This chapter describes the social background of our research. It summarizes the latest information concerning the global damage of air pollution and its impacts on society. It also explains Africa's current environmental problems and the lack of Life-Cycle Assessment (LCA) networks in Africa.

1.1 Social Background

1.1.1 Air Pollution

According to the World Health Organization (WHO) estimations in 2018 [1], air pollution kills 7 million people every year. Among these 7 million deaths, ambient air pollution is responsible for 4.2 million deaths, whereas 3.8 million deaths are attributed to household air pollution. As shown in Figure 1.1, the diseases associated with air pollution are mainly "Stroke", "Heart disease", and "Lung cancer", following the pathway shown in Figure 1.2. Table 1.1 shows the damage of air pollution per disease in 2016 with 1.6 million deaths related to Ischeamic heart disease; 0.8 million deaths related to Stroke; 0.8 million deaths related to Chronic obstructive pulmonary disease; 0.8 million deaths related to lower respiratory infections; 0.3 million deaths related to trachea, bronchus and lung cancers.

Figure 1. 1 Annual Burden from Air Pollution

Table 1.1 Global burden of ambient air pollution per type of disease (2016 data)

Type of disease	Number of deaths
Ischaemic heart disease	**1,598,336**
Stroke	**832,053**
Chronic obstructive pulmonary disease	**779,869**
Lower respiratory infections	**772,074**
Trachea, bronchus, lung cancers	**263,914**
Total	**4,246,247**

In recent years, air pollution has risen to the top of environmental concerns worldwide [2], being the 4th leading risk factor for death globally (it used to be outside the top 10, back to 1990) higher than cholesterol or malnutrition as shown in Table 1.2. Moreover, among all these risk factors, ambient air pollution has shown the highest increase in developing countries from 2010 to 2019 [3].

Table 1.2 Global ranking of risk factors by total number of deaths from all causes in 2019 [3]

Type of disease	Number of deaths (million)
High systolic blood pressure	**10.8**
Tobacco	**8.7**
Dietary risks	**8.0**
Air pollution	**6.7**
High fasting plasma glucose	**6.5**
High body-mass index	**5**
High LDL	**4.4**

Concerning outdoor air pollution, multiple sources exist depending on the type of pollutant: Black Carbon or Organic Carbon (BCOC), Nitrogen Oxide (NO_x) or Nitrogen Dioxide (NO_2), Sulfur Oxide (SOx) or Sulfur Dioxide (SO2), and Ammonia (NH3). Concentrations of particulate matter with a diameter of 2.5 microns or less (PM2.5) or with a diameter of 10 microns or less (PM10) are often used as a reference to evaluate the quality of air, which is having a significant impact on human health through lungs or blood system.

All the different pollutants cited previously contribute to the increase of the concentration in particulate matter. BCOC emissions are mainly occurring due to the combustion of fossil fuels or biomass [4]. NOx or NO2 emissions are due to the generation of power or internal combustion engine vehicles. SO2 or SOx emissions are also due to these vehicles, as well as the burning of coal or oil. Agriculture represents the largest source of NH_3 emissions.

The global map of ambient PM2.5 concentration for 2016 is shown in Figure 1.3. It can be seen that the concentrations are particularly high in Western Africa and Southern Asia, far above the WHO guidelines of 10µg/m^3 annual mean. There exist three major ways to estimate the PM2.5 background concentration: Ground-station measurement, Satellite-remote measurement, or calculation through chemical transport model. Each of them has advantages and disadvantages:

- Ground-stations (Good accuracy but the number is limited, especially in developing countries)
- Satellites (Possibility to measure the concentration at a very-high-resolution but medium accuracy)
- Chemical Transport Model (Good accuracy but emissions inventories are needed, the time of calculation using supercomputer can also be very important)

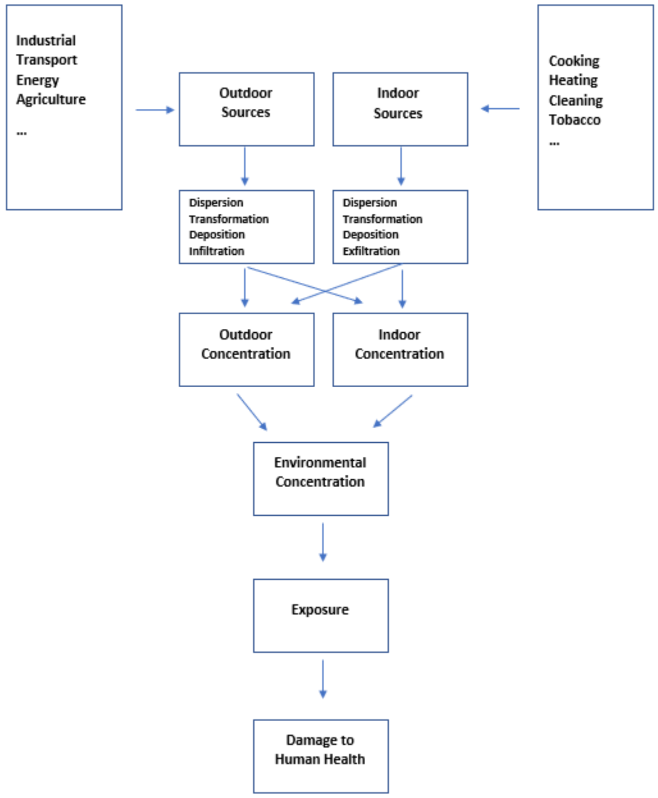


Figure 1. 2 Relationship between outdoor and indoor sources, personal exposure, damage to human health

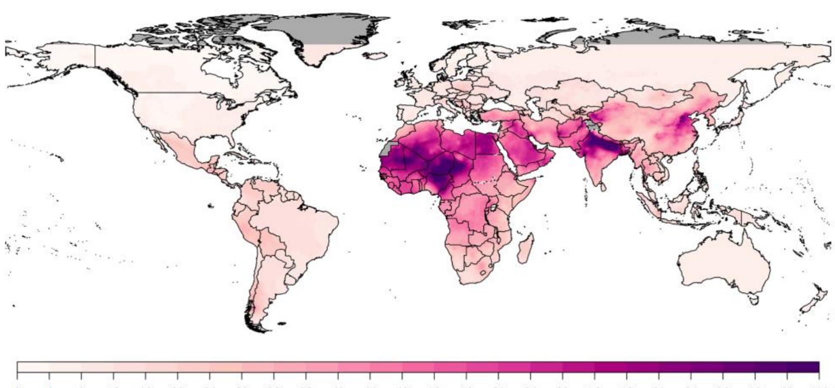


Figure 1. 3 Global ambient PM2.5 concentration in 2016 (µg/m3)

Even though several uncertainties exist [5], several reasons [6-9] can explain the high concentration of ambient PM2.5, especially in China, India, and Western Africa. First of all, biomass burning (e.g., crop residues and wood) is an important air pollution source, representing 30 to 50% of the PM2.5 emissions. Road dust (poor infrastructure) and vehicle emissions can represent up to 30% of the emissions. For China, industrial emissions also contribute to PM2.5 concentration up to 20-30%. Natural phenomena also contribute to the rise of the PM2.5 in Western Africa and India with dust from Sahara and Thar (Great Indian) deserts. According to EDGAR v5.0 database [6], the major source globally of air pollution in 2015 (latest data) are:

- PM2.5: Manufacturing Industries and Construction (24%), Emissions from biomass burning (10%), Electricity and Heat production (7%)
- SO2: Electricity and Heat production (43%), Manufacturing Industries and Construction (29%)
- NOx: Road Transportation (27%), Electricity and Heat production (25%), Manufacturing Industries and Construction (17%)
- NH3: Agricultural soils (54%), Manure Management (24%)

The largest emitters are:

- PM2.5: China (29%), India (16%), Brazil (5%), Nigeria (4%), Indonesia (4%), USA (4%), Ethiopia (2%), Viet Nam (2%), Pakistan (2%)
- SO2: China (29%), India (11%), USA (8%), Saudi Arabia (3%), South Africa (3%), Indonesia (2%), Russia (2%), Brazil (2%), Kazakhstan (1%)
- NOx: China (21%), USA (11%), India (8%), Brazil (3%), Russia (3%), Iran (2%), Indonesia 2%), Saudi Arabia (2%), Japan (2%), Mexico (2%)
- NH3: China (18%), India (12%), USA (8%), Brazil (6%), Indonesia (3%), Pakistan (3%), Russia (2%), Nigeria (2%), France (2%), Germany (2%)

Concerning indoor air pollution, around half of the global population (3 billion people) cook using solid fuels or kerosene [10]. These populations are mainly located in Sub-Sahara Africa, South and South-East Asia, the lack of indoor ventilation is a factor aggravating the issue for these populations. The indoor combustion of fuels is contributing to the formation of smoke (source of particulate matter and volatile organic compounds (VOC). Some other toxic pollutants having an impact indoors include carbon monoxide (CO) and formaldehyde (CH_2O) or polycyclic aromatic hydrocarbons (PAHs). In developed countries, the main indoor air pollution sources are cleaning [11] and tobacco smoking [12]. Globally only a few countries (e.g., China, Portugal) have established indoor air pollution standards. Finally, another source of indoor pollution is outdoor sources' infiltration, contributing a lot to indoor concentrations [13].

Finally, it has to be noted that ambient air pollution can be transported over a more or less short distance following the pollutant's lifetime [14]. The longer is the lifetime, the more the dispersion is important. For example, NO_x has a lifetime of about a 1 day and a dispersion range of 1-10km, SO_2 has a lifetime of about a 1 day and a dispersion range of 1-3 months and a dispersion range of 10-100km. The meteorological condition (wind, precipitation) can also affect the transport of pollutants, such as in Asia with the monsoon during the summer [15]

1.1.2 State of environmental problems in Africa

There exist several environmental problems occurring on the African continent [16]. As described previously, Outdoor and Indoor pollution are an important issue in Africa. Some African megalopolises are among the top 500 most polluted cities in the world [17], such as Kampala in Uganda (104µg/m^3), Accra in Ghana(55g/m^3), or Johannesburg in South Africa (41µg/m^3). One of the reasons is the high number of second-hand vehicles and the lack of sufficient road infrastructure. Indoor air pollution is also a problem with the combustion of wood or animal waste (more than 3 people out of 4 are using solid fuels in Central and Western Africa). The burning of savanna and desert dust also contributes to the rise of air pollution levels.

This Air pollution has a severe impact on human health in Africa with nearly one million death every year. Ambient air pollution is related to nearly 60% of these deaths, with especially a burden in Nigeria (140,555 Deaths), Egypt (67,434 Deaths), Ethiopia (32,905 Deaths), and DR Congo (31,554 Deaths). The number of deaths in African countries due to ambient air pollution is presented in Table 1.3:

Table 1.3 Deaths related to ambient air pollution in African countries (2016) [18]

Country	Deaths related to ambient air pollution	Death related to ambient air pollution (per 100,000 population)
Nigeria	140,555	75.6
Egypt	67,434	70.5
Ethiopia	32,905	32.1
Democratic Republic of the Congo	31,554	40.1
South Africa	22,917	40.9
Sudan	22,083	55.8
United Republic of Tanzania	14,831	26.7
Cameroon	14,430	61.6
Niger	14,327	69.3
Algeria	14,192	35.0
Uganda	13,416	32.3
Morocco	13,088	37.1
Côte d'Ivoire	12,614	53.2
Chad	12,033	83.3
Saudi Arabia	11,915	36.9
Ghana	11,739	41.6
Angola	8,706	30.2
Somalia	8,071	56.4
Mali	7,366	40.9
Burkina Faso	7,182	38.5
Kenya	7,135	14.7
Tunisia	6,397	56.1
Madagascar	6,349	25.5
Mozambique	5,670	19.7
South Sudan	5,551	45.4
Senegal	5,239	34.0
Benin	5,217	48.0
Guinea	5,065	40.9
Burundi	4,036	38.4
Zambia	3,768	22.7
Zimbabwe	3,686	22.8
Togo	3,448	45.3
Sierra Leone	3,405	46.0
Malawi	3,139	17.4
Central African Republic	2,826	61.5
Rwanda	2,811	23.6
Libya	2,725	43.3
Eritrea	2,129	43.0
Mauritania	1,910	44.4
Congo	1,671	32.6
Liberia	1,088	23.6
Lesotho	1,051	47.7
Gambia	760	37.3
Namibia	758	30.6
Guinea-Bissau	692	38.1
Gabon	675	34.1
Equatorial Guinea	624	51.1
Botswana	601	26.7
Mauritius	478	37.9
Djibouti	407	43.2
Eswatini	349	26.0
Comoros	236	29.7
Cabo Verde	222	41.2
Sao Tome and Principe	58	29.1
Seychelles	41	43.3

Another environmental problem is the heavy use of chemicals, especially for agriculture and mining. Toxic pesticides and fertilizers are heavily used and cause health troubles, such as in Burkina Faso for the cotton plantation workers. Mining activities lead to the contamination of the biodiversity with the ingestion of mercury for fishes.

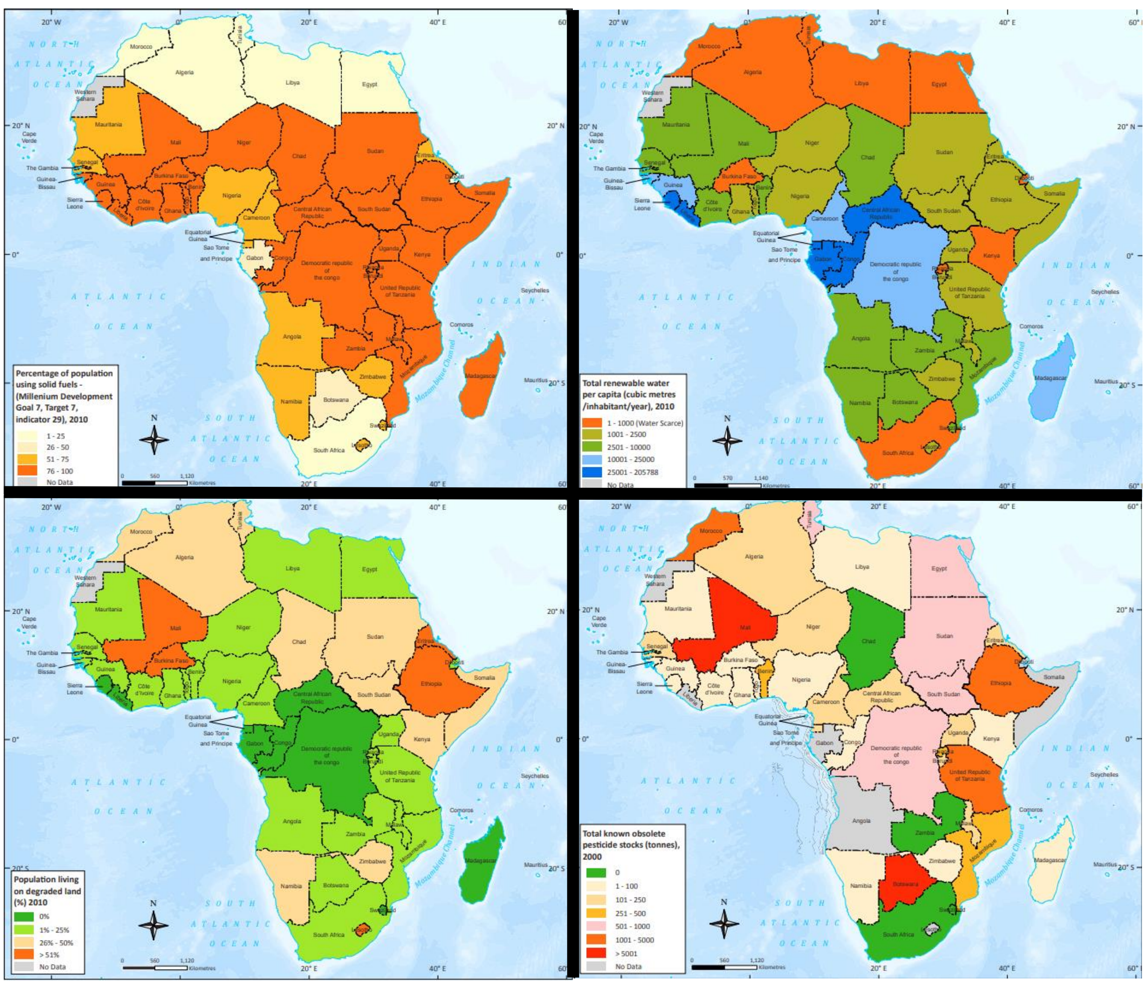
Water is also well-known problem in Africa; annual water availability per capita (around 4000 m3) is below the global average (6000m3). Water quality is also a serious problem causing diarrhea, cholera, and other related diseases due to unsafe drinking water.

Land degradation is another critical problem: the continent produces several crops for its domestic market and exportation. In several African countries, more than half of the population is living on degraded land. This degraded land does not produce enough food and therefore is a factor of malnutrition.

Finally, even though the contribution of African countries to climate change is still small compared to developed countries, Fossil Carbon dioxide (CO_2) emissions in Algeria (181Mt of CO_2 in 2019) or Egypt (255Mt) have been multiplied by three times since 1990 [19].

A summary of the different environmental problems in Africa is shown in Figure 1.4:

(a) (b)



(c) (d)

Figure 1. 4 Summary of various environmental issues occurring in Africa: (a) Solid fuel utilization rate per country; (b) Total renewable water per capita; (c) Population living on degraded land; (d) Total known obsolete pesticide stocks [16]

1.1.3 State of LCA research in Africa

Life-Cycle Assessment (LCA) is one of the popular tools to support decision-making for sustainable development. It is used to evaluate products or services' impacts over a full life cycle (See Section 1.2.1). Even though several LCA networks have been developed in several parts of the world, including in developing countries/newly industrialized countries (e.g., Peru, Thailand), LCA's development in Africa is still minimal. As shown in Figure 1.5, only a few African countries (South Africa, Ethiopia) have working groups focusing on LCA. Even though global Life-Cycle Impact Assessment methods (also known as LCIA methods, it is used to evaluate the impacts of products and services) have been developed, such as LIME3 or Recipe 2016, there is still no specific LCIA method for Africa.

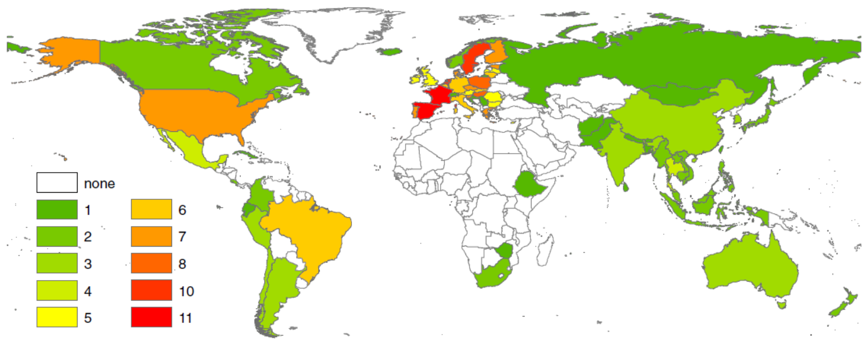


Figure 1. 5 Global LCA networks in 2013

A survey for Africa was made to evaluate the current interest and gaps in LCA African research. The survey was conducted on Scopus and Google scholar. 168 research articles were found (compared with the total number of 26,000 articles containing the keywords "Life Cycle Assessment" in Scopus database). Among these 201 research articles (Figure 1.6), the most studied products belong to the food and agriculture sector with 55 articles (Fruits, Vegetables…) followed by Waste (42 articles), electricity (32 articles) and energy (31 articles articles).

Figure 1. 6 Number of LCA studies in Africa per theme

Several remarks can be made based on the research papers collected:

Basset-Mens et al. (2016) [**108**] and Payen et al. (2015) [**106**] highlighted the importance of considering the LCIA of respectively clementine and tomatoes. These agricultural products are heavily exported to developed countries, especially France. It was found that when applying LCIA, the damage due to energy use and water use was high. This is explained by the reliance of Morocco on Coal to produce electricity (More than 50% of the electricity mix); for water, the inventory (the quantity of water consumption) to cultivate tomatoes in France and Morocco is quasi similar (32.8 vs. 28.6 $L.kg^{-1}$). However, due to the water scarcity in Morocco, the impact of tomatoes cultivation was four times higher. In a similar vein, by calculating the water footprint of feed in different Tunisian region, Ibidhi et al. (2017) [**193**] shown that the aridity is leading to a lower grass yield, and therefore, a higher water footprint in the south of Tunisia (1033 m3/ kg of feed vs. 315 for the global average).

Mashoko et al. (2018) [**142**] calculated the sugar industry's impacts in South Africa and compared it with Mauritius. They found out that fertilizers and herbicides are the greatest contributors to global warming potential through the use of fossil fuels in the manufacture. They also highlighted the high energy consumption and the importance of irrigation as more land is needed due to rain-fed in South Africa.

Woldegebriel et al. (2017) [**25**] evaluated the impact of milk production in Ethiopia in different systems (large-scale, urban or rural systems). The impact per kg milk (1.75-2.25) was found higher than in India (1.7kgCO_2eq) or in other OECD countries (0.8-1.3) due to low quality of the feeds provided to the cows (scarce amount of crude protein).

Ibrahim et al. (2017) [**26**] reported that that the impact of the Egyptian brick industry was 69% higher than the one produced in Japan due to the lower efficiency of the calcination process, the consumption of fuel and electricity were reported higher.

Lansche et al. (2017) [**64**] showed the advantage of using biogas compared with dung combustion, often used in developing countries. The case study mainly focused on Ethiopia and found out that annually 130,542t of carbon dioxide could be avoided while switching to biogas.

Brizmohun et al. (2015) [**28**] compared with other countries the air pollution impact of electricity in Mauritius, they showed that for example that the electricity from coal had a much higher impact than in other counties (about 6 times the minimum value obtained in the literature). This is explained by the low efficiency of the plants, the lack of abatement technology for PM2.5, SO2, and NOx, as well as the higher Sulphur content of the coal used.

Ndong et al. (2009) [**104**] focused on the production of Jatropha biodiesel produced in Western Africa, finding that average energy yields were similar to those in other developing countries such as Thailand. However, the lack of machinery in Africa is a limitation for higher yields.

A description of each study in provided in Table 1.4. The main details of each research article are provided such as: year of publication, country, product, main environmental impact targeted, Functional unit, LCI database and LCIA method used.

Concerning the Life-Cycle Inventory (LCI) database chosen, almost half the research article (100) used Ecoinvent as a LCI database, including 35 studies using Ecoinvent v2 (containing mainly processes based on the situation in developed countries).

Concerning the Life-Cycle Impact Assessment (LCIA) method, CML was the most chosen (45) followed by Recipe (39) and Eco-indicator (24). It has to be noted that only 9 studies chose Recipe2016 [10], one the latest global LCIA method, that contains characterization factors specific to African countries.

It can be observed that air pollution was not a popular focus of attention until now in African LCA research except in Egypt ([52],[55],[58]). Climate change and energy received much more attention until now.

Using Table 1.5 (main African agriculture products) and Table 1.6 (main African exports), it can be seen that several key drivers of the African economies have not received attention yet. Several key agriculture products such as Sorghum, yams, wheat were not assessed whereas Cassava or Maize received little attention. Same observations can be done for rubber, second-hand vehicles, natural gas extraction, mining activities (copper, rare materials, uranium). North African's textile products did not receive attentions also.

In addition a summary of each study in added in Appendix 1.1.

Table 1.4 LCA research articles review

Year	Country [Ref.]	Product/Main environmental impact targeted	Functional unit	LCI database	LCIA method
2011	Algeria [20]	Drilling mud/Human toxicity	1 well drilled on 4100 m deep	Primary data/Existing Literature/Simapro	Impact 2002+
2012	Algeria [21]	Recycled water/Not Specified	5 L of recycled water intended to be used for irrigation	Primary data/Existing literature/Ecoinvent	eco-indicator 95
2013	Algeria [22]	Potable water/Not Specified	1 liter of potable water.	Primary data/Simapro	Eco indicator 99
2015	Algeria [23]	Cement	1 ton of cement	Primary data/Simapro 7.1	Impact 2000+
2015	Algeria [24]	Ammonia/Energy, Climate change	1 ton of anhydrous ammonia with 99.9% purity.	Primary data/GEMIS	Other
2016	Algeria [25]	Drilling mud/Human toxicity	Drilling mud treatment scenario	Simapro 7	Eco indicator 99
2017	Algeria [26]	Mussel/ Energy, Climate change	1 ton of fresh Mediterranean mussels	Primary data/Existing Literature/Ecoinvent v3	CML
2017	Algeria [27]	Hotel building/Not Specified	impact/occupant/m2.	Primary data/Ecoinvent	Other
2017	Algeria [28]	Biodiesel/	1 ton of biodiesel	Primary data/Existing Literature/Ecoinvent v3.1	impact 2002+
2020	Algeria [29]	PV Energy/ Energy, Climate change	1 year of utilization	Primary data	Other
2014	Benin [30]	Tomato/Eutrophication	1 hectare	Primary data	ILCD
2017	Benin [31]	Tomato/Energy, Eutrophication	1 kg of product	Primary data/Existing literature/Ecoinvent v2.2	Recipe2008
2016	Burkina Faso [32]	Energy sources for a water purification plant/ Not Specified	One year	Ecoinvent v3	Recipe
2018	Burkina Faso [33]	Jatropha biofuel/Energy, Climate change	hectare.year/ gigajoule of J.curcas SVO or JME	Primary data/Existing literature	Recipe
2018	Burkina Faso [34]	PV/Not specified	1 liter of oil	Ecoinvent	ReCiPE World E/A
2010	Cameroon [35]	Palm Oil/Climate change	1 MJ in a car engine	Primary data/Existing literature/LCA database	Other
2010	Cameroon [36]	Road/Energy	Number of vehicles moving on that road for a period of fifty years	Primary data/Existing literature	Other
2012	Cameroon [37]	Farms/Eutrophication	1 ton of fresh fish (both tilapia and African catfish) at the farm exit gate.	Existing Literature/Ecoinvent	CML2001
2016	Cameroon [38]	Waste Water/Not specified	1 life-cycle	Primary data/Existing literature	Other
2019	Cameroon [39]	Jatropha/Human toxicity	1 MJ of JVO obtained.	Primary data/Existing literature/Ecoinvent v2	Other
2010	Egypt [40]	Wastewater/Not specified	Treatment of 1 cubic meter of wastewater.	Primary data/Existing Literature	Eco-Indicator 99
2012	Egypt [41]	Wastewater/Not specified	Treatment of 1 cubic meter of wastewater	Existing Literature	Eco-Indicator 99
2014	Egypt [42]	Building materials (Method)	-	-	-
2014	Egypt [43]	Residential building/Not specified	1 usable floor space (m2)	Primary data/Existing literature/Ecoinvent V3	Impact 2002+
2014	Egypt [44]	Building database	-	-	-
2014	Egypt [45]	Cotton/Climate change	1 kg of dyed cotton yarn	Primary data/Ecoinvent v2	Eco-Indicator 99
2015	Egypt [46]	Diesel fuel, solar pump/Not specified	Irrigation of 1 feddan of rice	Primary data	Impact2002+
2015	Egypt [47]	Jatropha Biodiesel/Not specified	1 ton of Jatropha Biodiesel	Primary data	Impact2002+
2016	Egypt [48]	Dredged Material/Not specified	1 trip per day	Primary data/Simapro 8	Impact2002+
2016	Egypt [49]	Energy system/Not specified	The operation of the power supply system for a calendar year	Existing literature/ecoinvent	Eco-indicator 99
2016	Egypt [50]	Aquaculture/Not specified	1 ton of live tilapia at farm-gate	Primary data/Existing Literature/Ecoinvent v2.2	Other
2016	Egypt [51]	LCA tool	-	-	-
2016	Egypt [52]	Transport vehicles/Air Pollution	Total Vehicle Kilometer Travelled (VKT) in Egypt	Primary data?/Existing Literature	Impact 2002+
2016	Egypt [53]	Tilapia/Climate change	1 ton of Tilapia	Primary data/Existing Literature/Ecoinvent v2	CML baseline 2000
2016	Egypt [54]	Acrylic fiber/Energy	1 kg production of acrylic fiber.	Primary data/Existing Literature/Ecoinvent v2.2	Eco-Indicator 99
2016	Egypt [55]	Cement/Air pollution	1 kilogram of cement	Primary data/Ecoinvent v3	IMPACT 2002+
2016	Egypt [56]	Acrylic fiber/Toxicity	1000 kg production of acrylic fiber.	Primary data/Ecoinvent v2	Eco-Indicator 99

2017	Egypt [57]	Brick/Not specified	1 kg of brick products	Primary data/Existing Literature/IDEA	LIME2
2017	Egypt [58]	Lubrication oil/Energy, Air pollution	1000 kg lubrication used oil	Existing Literature/Ecoinvent v2	Eco-Indicator 99
2019	Egypt [59]	Waste water/Not specified	1 m3 of treated wastewater	Primary data/Existing Literature/Ecoinvent v2	CML2000
2020	Egypt [60]	Waste/Not specified	1 ton of waste	Primary data	Other
2020	Egypt [61]	Wastewater/Not specified	1 m3 of treated wastewater	Primary data/Gabi	Recipe
2020	Egypt [62]	Bioethanol/Climate change, Acidification	1 ton of bioethanol	Primary data/Existing Literature/Ecoinvent v3	CML-IA
2012	Ethiopia [63]	Rose cultivation/Not specified	1 bunch of roses consisting of 20 stems	Ecoinvent v2	CML 2 baseline 2000
2017	Ethiopia [64]	Biogas, dung/Climate change	Amount of primary energy needed to provide energy carriers	Primary data/Existing literature/ecoinvent v2.2	CML2001
2017	Ethiopia [65]	Milk/Climate change	1 adult cattle unit (cu)/1 kg of milk produced by a cow	Primary data/Existing Literature/Ecoinvent v2.2	Other
2020	Ethiopia [66]	Electricity from wind farm/Not specified	The generation of 1 kWh of average electricity	Primary data/Existing literature/Ecoinvent v3	ReCiPe 2008
2012	Ghana [67]	cooking fuels/Not specified	1 MJ of energy delivered to the cooking pot	Primary data/Ecoinvent/Gabi 4	CML2001
2020	Ghana [68]	Building/Energy, Climate Change	180.50 m2 gross floor area (GFA) for a lifespan of 50 years	Primary data/ICE	Other
2020	Ghana [69]	Food products/Climate Change	1 kg of product/1 kcal unit	Existing Literature/Ecoinvent v3.5	CML2001/Recipe2008
2011	Ghana [70]	Timber/Land Use	1 kg/1 euro/1 m3 of product produced	Existing literature	CML2000
2011	Ghana [71]	Biogas/Climate Change, Human Toxicity	Production of 1 MJ of useful energy	Primary data/Ecoinvent/Gabi 4	CML2001
2011	Ghana [72]	cyanide containers/Not specified	1 packaging?	Primary data/Existing Literature	Eco-indicator 99
2010	Ghana [73]	Timber/Climate Change	1 m3/1 kg/1 euro	Primary data	Other
2008	Ghana [74]	Cocoa/Not specified	1 kg of cocoa beans processed	Primary data/Ecoinvent/Gabi 4	CML2001
2009	Ivory Coast [75]	Biofuel/Climate Change	1 MJ of JME	Primary data/Ecoinvent	Other
2007	Kenya [76]	Food products/Not specified	1 ton of grade 1 product	Existing literature/Ecoinvent	CML baseline 2000
2016	Kenya [77]	Biowaste/Not specified	1 kg of wet biowaste	Primary data/Existing literature/Ecoinvent v3.3	ReCiPe 2016
2017	Kenya [78]	solar photovoltaic microgrid system/Not specified	1 kWh of electricity consumed by the community	Ecoinvent v2.2/Gabi 6	recipe 2008
2020	Kenya [79]	Food products/Climate Change, Water	1 kg of edible boneless weight	Existing Literature	IPCC/Aware
2020	Kenya [80]	Bioenergy/Not specified	Different scenarios	Existing Literature/Ecoinvent v3.1/Agrifootprint	Recipe2016
2020	Lesotho [81]	Wastewater/Not specified	1 L of wastewater.	Primary data/Existing literature/Ecoinvent v3	ReCiPe 2016
2014	Libya [82]	Crude oil/Not specified	ultimately presented in terms of the functional unit (km).	Primary data/Ecoinvent	Eco-indicator 99
2015	Libya [83]	wind farm/Climate Change	1 kWh of electricity produced	Primary data	Other
2014	Madagascar [84]	Solar Cooker/Not Specified	1 meal	Primary data	Other
2017	Madagascar [85]	Electricity generation/Not specified	1 year	Primary data/GEMIS	Other
2016	Malawi [86]	Tea/Climate Change	1 kg of tea	Primary data/Existing Literature	CML2002
2016	Malawi [87]	Building materials/Energy, Climate Change	1 m2 wall	Primary data/Existing Literature	Other
2019	Malawi [88]	Mining products/Climate Change	1 kg of rare earth oxide (REO)	Primary data/Existing literature/Ecoinvent v3/Gabi	Traci
2004	Mali [89]	Thermosyphon solar water/Energy	1 complete solar hot water system	Primary data/Existing literature	Other
2014	Mali [90]	Jatropha-based bioenergy/Climate Change	1 MJ of electricity.	Primary data/Ecoinvent v2.2	Recipe
2017	Mali [91]	Insect Based Feed Production/Not specified	1 kg whole dried larvae with a residual water content of less than 10%.	Existing literature/Ecoinvent v3.0	Other
2017	Mali [92]	Shea butter/Climate Change, Energy	1 kg of shea butter	Primary data/Existing Literature	CML 2001
2020	Mali [93]	Cotton/Not specified	1 t and 1 ha of seed cotton at farm gate and 1 t and 1 ha equivalent of baled cotton fiber and cottonseed at the ginning plant gate	Primary data/Ecoinvent v3/World Food LCA Database	ILCD

2012	Mauritania [94]	Octopus/Not specified	24 kg carton of frozen common octopus up to the point of import in the year 2009.	Primary data/Ecoinvent/LCA Food Database	CML baseline 2000
2014	Mauritania [95]	Building materials/Not specified	Structure and envelope of a classroom block consisting of 8 modules in Nouakchott for a period of 30 years	Ecoinvent v2.2	Other
2004	Mauritius [96]	Sugarcane/Not specified	1 ton of raw cane sugar exported	Primary data/Existing literature	CML
2005	Mauritius [97]	Biodegradable waste/Climate Change	Treatment of 1 kg of biodegradable wastes by composting and Anaerobic Digestion (AD)	Primary data	Other
2008	Mauritius [98]	electricity generation bagasse/Climate Change	1 GWh of electricity exported to the national electricity grid	Primary data/Existing literature/BUWAL 2000	Eco-indicator 99/CML World 92
2008	Mauritius [99]	PET bottle/Not specified	Use and disposal of 1000 packs of 1.5 LPET bottles, used for the packaging of 9000 liters of beverage	Primary data/BUWAL 2000	Eco-indicator 99
2011	Mauritius [100]	Waste/Energy	The disposal of 300,000 tons of MSW in one year	Primary data?	Impact2002+
2012	Mauritius [101]	PET bottle/Not specified	1 ton of used PET bottles to the respective disposal facilities	Primary data	Eco-indicator 99
2012	Mauritius [102]	PET bottle/Not specified	1 ton of used PET bottles	Primary data/Existing Literature/Simapro 7.1	Eco-Indicator 99
2012	Mauritius [103]	PET bottle/Not specified	1 ton of used PET bottles	Primary data/Existing Literature/Ecoinvent	Eco-Indicator 99
2015	Mauritius [104]	electricity generation/Air pollution, Climate change	1 MWh of electricity delivered to the consumer	Primary data/Ecoinvent v2	CML 2 Baseline 2001
2017	Mauritius [105]	Waste/Not specified	The management of 427,687 t of MSW generated in the year 2010	Existing literature/Ecoinvent v2.0	CML-IA
2014	Morocco [106]	Tomato/Water	1 kg of fresh bulk tomato delivered at the Saint-Charles International Market entry gateway	Primary data/Ecoinvent v2.2	Recipe
2014	Morocco [107]	perennial crops/Not specified	1 kg of fresh fruits.	Primary data/Ecoinvent v2.2	recipe 2008
2016	Morocco [108]	Clementine/Energy,Climate change, Eutrophication	1 kg raw fruit at the farm gate.	Ecoinvent v2.2	Recipe
2016	Morocco [109]	Photovoltaic power plant/Climate Change	1 MWh	Ecoinvent v3	Recipe
2016	Morocco [110]	Photovoltaic power plant/Not specified	1 MW	Ecoinvent v2.2	Other
2016	Morocco [111]	Fresh fruit/Not specified	1 kg of fresh fruits	Primary data/Ecoinvent v2.2	ReCiPe 2008
2018	Morocco [112]	Electric energy/Climate Change	1 kWh of produced electric energy	Primary data/Gabi/Ecoinvent v3.1	CML2001
2019	Morocco [113]	Automotive headrest/Not specified	1 headrest for automotive seating	Primary data/Ecoinvent	IMPACT 2002+
2020	Morocco [114]	hybrid solar/biomass micro-cogeneration/Climate change	1 kWh of electricity	Primary data/WIOD/EORA	ILCD
2020	Morocco [115]	Solar water heater/Energy	Utilization during a year	Primary data	Other
2020	Morocco [116]	Waste Water/Not specified	Treat effluent of one population equivalent for one day	Primary data	ReCiPe midpoint 2014
2013	Mozambique [117]	Jatropha oil/Water	1 MJ of energy in the form of jatropha oil or fossil diesel.	Primary data/Existing Literature	Other
2016	Mozambique [118]	Biomass power plant/Not specified	1-GJ pellets delivered to a combined heat and power (CHP) plant	Primary data/Existing Literature	Other
2010	Nigeria [119]	Future electricity scenarios/Not specified	56,160 TJ/yr for 2003; 346,000 TJ/yr for 2010; 551,000 TJ/yr for 2020; 764,000 TJ/yr for 2030	Primary data/Existing literature/GEMIS 4.3/Simapro	Other
2014	Nigeria [120]	Biodigesters/Climate Change, water	One meal	x	Other
2015	Nigeria [121]	Residential building	One life-cycle	Primary data	Other
2015	Nigeria [122]	Municipal solid waste management/Not specified	Waste Management scenarios	Primary data/Ecoinvent	Other
2015	Nigeria [123]	Jatropha biofuel/Not specified	1MJ of fuel used in a typical biodiesel fired power plant/Jatropha plantation of 1 hectare (ha) over a 20-year period	Literature review/Agrifootprint/Ecoinvent	Recipe
2016	Nigeria [124]	Shea butter/Climate Change	1 kg of shea butter	Primary data/Ecoinvent	TRACI
2019	Nigeria [125]	Electricity/Not specified	1 kWh of electricity generation	Existing literature/Gabi	CML2001
2020	Nigeria [126]	Electricit/Climate Change, Energy, Acidification	1 MWh of net electricity produced.	Primary data/Ecoinvent	CML2001
2020	Nigeria [127]	Cowpea/Climate Change, Acidification	1 ton of grain	Primary data/Gabi 8.7	CML
2020	Nigeria [128]	Cassava/Energy	1ha land area	Primary data/Existing Literature	Other

2020	Nigeria [129]	Sweet Orange/Energy	1 hectare	Primary data	Other
2013	Nigeria [130]	passenger transport/Not specified	467 billionperson.km in2003/721 billionperson.km in 2020/942 billionperson.km in 2030	Existing Literature/GEMIS4.3	cml2001
2013	Nigeria [131]	Biodiesel/Climate Change	The functional unit was defined as one kilogram of soybean	Primary data?/Existing literature	Other
2017	Nigeria, Ghana, ivory coast [132]	review	-	-	-
2019	Rwanda [133]	Tomato/Ecotoxicity	1 kg of tomato at farm-gate	Existing literature/Ecoinvent v2.2	ILCD
2011	Senegal [134]	Shrimp products/Not specified	1 kg of shrimp and the accompanying packaging material at the point of import to Europe.	Primary data/Existing Literature/Ecoinvent v2	CML 2002
2019	Somalia [135]	Treated water/Not specified	1 liter of treated water	Existing literature/Ecoinvent v3.4	ReCiPe 2008
2002	South Africa [136]	Review	-	-	review
2002	South Africa [137]	Wool/Not specified	1 kilogram of dyed two-fold wool yarn	Primary data/Existing Literature	Method
2002	South Africa [138]	Potable water/Not specified	1 kiloliter (kL) of potable water	Primary data/Gabi 3	Recipe
2003	South Africa [139]	Method	-	-	-
2006	South Africa [140]	water supply/Toxicity	1 Mℓ/d of potable water supplied at Rosslyn	Primary data	special African
2009	South Africa [141]	Urban water/Not specified	1 kl of water	Primary data/Existing Literature/Gabi 3	CML
2010	South Africa [142]	Sugar/Energy, Climate change	1 ton of raw sugar	Primary data/Ecoinvent	Eco-indicator 99
2012	South Africa [143]	Photovoltaic/Wind Radio/Climate Change, energy	One radio base station utilization during 10 years	Primary data	recipe2008
2014	South Africa [144]	Container glass waste/Climate Change, energy	1 ton of container glass waste	Primary data/Ecoinvent v2	Other
2014	South Africa [145]	Clay brick Walling/Not specified	1 standard brick equivalent (SBE)	Primary data/Ecoinvent v2.2	Impact2002+
2014	South Africa [146]	polymer bag/Not specified	1 m2 of plastic film	Primary data/Ecoinvent v2.2	Impact 2002+
2015	South Africa [147]	Biofuel/Energy	1 km traveled	Aspen simulation/Existing Literature/Ecoinvent v2.2/Greet 2.7	Other
2016	South Africa [148]	Agriculture/Not specified	1 metric ton of extractable sucrose delivered at the mill gate in the form of sugarcane stems or billets.	Primary data/Existing Literature/Greet	Other
2016	South Africa [149]	Method for building LCA	-	-	-
2016	South Africa [150]	Books/Not specified	The reading of 21 books by a single user two hours per day over a four-year period	Ecoinvent v3	recipe2008
2016	South Africa [151]	lignocellulosic lactic acid/Not specified	1 ton of Lactic Acid (LA) produced	Aspen/Ecoinvent	Recipe
2017	South Africa [152]	Timber/Climate Change	Quantity of materials required to construct the roof truss system of a house	AUSLCI/Ecoinvent v3.1	recipe
2017	South Africa [153]	Maize/Climate Change	one kilogram of maize at silo storage	Primary data/Existing Literature/Ecoinvent v3.3	ILCD
2017	South Africa [154]	Meat/Climate Change	1 kg of LW meat/1kg of CW meat	Primary data/Ecoinvent	CML IA
2017	South Africa [155]	Biorefineries/Not specified	a biorefinery with the capacity of processing 65 (tDM/h) tons bagasse and trash per hour	Primary data/Existing Literature	Eco-Indicator 99
2017	South Africa [156]	Biorefineries/Not specified	1 MWh electricity produced	Aspen simulation/Existing Literature/Ecoinvent v3	CML-IA baseline 3.02
2017	South Africa [157]	Biorefineries/Not specified	1 MWh electricity produced	Aspen simulation/Existing Literature/Ecoinvent	CML-IA baseline 3.02
2017	South Africa [158]	Biorefineries/Not specfied	1 ton BD produced/1 MWh electricity produced	Aspen simulation/Existing Literature/Ecoinvent v3	CML-IA baseline 3.02
2017	South Africa [159]	Zinc Oxide/Not specified	ZnO surface area (1 m2/g)	Primary data/Existing Literature	Recipe
2017	South Africa [160]	Domestic Biogas Digester/Not specified	1 MJ?	Primary data?	Other
2018	South Africa [161]	Sandstone/Climate Change	1 t of sandstone	Primary data/Existing Literature	IMPACT 2002+
2018	South Africa [162]	Acid mine drainage (AMD) treatment/Climate Change	1 m3 of effluent generated by the AMD reactor	Primary data/Existing Literature/Ecoinvent v3	ReCiPe2016
2018	South Africa [163]	sanitation system/Not specified	The provision of a sanitation service for the daily defecation of a 10-adult occupant household in South Africa	Primary data/Ecoinvent v3.0	Recipe2016

2018	South Africa [164]	Soybean Biodiesel/Climate Change	1L of Biodiesel	Existing Literature	Other
2018	South Africa [165]	Sugarcane Ethanol (Inventory)	-	-	-
2019	South Africa [166]	Seawater desalination/Climate Change	1 kL of potable water	Primary data/Existing Literature/Ecoinvent v3	Recipe
2019	South Africa [167]	Method for the Construction industry	-	-	-
2019	South Africa [168]	Coal power plant/Not specified	712-MW power-generating unit	Primary data/Ecoinvent	Eco-indicator 99
2020	South Africa [169]	Straws/Not specified	Annual straw consumption per capita	Primary data/Existing Literature/Ecoinvent v3.5	Recipe
2020	South Africa [170]	Review	-	-	-
2020	South Africa [171]	Wastewater/Not specified	1 L of real wastewater	Primary data/Existing Literature/Ecoinvent v3.6	Recipe2016
2015	South Africa [172]	Sugarcane/Not specified	1 ton of extractable sucrose produced leaving the farm gate	Primary data	Other
2012	South Africa [173]	Pork/Climate Change, Eutrophication, Acidification, Enegy	one kg of pork (carcass weight)	Existing Literature/Gabi 2006	CML2001
2012	South Africa [174]	Saline wastewater/Climate Change	a daily production of 40 ton of dehydrated sodium sulphate by each process and another 960 ton/day of "ice + liquid water" mixture in the amounts obtained by EFC.	Existing Literature/Ecoinvent v2.2	Impact2002+
2012	South Africa [175]	Water treatment/Energy, Climate Change	f 1 Mℓ of boiler feed water (BFW)	Existing Literature/Ecoinvent	(CML 2 baseline 2000 V2.04
2010	South Africa [176]	Biodiesel/Climate Change, Energy	1 ton of biodiesel	Primary data/Existing Literature	Other
2010	South Africa [177]	Biofuel/Land Use, Climate Change	a unit of product, over a one-year production period	Primary data/Existing Literature	-
2002	South Africa [178]	Water recycling plant/Material, Energy	1 kL of water as supplied to industry	Primary data/Gabi3	CML
2002	South Africa [179]	Water treatment/Not specified	1 kiloliter (kL) of potable water	Primary data/Gabi 3	CML
2007	Tanzania [180]	Production of biofuels from pyrolysis of wood	One year	Primary data?	Other
2012	Tanzania [181]	Electricity/Not specified	The functional unit for this study is 1 MW h net electricity at the power plant.	Ecoinvent v2.2/USLCI 1.6.0	CML(IA)
2013	Tanzania [182]	Bioethanol produced from sugarcane molasses/Climate Change	1 ton of combusted jatropha biodiesel.	Primary data/existing literature/Ecoinvent	CML (IA)
2014	Tanzania [183]	Electricity/Not specified	1 MWh gross electricity generated at the power plant.	Ecoinvent v2.2/USLCI 1.6.0	CML (IA)
2014	Tanzania [184]	Maize/Not specified	One ton of Maize	Primary data/Existing Literature/Gabi 4	Other
2016	Tanzania [185]	Review	-	-	-
2020	Tanzania [186]	PV Electricity/Not specified	1 m2 of PV module	Primary data	Other
2007	Tunisia [187]	Coastal area/Eutrophication	1 L of water sample	Primary data	Other
2011	Tunisia [188]	sea bass/Energy	1 ton of live fish weight produced.	Primary data/ecoinvent	CML 2 Baseline 2000
2012	Tunisia [189]	Jatropha biodiesel/Energy	1 hectare of Jatropha	Primary data/Existing Literature	Other
2013	Tunisia [190]	olive-waste cake/Climate Change, Energy	1 kg of AC from by-product olive-waste cakes.	Primary data/existing literature/Ecoinvent v2.2	CML 2 Baseline 2000
2014	Tunisia [191]	groundwater pumping system/Not specified	1m3 pumped at a 35m depth, 2 bars of pressure, and 0.9 bars of friction losses in pipes.	Ecoinvent v2.2	recipe
2015	Tunisia [192]	shale gas/Not specified/Land Use, Water, Climate Change	1 MJ of shale gas,	Primary data	Recipe v1.06
2017	Tunisia [193]	Sheep/Chicken Meat/Not specified	One kg of carcass	Primary data/Existing literature	Other
2017	Tunisia [194]	sea cage/Eutrophication	1 ton of live fish	Primary data/Ecoinvent v3	Other
2017	Tunisia [195]	Seabass/Not specified	1 ton of fish at the fish farm gate	Primary data/Ecoinvent v3	CML2 baseline 2000
2017	Tunisia [196]	sulfuric acid production syst/Not specified	1 ton of sulfuric acid.	Primary data/Ecoinvent v3	ilcd
2017	Tunisia [197]	Tomato/Not specfied	1 ton of soilless geothermal greenhouse cherry tomatoes	Primary data/Ecoinvent v3.3	ilcd
2018	Tunisia [198]	fisheries (seafood)/ Acidification, Eutrophication, Climate Change, Photochemical oxidant	1 ton of landed seafood by demersal trawlers in the Gulf of Gabes	Primary data/Ecoinvent v3	CML baseline 2000

2019	Tunisia [199]	Agricultural practices/Not specified	1 hectare/1 dinar	Primary data/Existing literature/Ecoinvent	ReCiPe2016
2020	Tunisia [200]	Ground water irrigation/Water	area of land cropped over 1 year	Primary data/Existing Literature	ReCiPe 1.07
2020	Tunisia [201]	Tomato/Climate Change, Water, Acidification, Eutrophication	one ton of soilless cherry tomato produced.	Primary data/Ecoinvent v3.3/Agrifootprint 3.0	ILCD
2020	Tunisia [202]	Electricity/Climate Change	1 MWh of electricity generated	Primary data/WIOD/Simapro	ILCD
2020	Tunisia [203]	Electricity/Climate Change	1 kWh of electricity output	Primary data/Existing Literature	ILCD
2020	Tunisia [204]	Olive/Not specified	1 ton of olives and 1 ha of cultivated olive growing area	Primary data/Ecoinvent v3.2	ILCD
2020	Tunisia [205]	Seafood/Not specified	1 t of landed seafood	Primary data/Ecoinvent v3	ILCD
2013	Uganda [206]	Sanitary products/Not specified	Number of sanitary pads needed to provide effective protection from menstruation for one woman over one year.	Ecoinvent v2.2	Impact 2002+
2014	Uganda [207]	Waste/Climate Change, Ozone formation, human toxicity	The waste production for the base year 2011	Primary data/Existing literature	Other
2014	Uganda [208]	Charcoal/Climate Change	1 kg of charcoal produced and utilized	Primary data/Existing literature	CML2001
2016	Uganda [209]	Water/Land Use, Climate Change	3.57 liters (L) of potable water	Primary data/Existing Literature/Simapro	Eco-indicator 99
2016	Uganda [210]	Waste/Not specified	1 ton of impurity-free anima waste treated to produce a quality soil improver/fertilizer.	Primary data/Existing literature	CML
2019	Uganda [211]	Juice, dry fruits/Not specified	1 liter of packaged juice ready for consumption/1 kg of packaged dried fruits including the non-edible parts.	Primary data/Existing literature	CML2001
2012	Zambia [212]	Biochar/Air pollution, Climate Change	1 ton of maize	Primary data/Existing literature/Ecoinvent v2.2	Recipe (a voir)
2017	Zambia [213]	Biochar production System/ Climate Change	Preparation and sequestration of 1 kg biochar	Primary data/Existing literature/Ecoinvent v3.2	Recipe
2007	Zimbabwe [214]	Plastic carrier bag/Not specified	1kg of polyethylene	Primary data/Existing Literature/Gabi 3	Other
2007	Zimbabwe [215]	Paper/Climate Change	53gsm newsprint paper produced in Zimbabwe from the pulping of pinewood	Primary data	Eco-indicator 99
2008	Zimbabwe [216]	Vehicle leaf spring/Not specified	One life-cycle	Primary data	Eco-indicator 99
2008	Zimbabwe [217]	Cement/Not specified	1 ton of cement	Primary data	Eco-indicator 99
2015	Zimbabwe [218]	Steel balls/Not specified	1 kg of steel	Primary data	Other
2019	Zimbabwe [219]	Municipal solid waste management/Not specified	Annual generation of MSW	Ecoinvent v3	ReCiPe 2016
2020	Zimbabwe [220]	Waste/Climate Change, Eutrophication, Acidification	Annual biodegradable waste generation for Harare and its dormitory towns	Existing literature/Ecoinvent v3	Recipe 2016 v1.02

Table 1.5 Number of LCA research articles focusing on the main African agriculture products

Item	Value (tonnes)	Value (Mil USD)	Nb of research articles
Cassava	184,593,170	22,699	1
Sugar cane	95,840,702	3,717	3
Maize	82,896,881	14,121	1
Yams	71,730,960	13,445	0
Rice, paddy	34,535,315	7,737	1
Sorghum	30,377,045	5,596	0
Wheat	29,068,219	7,926	0
Sweet potatoes	26,622,564	4,423	0
Plantains and others	26,480,089	3,834	0
Potatoes	25,399,845	6,689	0
Oil palm fruit	21,496,241	2,748	1
Bananas	21,405,093	4,965	0
Tomatoes	20,945,245	6,612	6
Groundnuts, with shell	16,806,298	4,489	0
Millet	16,086,206	4,068	0
Sugar beet	14,171,993	520	0
Onions, dry	13,355,396	2,239	0
Oranges	9,448,539	2,884	1
Cow peas, dry	8,516,186	1,413	1
Mangoes, mangosteens, guavas	8,307,206	1,766	0
Barley	7,698,573	1,891	0
Taro (cocoyam)	7,575,329	1,985	0
Watermelons	7,053,887	1,350	0
Beans, dry	6,805,194	2,789	0
Cereals nes	6,144,760	1,600	0
Pineapples	5,750,509	1,324	0
Grapes	4,735,612	3,553	0
Seed cotton	4,714,532	1,589	2
Olives	4,475,264	1,355	1
Cocoa, beans	3,828,171	4,027	1

Table 1.6 Number of LCA research articles focusing on the main African exports

Product	Netweight (kton)	Trade Value (Million USD)	Nb of research articles
Vehicles	4,460	33,906	0
Petroleum spirit for motor vehicles	42,791	24,992	0
Light petroleum distillates nes	31,837	24,929	1
Cereals	64,108	19,146	0
Oils	35,026	14,967	1
Iron or non-alloy steel	20,699	13,932	1
Medicaments	395	11,248	0
Iron or steel	4,694	10,546	1
Machinery	5,051	8,321	0
Plastics	2,280	6,537	2
Rubber	3,474	6,126	0
Petroleum gases and other gaseous hydrocarbons	16,720	5,852	1
Vegetable oils	6,743	5,262	0
Fabrics, woven	1,012	4,600	0
Electrical apparatus	63,546	4,538	0
Vessels	539	4,497	0
Communication apparatus (excluding telephone sets or base stations)	1,607	4,152	0
Insulated electric conductors	562	4,020	0
Telephones for cellular networks or for other wireless networks	3,528	4,018	0
Floating or submersible drilling or production platforms	492	3,954	0
Dairy produce	1,680	3,935	1
Ethylene polymers	2,551	3,855	0
Fertilizers, mineral or chemical	8,034	3,810	0
Paper and paperboard	3,308	3,747	1
Aluminium	1,146	3,671	0
Data processing machines	2,104	3,495	0
Food preparations	2,008	3,424	0
Fish	2,714	3,342	7
Machines	435	3,234	0
Copper	520	3,207	0
Engines	405	3,113	0
Diamonds	0	3,065	0
Aeroplanes and other aircraft	3	2,912	0
Turbines	143	2,847	0
Tractors	451	2,588	0
Electric generating sets	227	2,474	0
Meat	867	2,337	4
Sugars	5,004	2,285	3
Footwear	475	2,274	0
Taps, cocks, valves and similar appliances	148	2,168	0
Oil-cake and other solid residues	4,438	2,104	1
Propylene, other olefin polymers	1,367	2,044	0
Sucrose	4,514	1,980	0
Wood, coniferous	4,112	1,898	0
Pumps	17,451	1,880	0
Machines and mechanical appliances	878	1,809	0
Telephone sets and other apparatus for the transmission or reception of voice, images or other data, via a wired or wireless network	49	1,796	0
Odoriferous substances and mixtures	153	1,732	0
Machine-tools	285	1,618	0
Motorcycles (including mopeds) and cycles	282	1,578	0

An example of a case study conducted in Africa is shown in Figure 1.7 with the environmental impacts of imported and locally grown fruits for the French market. Apple and Peach grown in France are compared with Mango (grown in Brazil) and Clementine (a kind of mandarin, grown in Morocco).

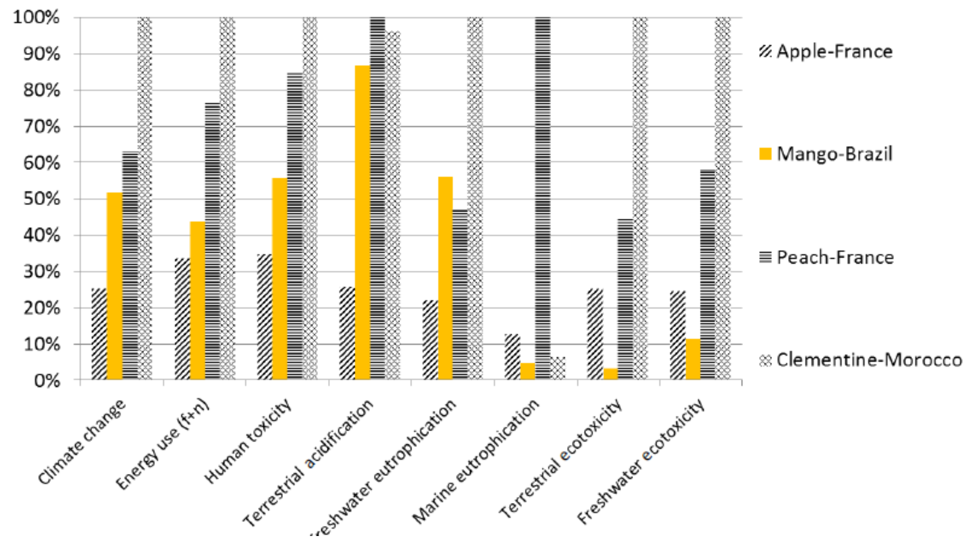


Figure 1. 7 Cradle-to-farm-gate life cycle assessment (LCA) results per kg of raw fruit for a selection of environmental indicators [108]

It can be observed that except for terrestrial acidification and marine eutrophication, the results are higher for all the other impacts categories in Morocco. There are several reasons that explain these results: at first, the higher amount of fertilizer used (6 kgN/kg). The high amount of water needed to grow clementine (8000 m3/hectare compared with 2.767 for Apple grown in France), despite the fact that water is scarce in Morocco and it has to be withdrawn from more than 100 meter-deep wells. The energy required to pump this water is also important (22,830 MJ per hectare compared with 2,946 for Mango grown in Brazil). Moreover, the Moroccan electricity mix is more than 50% based on fossil energy (coal) which explains why the impact of climate change is also high. Morocco is concerned about the environmental impact of energy consumption. Therefore, it pushes for a shift to renewable energy, with Ouarzazate Solar Power Station opening in 2016, a 510MW capacity solar power station located in the central part of the country.

Finally, when looking at the African countries focusing on LCA, we find out that Africa’s top economies are also the ones focusing the most on LCA: Egypt, Nigeria, South Africa (Figure 1.8). To further develop LCA in Africa, the UNEP Life Cycle Initiative has promoted the creation of national LCA databases in South Africa and Uganda [221]. This is a crucial step as LCA's history has shown that its development in each country always started with a focus on Life Cycle Inventories (e.g., In Japan, 20 years ago, with several works from AIST).

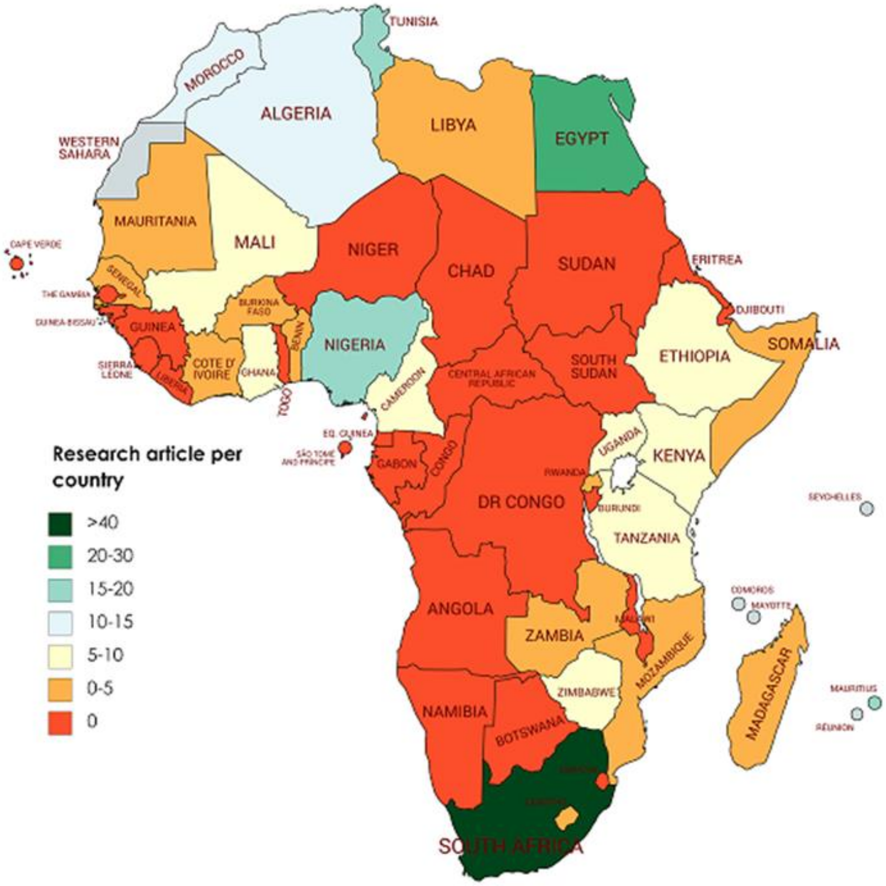


Figure 1. 8 Number of LCA studies per African country

1.2 Research Background

1.2.1 Life Cycle Assessment (LCA)

1.2.1.1 Description

Life-Cycle Assessment (LCA) is one of the tools to support decision-making for sustainable development. It is used to evaluate and compare the impacts of products & services; it covers all the stages from resource extraction to end-of-life, including production stage or use stage (Figure 1.9).

According to the International Organization for Standardization (ISO) standard 14040 [222] of four mandatory steps: Goal and Scope definition, Inventory analysis (LCI), Impact assessment (LCA), and interpretation (Figure 1.10). The “Goal and Scope definition” is aiming at answering the question “why” (why is this research conducted? What is the aim?) and “how”(what is the functional unit? What about the system boundaries?). The functional unit of a product is a unit of reference specific to the product, used to compare its function. The system boundaries are like “the perimeter” of the study. The inventory analysis analyzes the elementary flows related to the product, such as the input of resources (materials) or the emissions of pollutants. The “Impact assessment” (LCIA) helps to translate a long list of elementary flows into a much shorter list of impact categories such as climate change or water use (see Section 1.2.1.3).

Finally, the interpretation is based on the three previous steps; it aims at explaining the results and reaches a conclusion for the LCA study.

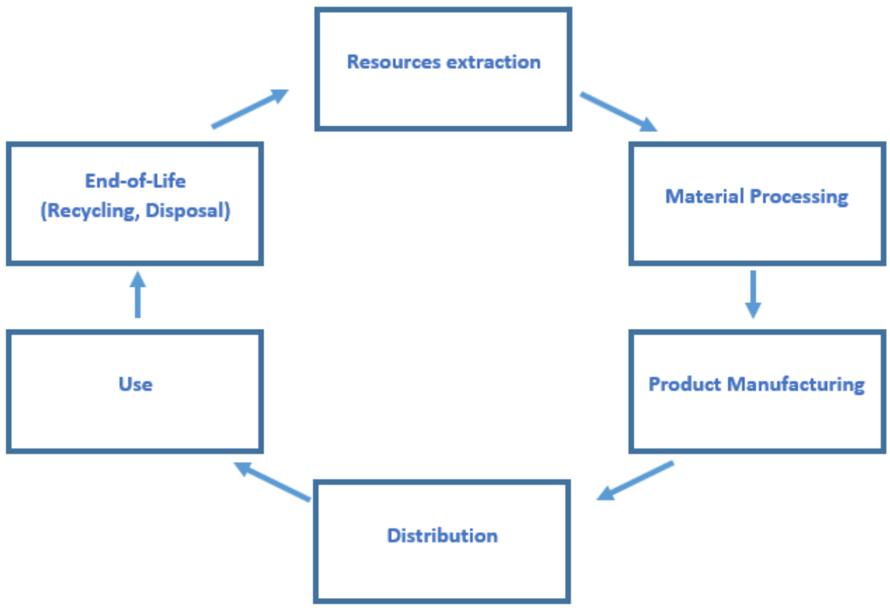


Figure 1. 9 Life Cycle Assessment steps

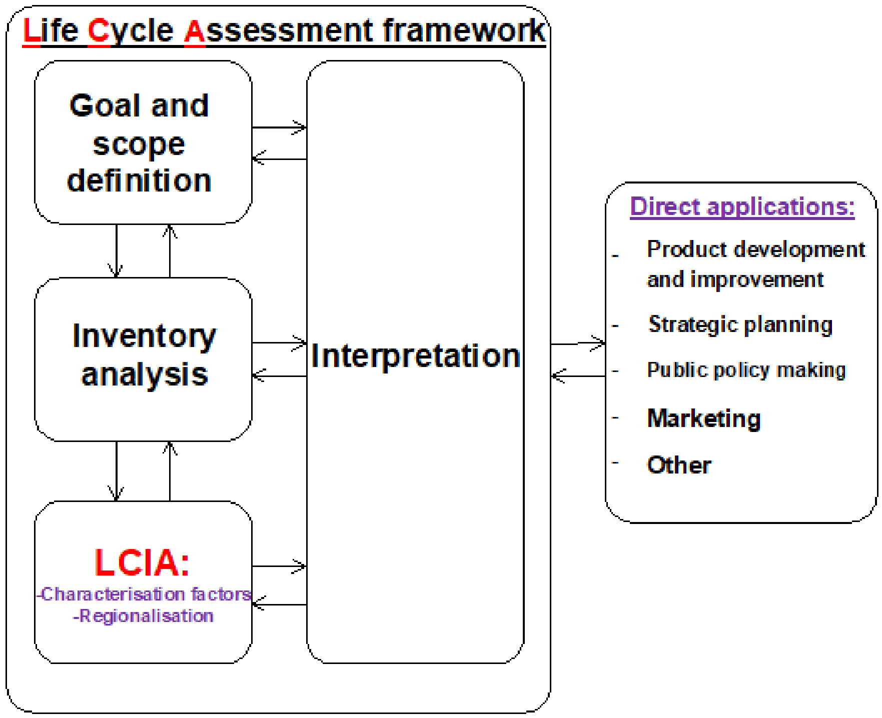


Figure 1. 10 Life Cycle Assessment framework

1.2.1.2 Focus on LCI

There are mainly two types of approaches for life cycle inventory (LCI) analysis in Life Cycle Assessment (LCA). The most common is called "process-based", using elementary flows (for example, emissions, resource consumption) linked to the system's functional unit. The other one is called "input-output", using monetary flows related to the system.

For "process-based" LCA, flows are usually obtained through data collected directly or using a life cycle inventory database such as Ecoinvent [223] or IDEA [224].

For "Input-output" LCA, flows are calculated by multiplying the total demand per functional unit by the emissions per monetary unit in each sector. Several different databases detail emissions per monetary unit, such as 3EID [225] for GHG emissions in Japan. The input-output approach is useful when detailed inventory is not available as the calculation can be done based on a monetary value. National economic transaction matrices are available for several countries, especially developed countries. Global input-output tables can also be used to assess countries' environmental footprint of countries, such as the carbon footprint of global tourism [226]. Such Global input-output tables are referred to as Multi-regional input-output tables (MRIO). Examples include EORA [227] or WIOD [228].

1.2.1.3 Focus on LCIA

As explained above, Life Cycle Impact Assessment (LCIA) is the third step of an LCA study. It is a critical step whom the roots are sometimes unknown, even for some LCA users. The step links the elementary flows (consumptions and emissions) to different impact categories (e.g., Climate change, Air Pollution, Water Use). For example, the impact of 1 kg of carbon dioxide (CO_2) is not equal to 1 kg of methane; the impact of 1kton of Nitrogen Oxide (NO_X) is not equal to 1kton of Sulfur Dioxide (SO_2). The impact of water use in Japan is not the same as the water use in Morocco due to the scarcity.

The LCA results are the product of elementary flows' inventory with the characterization factor (Figure 1.11).

The characterizations factors for different impacts, substances are obtained through models (e.g., Chemical Transport Model, Hydrological Model, or Global Climate Model).

An example of an LCIA method (Recipe 2016 [229]) is given in Figure 1.12. An LCIA method is a set of different LCIA models. As shown in the figure, the impacts are usually classified into two categories: midpoint and endpoint. The latter affects an area of protection, which is often defined as Human Health, Ecosystem, and Natural resources. The midpoint impacts happen between the emission/consumption of substance and the area of protection. The inventory, midpoint impact categories, area of protection are related following different impact pathways. Finally, weighting (weighting between midpoint impact category or area of protection) can also be applied (e.g., LIME3 [230]) to convert all the different impacts into one single indicator (e.g., US dollar) in order to distinguish which impact(s) is/are the most important.

$$\text{IndicatorResult}_{category} = \sum_{substance} \text{CharFact}_{cat,subs} \times \text{InventoryResult}_{subs}$$

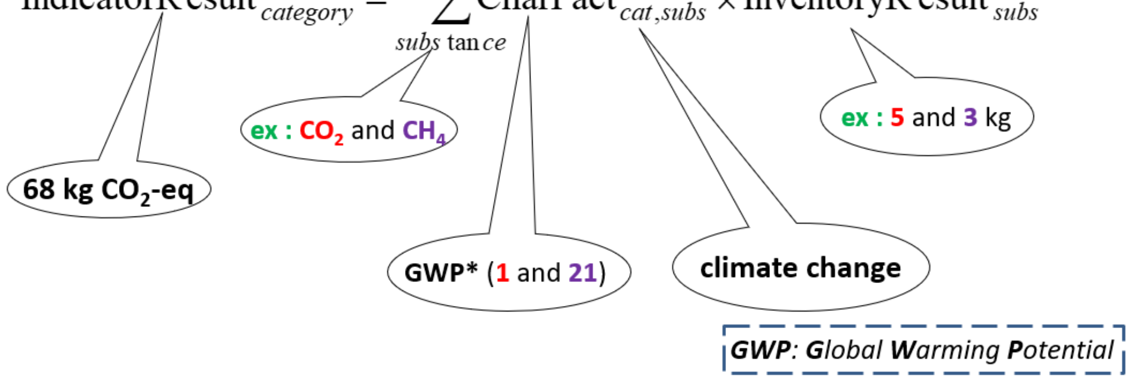


Figure 1. 11 Example of characterization factors application for climate change

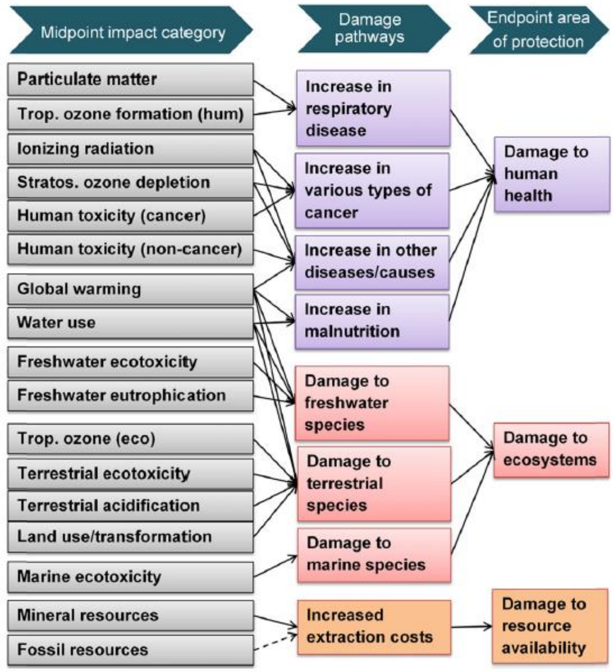


Figure 1. 12 Overview of Recipe 2016 LCIA method

A summary of the leading global LCIA methods (Recipe2016 [229], LIME3 [230], and Impact World+ [231]) is provided in Table 1.7. Each of them includes several impacts categories; all of them consider Air Pollution, Climate change, Fossil and mineral resources use, land transformation, Photochemical ozone formation, and water-related impacts. For the different areas of protection, three are mainly considered: Human health, Ecosystems, and Resources. The specificity of LIME3 is that it includes global weighting factors for the G20 countries, based on the Willingness to Pay (WTP). It helps to convert all the different environmental impacts into a single monetary indicator (US Dollar).

Table 1.7 Comparison of the different global LCIA methods (in light orange- Impact categories, in Green-Area of protection, in dark orange- Weighting)

	Impact World+	LIME3	Recipe2016	Example of indicator
Acidification	x	-	x	kgSO2eq/kg
Air Pollution	x	x	x	kgPM2.5eq/kg
Climate Change	x	x	x	kgCO2/kg
Eutrophication	x	-	x	kg N N-limeq/kg
Fossil resources	x	x	x	USD/kg
Ionizing radiation	x	-	x	MJ/kg
Land transformation	x	x	x	m2/m2
Mineral resources	x	x	x	kg/kg
Photochemical ozone formation	x	x	x	kg NMVOCeq/kg
Ozone Depletion	x	-	x	kg CFC11eq/kg
Toxicity	x	-	x	CTUh/kg
Water	x	x	x	m3/m3
Ecosystem quality	x	x	-	PDF·m2·yr/kg
Ecosystem services	x	x	x	PDF·m2·yr/kg
Human Health	x	x	x	DALY/kg
Resources	x	x	x	USD/kg
Weighting	-	x	-	USD/kg

At endpoint, the use of Disability-adjusted life year (DALY) as measurement indicator for the damage of air pollution on human health is particularly relevant as it provides a consistent measure of population health which can be used to evaluate the relative burden of different diseases and injuries, not only mortality but also disability. It is also consistent with the method chosen by the WHO but also the global burden of disease (GBD), a reference from the Institute for Health Metrics and Evaluation (IHME).

DALY is the number of years lost due to ill-health, disability, or early death. It is composed of the years lived with disability (YLD) and years of life lost (YLL) as shown in Figure 1.13 and:

$$\mathbf{DALY = YLD + YLL}$$

With $\mathbf{YLD = I \times DW \times L_1}$**,**

$\mathbf{YLL = N \times L_2}$

I = number of incident cases in the population, DW = disability weight of specific condition, and L_1 = average duration of the case until remission or death (years); N= number of deaths due to condition, L_2= Standard life expectancy at age of death.

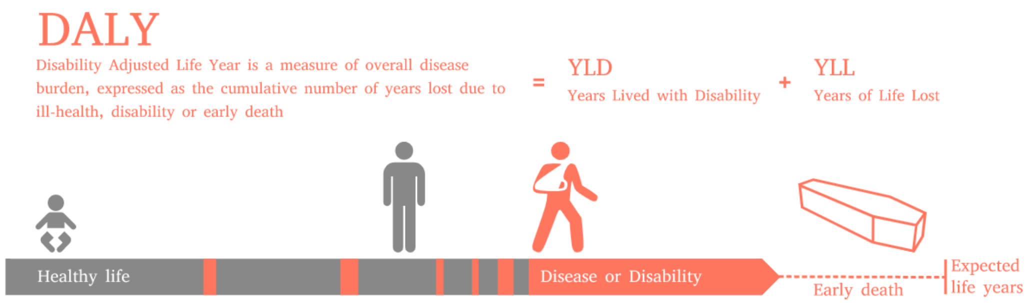


Figure 1. 13 Explanation of DALY indicator [232]

As shown in Table 1.8, the consideration of DALY as indicator has several advantages compared with "death". Both morbidity (YLD) and mortality (YLL) can be combined in a single indicator, it integrates the burden caused by a disease over the life (not only at a given moment). Further discussions can be conducted to compare different health hazards and different geographic region. The major limitation usually addressed to DALY [233-235], comes from the accuracy of disability weight (DW). of specific condition. This value is between 0 (no impact on life) to 1 (equivalent to death). Experts argues that it is difficult to compare the burden caused by different diseases, DW mostly depends on a subjective perception of the health loss or welfare loss. It does not evaluate how a society can adapt to the life with the disease. Also, this parameter is obtained at a global scale, it is difficult to consider the local situation due to the lack of data especially in developing countries. An easy example to understand these limitations, is blindness, previous agreement was toward the welfare loss (DW = 0.594) whereas current agreement focuses rather on health loss (DW=0.195) [236.237]. One might argue that depending on the point of view adopted or the location, DW can vary a lot.

Table 1.8 Advantage and disadvantages of Death vs DALY.

	Death	DALY
Advantages	-Explicit, easy to understand for everyone - Do not require any cohort study or expert panel to collect parameters	- Integrate the burden caused by a disease over the lifetime -Take into account the characteristics of a population (age distribution, health condition)
Disadvantages	- Capture the burden caused by a disease only at "t" - Do not take into consideration the characteristics of a population	- The YLD is based partly on a subjective opinion, depending on the point of view adopted, DW can change - It is difficult to collect specific information for each country or at a local-level

1.2.2 Importance of regionalization in LCA

1.2.2.1 LCIA and regionalization: Global LCIA method

Global LCIA methods were developed to improve the quality and accuracy of LCA studies. One keyword is "regionalization": Emissions or resource consumption from a product and its related environmental impacts can occur at different locations (e.g., electric vehicle). By taking the country-average emissions of a product (e.g., PM2.5 emissions) and the country-average damage for these emissions, it is difficult to provide specific recommendations to decision-makers at the local level. Significant misrepresentation of the regional environmental impacts might occur. An example is given in Figure 1.14. The emissions (e.g., NOx) might occur in "area 1" and be transported to areas 2 and 3 and finally have the most impact in area 3.

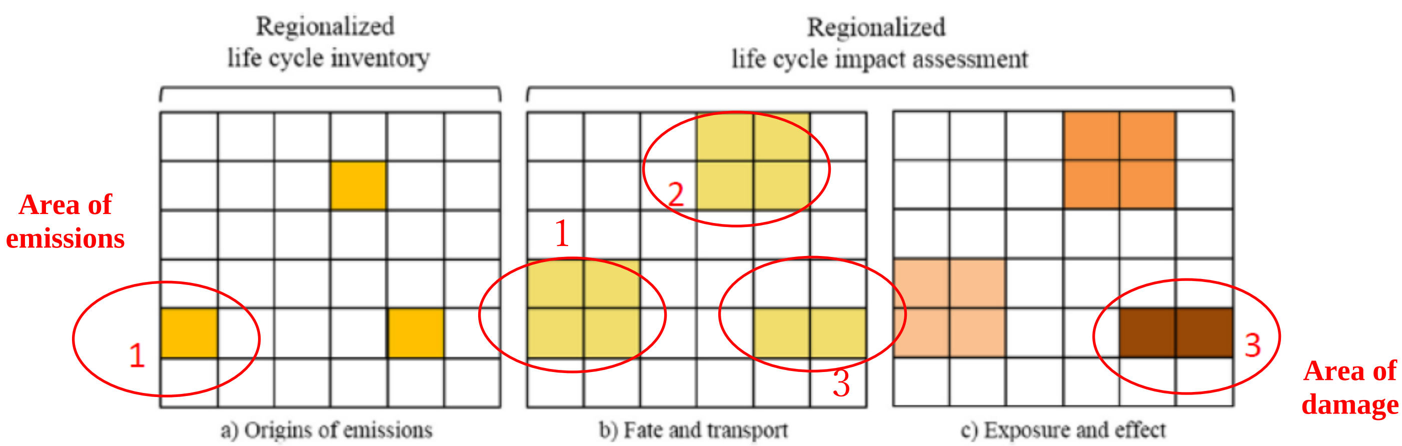


Figure 1. 14 Description of the regionalization in LCIA

Global LCIA methods such as LIME3 [230], Recipe 2016 [229], and Impact World + [231] have been developed in the past 10 years to account for these differences. Each of them introduces different models that can evaluate damages at the local level (with more or less resolution). This is a significant change from the methods developed at the beginning of 2000 (LIME1 specific to Japan only, Traci specific to the USA or, CML specific to Europe). LCIA used to be done by considering characterization factors common to a whole continent or even to the world.

1.2.2.2 Regionalization in Air pollution models

Chemical Transport Models (CTMs) are computer programs that are used to simulate chemical and meteorological processes. They can estimate the concentration and deposition of air pollutants. Therefore, they are very useful in estimating the impact of air pollution on human health. Another asset is their high resolution, helping to assess at the grid scale level. Their resolution can be up to 5km (nearly 10,000 grid cells). They can be eulerian or lagrangian. Several examples with their description are provided in Table 1.9.

Table 1.9 Characteristics of the different chemical transport model (CTM)

Name	Type	Resolution
CMAQ [238]	Eulerian	5km
GEOS-Chem[239]	Eulerian	12.5km
MIROC-CHASER [240]	Lagrangian	About 100km
TM5-FASST [241]	Eulerian	About 100km

In the models used in Recipe 2016 [242] or LIME3 [243], regions were aggregated to speed-up the calculation time: 14 regions in LIME3 model, 56 in Recipe 2016. In both models, the region definitions for Africa is limited (respectively 6 and 2 regions). Therefore, the damage factors (expressed in DALY/kton of pollutants) proposed do not reflect the situation at the country-level. Gronlund et al. (2015) [244] showed for example, that differences between Urban and Rural-area could be observed for damage factors. The African population being heterogeneously spread on the continent, the same observations might be observed. That could be possibly the reason why both models provide different damage factors for Egypt (2000 vs. 398 DALY/kton).

1.2.3 Importance of regionalization: example with the external cost of electricity in G20 countries

The impact of regionalization should not be unevaluated as different LCI or LCIA method can bring different results [245, 246]. We decided to evaluate the external cost of electricity in G20 countries using LIME3 method [247] (An overview of LIME3 method is provided in Appendix 1.2 & 1.3). It is a good example as different types of power plants or different technologies can have different emissions. The location is important too as for example the impact of fossil fuel power plants emissions have different impacts following the population living around the plant. Electricity sector is also one of the sectors with the highest impact on air pollution (in India, the public-electricity and heat-production sector was responsible for 44% and 65% of total NOx and SO2 emissions in 2012, respectively [248]) or climate change (42% of total annual CO_2 emissions [249]). Electricity generation reached 26,615 TWh in 2018 [250], increasing by 3.7% from the previous year, with around 85% of consumption occurring in G20 countries. With the steadily growing economy of newly industrialized countries such as India or Indonesia, the damage caused by the electricity sector could keep growing in the future if no measures are taken to mitigate the effect of population and economic growth on energy consumption. As shown in Figure 1.15, different electricity generation sources have a different lifecycle.

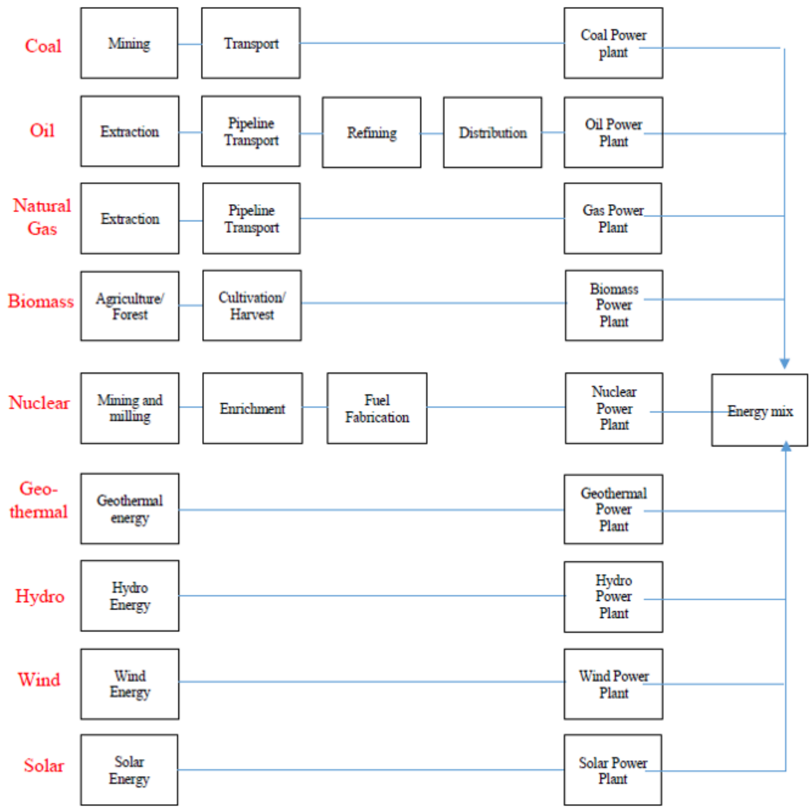


Figure 1. 15 Pathways for electricity generation

Turconi et al. (2013) [**251**] conducted a review of 167 case studies found in the literature and reported that the range of values for carbon dioxide emissions was large depending on the source: between 2 (hydropower) and 1050 kg CO2 eq/MWh (hard coal). Similarly, the same trend for these two technologies was observed for NOx and SO2 emissions: 0.004–3.9 kg NOx/MWh and 0.001–6.7 kg SO2/MWh. Therefore, to perform a transparent analysis, an approach based on life-cycle thinking was adopted: The life cycle impact assessment method based on endpoint modeling (LIME3) was used to evaluate the environment impact assessment. The system boundaries and the approach used in this study is detailed in Figure **1.16** & Figure **1.17**. Resources consumption and emissions that have an environmental impact during the electricity generation life-cycle are taken into account and later assigned to environmental impact categories. These different impacts having damages on the area of protection such as human health or biodiversity. These damages are expressed in their own specific unit (e.g., DALY) therefore an economic weighting is applied to convert and aggregate these damages into a single monetary value: the external cost.

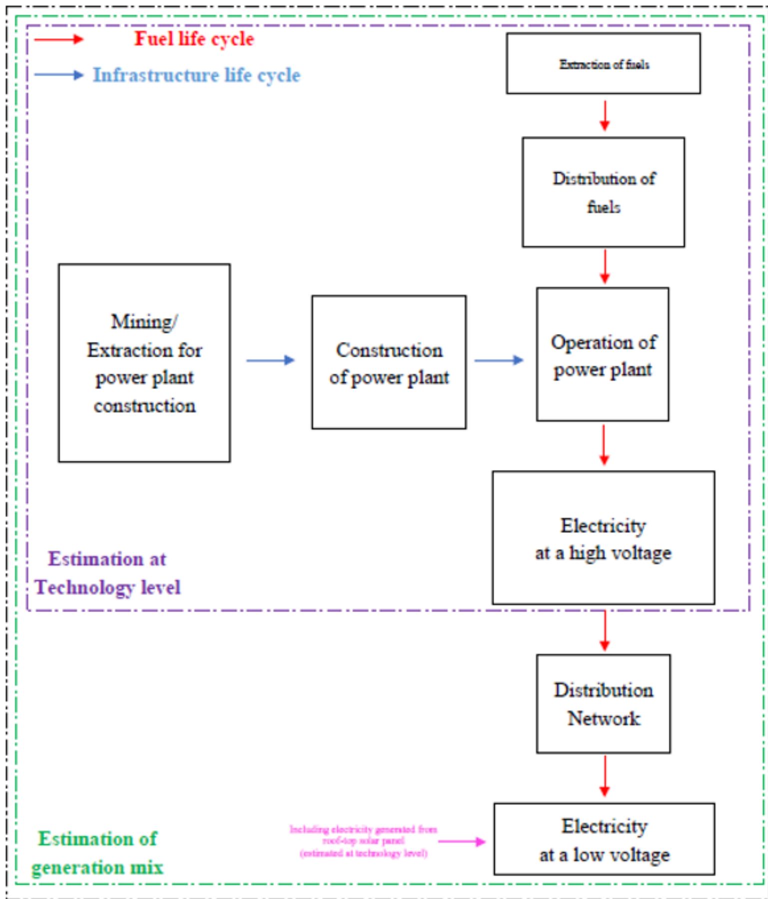


Figure 1. 16 System boundaries for the study

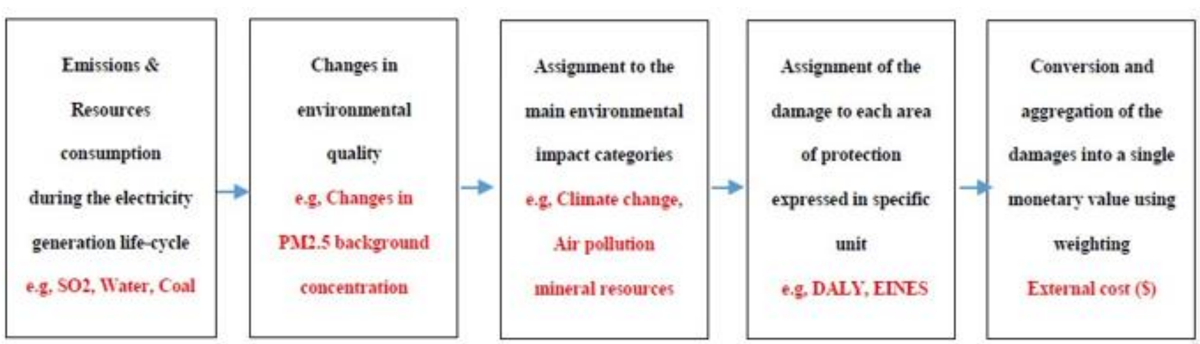


Figure 1. 17 Framework of the study

The data contained in the Ecoinvent Database v3.4, which is included in LCA Software SimaPro v8 were used. They correspond to global electricity generation in 2014 (for each country), and are the latest data available in the database. According to these data, Saudi Arabia, South Africa, and Indonesia have the highest dependence on fossil fuels (100%, 92%, and 86% of the energy mix, respectively). On the other hand, France, Canada, and Brazil have the lowest dependence (5%, 20%, and 24% of the mix, respectively). Concerning electricity generation from renewable energy (hydropower, solar, and wind energy), Brazil, Canada, and Italy are the leading G20 countries (65%, 62%, and 35% of the mix). Reliance on biofuels is quite low for the G20 (3% in the non-weighted average of the G20 energy mix), but Germany (9%), the UK (8%), Italy (8%), and Brazil (8%) still rely on them. The electricity mix is provided in Figure 1.18.

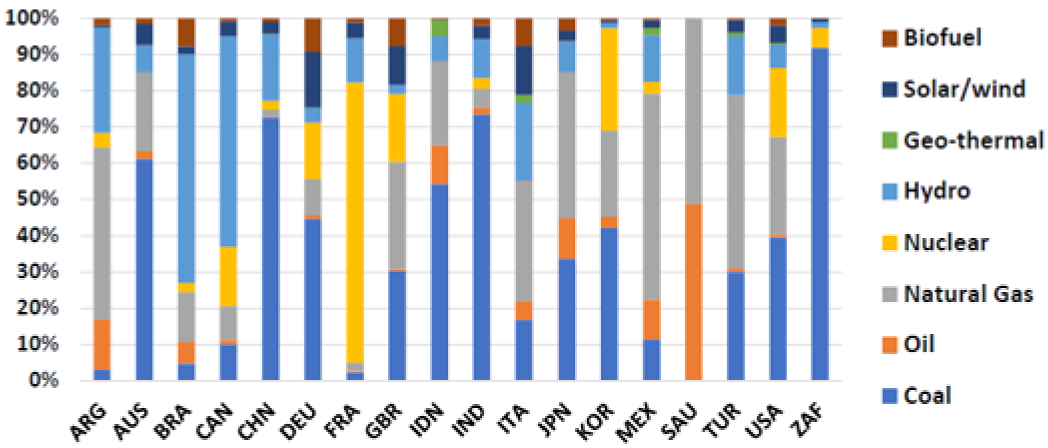


Figure 1. 18 Electricity mix in G20 countries

Using the data collected in Ecoinvent database combined with LIME3 it was possible to estimate the external cost of electricity in G20 countries. External costs for each country were determined as detailed in Figure 1.19. The results were estimated between 0.005 \$/kWh (France) and 0.172 \$/kWh (India). The non weighted average result for the 19 countries was 0.044 \$/kWh. As suggested by previous studies, the external cost is largely impacted by the dependence of a country on fossil-based energies.

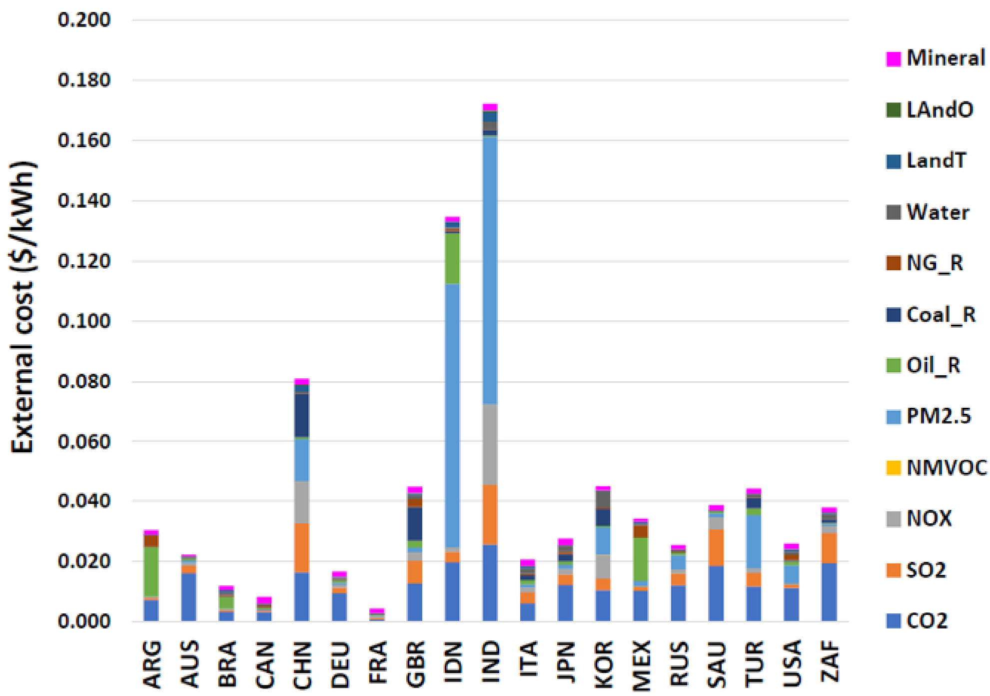


Figure 1. 19 External cost of electricity in G20 countries

To find these results the external cost of each electricity generation source in each country were at first determined (Table 1.9), several interesting findings can be highlighted:

For hard coal (HC), the results were between 0.021 (Germany) and 0.174 $/kWh (India): the emissions of PM2.5 for 1 kWh of electricity generated using coal in India were almost seven times higher than the G20 average (2.5 g/kWh). The PM2.5 integration factor was also the highest in the G20 with 36 $/kg due to higher population density. India had a population density of 416 inhabitants/km2 compared with the 25 inhabitants/km2 in Brazil, resulting in a much smaller integration factor for PM2.5 (1.8 $/kg). In addition, Germany had the lowest emissions of SO2, NOx, and PM2.5 from coal power-plants among G20 countries due its technological performance.

For lignite, the results were between 0.026 (Australia) and 0.282 $/kWh (South Korea). For South Korea, the results were mainly explained by the impact of PM2.5: even if the emissions per kWh (0.0088 kg) were close to the G20 emissions average, the integration factor of PM2.5 for South Korea was high (25 $/kg), the third highest among the studied countries (behind India and China). For Australia, the inventory and integration factors for air pollutants (very low population density of 3 inhabitants/km2) had both lower values than those of other countries.

For natural gas (NG), two types of power plants were assessed for this study: conventional and combined-cycle (CC). For the conventional type, results were found between 0.013 (Australia, Brazil) and 0.031 $/kWh (Russia). For Russia both the CO2 and natural-gas consumption inventories show the highest amounts among the G20 countries. The CO2 emissions of conventional plants in Russia are two times higher than the G20 average, but the national reserves of natural gas in the country are the highest in the world. Thus, the impact on this resource was still limited (0.001$). Indeed, as detailed in Table A5, the damage factors for fossil fuels and resource consumption in LIME3 are based on yearly extraction compared to the actual reserves [57]; the smaller the ratio is, the lower the damage factor is. Global trade was also taken into account in LIME3; as a result, a country that imports resources from another where scarcity was low (e.g., oil from Saudi Arabia) had a smaller damage factor. On the other hand, a country that had limited reserves and mainly used these resources had a higher damage factor (e.g., oil in Argentina). For Turkey, natural-gas imports were mainly from Russia, and CO2 emissions were also on the same level of the G20 country average, so impacts were limited. Australia and Brazil both show lower air-pollutant impact due to their small population density. For combined-cycle plants, results were estimated to be lower than conventional ones, with values between 0.007 (South Africa) and 0.020 $/kWh (China, India). Combined-cycle plants had better efficiency, as they required about 30% fewer resources on average, and CO2 emissions were also reduced at about the same level. The difference of results between countries for this technology were mainly explained by higher natural-gas consumption and more CO2 emissions in China and India, while the air pollution damage in South Africa was low due to the population density.

Oil is the resource with the highest external costs (between 0.041 (Japan) and 0.240 $/kWh (UK)). For Japan, the low cost is explained due to the oil exports from Saudi Arabia, whose reserves are the second highest in the world, with a proven reserve of 266,455 million barrels [58]. For the UK, lower oil reserves coupled with much higher SO2 emissions (almost two times higher than the G20 average) justify this observation.

For wind power, results were between 0.002 (Australia, Indonesia) and 0.015 $/kWh (Russia). The difference of impact between onshore (ON) and offshore (OFF) wind turbines was not significant. The impacts mainly come from material consumption (more than 65% of the total impact); in particular, chromium (26%); nickel (24%), as one of the element of stainless steel; and copper (10%), used for cables.

For hydropower (Hydro), several types of systems were evaluated: Run-of-river (RR), reservoir I,

and pumped-storage (PS). The highest cost was determined for pumped storage, with 0.227 $/kWh in India; this impact is due to the use of electricity for pumpage, as more than 1.4 kWh of electricity is necessary on average to generate 1 kWh of electricity. Reservoir technology has the second highest impact, especially in countries where the damage factor for water is high, such as Korea (0.042$) and Japan (0.028$). Finally, run-of-river hydropower showed the lowest impact (0.001$ on average), mainly with an

impact on land transformation.
For nuclear power, the results were between 0.001 (Brazil, Russia) and 0.007 \$/kWh (South Korea). The impact is mainly due to the use of water (38%), uranium (12%), and chromium (11%). These findings should be treated with caution, as our method does not include the impact of radioactive leaks/waste or the potential risk of nuclear incidents.

For solar power, the results were between 0.003 (Australia) and 0.017 \$/kWh (UK); the impacts were shown to be similar for open ground and roof installations. For roof-top installations, the contribution of metals is mainly from copper (12%), gold (9.3%), and aluminum (5.1%).
Finally, for geothermal power, with emissions of carbon dioxide and air pollutants much lower than those of other technologies, the impacts were shown to be less than that of fossil-based electricity generation.

A summary of the inventory items having an influence on the external cost for each system is provided in Appendix 1.4.

Table 1.10 External cost of each electricity generation technology in each country

	HC	Lignite	NG	Oil	Wind	GEO	Hydro	Nuclear	Solar
			C/CC		ON/OFF		RR/PS/R	BW/PW	OG/Roof
ARG	-	-	-/-	-	-/-	-	-/-/-/-	-/-	-
AUS	0.026	0.026	0.013/0.008	0.096	0.002/-	-	0.000/0.031/-	-/-	0.004/0.003
BRA	0.023	0.047	0.013/0.009	0.081	0.003/-	-	-/-/0.002	-/0.001	-/0.006
CAN	0.034	0.029	0.022/0.014	0.071	0.004/-	-	0.001/0.017/0.002	-/0.004	0.008/0.009
CHN	0.101	-	0.021/0.020	0.146	0.009/0.006	0.009	0.001/0.112/-	-/0.004	0.015/0.014
DEU	0.021	0.027	0.019/0.012	0.083	0.005/0.004	0.005	0.001/0.024/0.004	0.002/0.002	0.011/0.010
FRA	0.037	-	0.017/0.012	0.087	0.003/0.003	0.004	0.001/0.005/0.004	-/0.002	0.009/0.008
GBR	0.064	-	0.017/0.012	0.24	0.004/0.005	0.007	0.001/0.058/-	0.005/0.005	0.014/0.017
IDN	-	0.194	0.020/0.012	0.133	0.002/-	0.006	-/-/0.005	-/-	-/0.010
IND	0.174	0.143	0.021/0.020	0.112	0.006/-	0.009	0.001/0.227/0.068	0.005/0.004	-/0.010
ITA	0.041	0.133	0.019/0.011	0.083	0.005/-	0.005	0.001/0.028/0.006	-/-	0.010/0.009
JPN	0.036	-	0.020/0.013	0.041	0.005/0.005	0.005	0.001/0.038/0.028	0.005/0.005	0.011/0.010
KOR	0.062	0.282	0.020/0.011	0.082	0.004/0.004	-	0.001/0.062/0.042	-/0.007	0.015/0.015
MEX	0.027	0.043	0.022/0.014	0.134	0.003/-	0.004	0.001/-/-	0.003/-	0.009/0.005
RUS	0.033	0.069	0.031/0.008	0.141	0.015/-	0.004	0.000/0.032/0.002	0.001/0.001	-/0.008
SAU	-	-	0.015/0.008	0.046	-/-	-	-/-/-	-/-	-/0.005
TUR	0.048	0.141	0.014/0.009	0.133	0.003/-	0.005	0.001/-/0.009	-/-	-/0.008
USA	0.028	0.055	0.020/0.013	0.138	0.003/-	0.004	0.001/0.029/0.011	0.002/0.002	0.007/0.007
ZAF	0.035	-	-/0.007	0.047	0.006/-	0.004	0.001/0.049/0.013	-/0.002	-/0.009
AVG	0.049	0.099	0.019/0.012	0.105	0.005/0.005	0.005	0.001/0.055/0.015	0.003/0.003	0.011/0.009

1.2.4 Importance of regionalization: example with the African damage factors for air pollution in different models

As explained previously, several LCIA models in the past tried to evaluate the damage of air pollution in Africa. Mainly four of them were developed: One for each global LCIA method + the one developed by Ono et al. [252]. A description of the models is provided in Table 1.11.

Table 1.11 Comparison of the different models for air pollution in LCIA

Model	Number of regions considered	Diseases Considered	Values obtained for BCOC emissions (DALY/kton)
Ono et al.	**4**	**ALRI COPD IHD LC Stroke**	**Northern Africa: 1100 Western, Central, Eastern Africa: 1210 Southern Africa: 376 South Africa: 668**
Gronlund et al.	**3**	**COPD IHD LC Stroke**	**Africa & Middle East (Utban): 2000 Africa & Middle East (Rural): 80 Africa & Middle East (Remote): 7**
Tang et al.	**2**	**COPD IHD LC Stroke**	**Northern Africa: 398 Other Africa: 176**
Van zelm et al.	**6**	**COPD IHD LC Stroke**	**Northern Africa: 660 Egypt: 2200 Western Africa 240 Eastern Africa: 140 Southern Africa 63 South Africa: 320**

It can be observed that differences exist for the same region among the different methods.

It is explained by the difference of resolution in each model. The model from Gronlund et al. is a very good example to understand the difference of results for the damages factors (more than 20 times different) when considering the urban or rural area. This is the explanation for the lower results in Tang et al. model, which divides Africa into only two parts: Northern and the rest. Therefore, the damage factors provided are, in a way, the average damage factors in Africa; it doesn't show the differences of the population between countries (e.g., Nigeria about 200 million inhabitants, Liberia 3.5 million). The difference of results for Egypt symbolizes this lack of resolution; when comparing the damages factors in Tang et al. and Van zelm et al. When comparing the damages factors in Tang et al. and Van zelm et al., we can also observe different damage factors for Egypt: 2,200DALY/kton in Van zelm et al. (considered as a single country in the model); 398 in Tang et al. (considered in a region composed with North Africa and the Middle East).

Another point has to be noted, Ono et al. showed that the impact of ALRI is important in Africa. Indeed, 73% of the global deaths related to respiratory infections happened in Africa. This is the second explanation for the lower results (=lower compared with other regions outside Africa) obtained in previous models, as most of them did not consider ALRI.

1.3. The situation of air pollution in 2020: the impact of COVID-19 pandemic

The COVID-19 pandemic triggered an unprecedented change in people's daily lives worldwide, significantly impacting both the economy and human health. The pandemic has officially caused more than 1,000,000 deaths (11 November, 2020 [253]).

The countermeasures against the progress of the COVID-19 pandemic had a severe impact on the economic activity. For example, the number of flights passenger decreased by nearly 90% in April-June [254]. In April, industrial production in the EU decreased by 20% [255]. The energy demand was also reduced by up to 25% in the period, sometimes in April [256]. Especially the demand for fossil fuels was reduced: Coal demand was decreased by 8% compared with the first quarter of 2019, oil also, about 5% following the reduction of road & air transport.

This reduction of activity impacted the emissions and concentration of pollutants worldwide: In Europe, Sicard et al. [257] found for example that the PM2.5 concentration was reduced by 8% in average during the lockdown. In large cities such as Sao Paulo, the PM2.5 concentration was reduced by 46%, [258].

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252. 小野 あかり(Ono Akari), **修士論文** （Master Thesis）. 化学輸送モデルを用いた影響評価手法の開発と越境移動を考慮した大気汚染フットプリント分析 (Development of impact assessment method using chemical transport model and air pollution footprint analysis which considering transboundary movement)

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Chapter 2: Research purpose

2.1 Research proposal

In this previous chapter, we presented the different environmental impacts currently existing in Africa. We also highlighted the importance of regionalization in LCA and the need for accurate tools to evaluate air pollution impacts in Africa. Based on these points, the aim of this research is set as follow:

1- Improve LCA regionalization in Africa by evaluating damage factors for air pollution considering four types of pollutants: NOx, SO2, BCOC, NOx
2- Evaluate the damages caused by African economic sectors in both production and consumption-based approaches
3- Estimate the reduction of air pollution damages in 2020 for Africa due to the Coronavirus (COVID-19) pandemic countermeasures, highlight the importance of the localization.

The expected results are:

A) Improve the accuracy of air pollution damage estimations in Africa. It is a key point to avoid an under-estimation of air pollution damages in Africa. It will also improve the quality and reliability of the LCA studies conducted in Africa.
B) Use these damage factors to identify which sectors are responsible for the damage in African countries. It is an important point to provide advice to policymakers in order to strengthen regulations/policies in some sectors (e.g., Agriculture). Estimate also the burden of trade for African countries, including the impacts due to exports outside Africa.
C) Estimate the reduction of air pollution impacts during the COVID-19 pandemic and provide suggestions for the post-COVID period.

2.2 Research plan

The structure of this thesis is shown below. (Figure 2.1)

Chapter 3 describes the method to determine the damage factors for air pollution; the steps are: divide the continent into 20 regions following different geographical, socio-economic parameters and possible interest for LCA research; collect an emissions inventory for these 20 regions; run a computer simulation using a chemical transport model; Analyze the output of the simulation.

Chapter 4 provides an example of an application of these damages factors, evaluating the impact of African activity sectors in both production and consumption-based approaches. It also evaluates the impact of trade.

Chapter 5 provides an insight into the impact of air pollution in 2020. It evaluates the reduction of air pollution impacts due to the COVID-19 pandemic countermeasures.

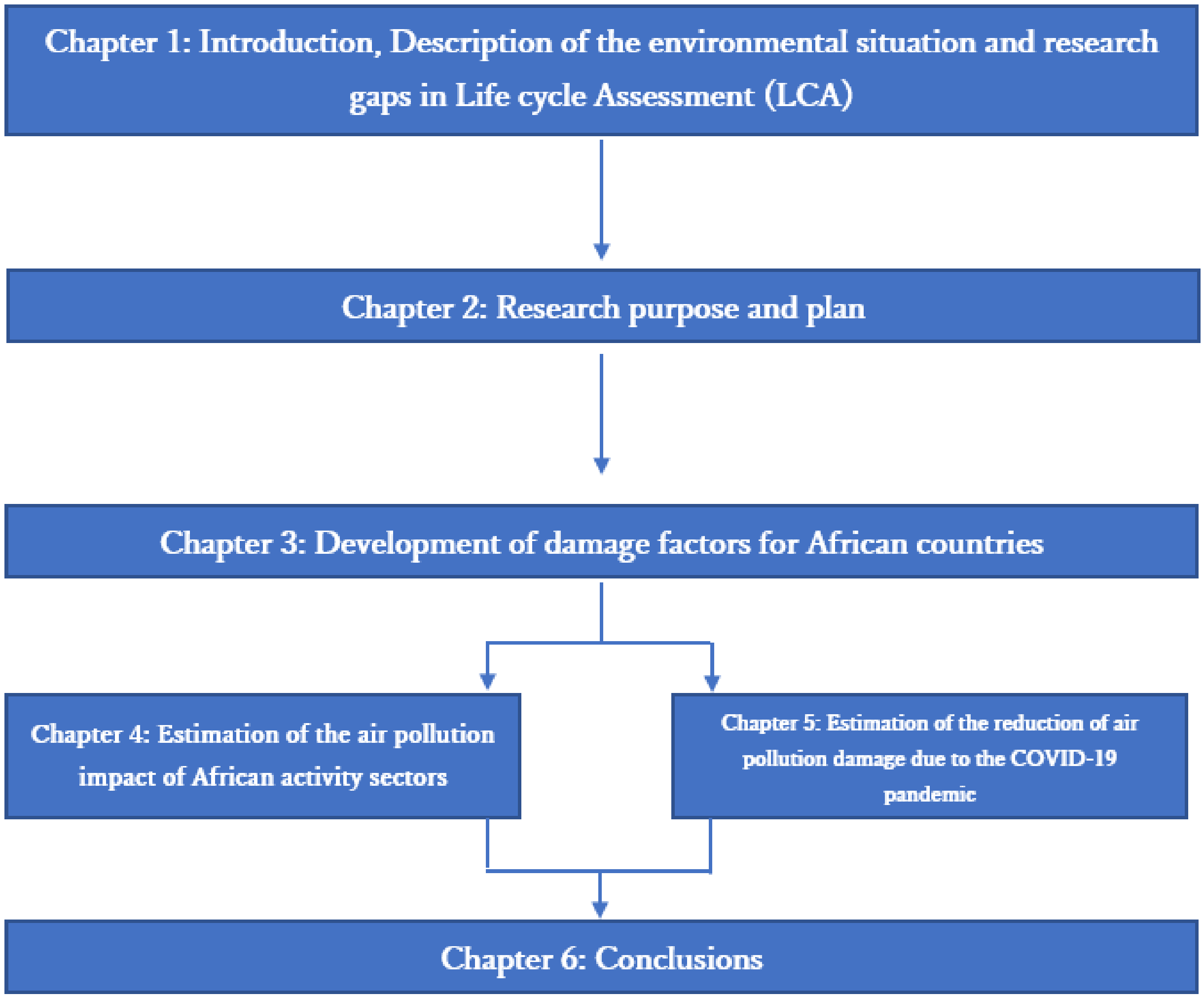


Figure 2. 1 Structure of the doctoral thesis

1.4. Summary

Several points can be highlighted from this first chapter:

- Air pollution is one of the important environmental impacts in Africa, causing more than one million deaths every year
- However, the research on Life-Cycle Assessment (LCA), a tool to tackle the different environmental impacts, is still limited, especially in the least developed African economies
- Regionalization, which aims at developing inventories, models specific to regions, countries, cities, is a key to improve LCA results in a near future
- Several models exist to evaluate the impacts of air pollution at a global level, but their resolution is relatively rough for Africa
- The example of the external cost of electricity shows that regionalization can create variation in

LCA results, especially between developed and developing countries.

- The COVID-19 pandemic through its countermeasures has modified drastically the consumption patterns worldwide, reducing several air pollution indicators

Chapter 3: Development of damage factors for air pollution in Africa

This chapter describes the procedure and the development of air pollution damage factors for African countries.

The following procedure (Figure 3.1) is used to obtain the damage factor for air pollution in Africa, the procedure is detailed in Section 3.1:

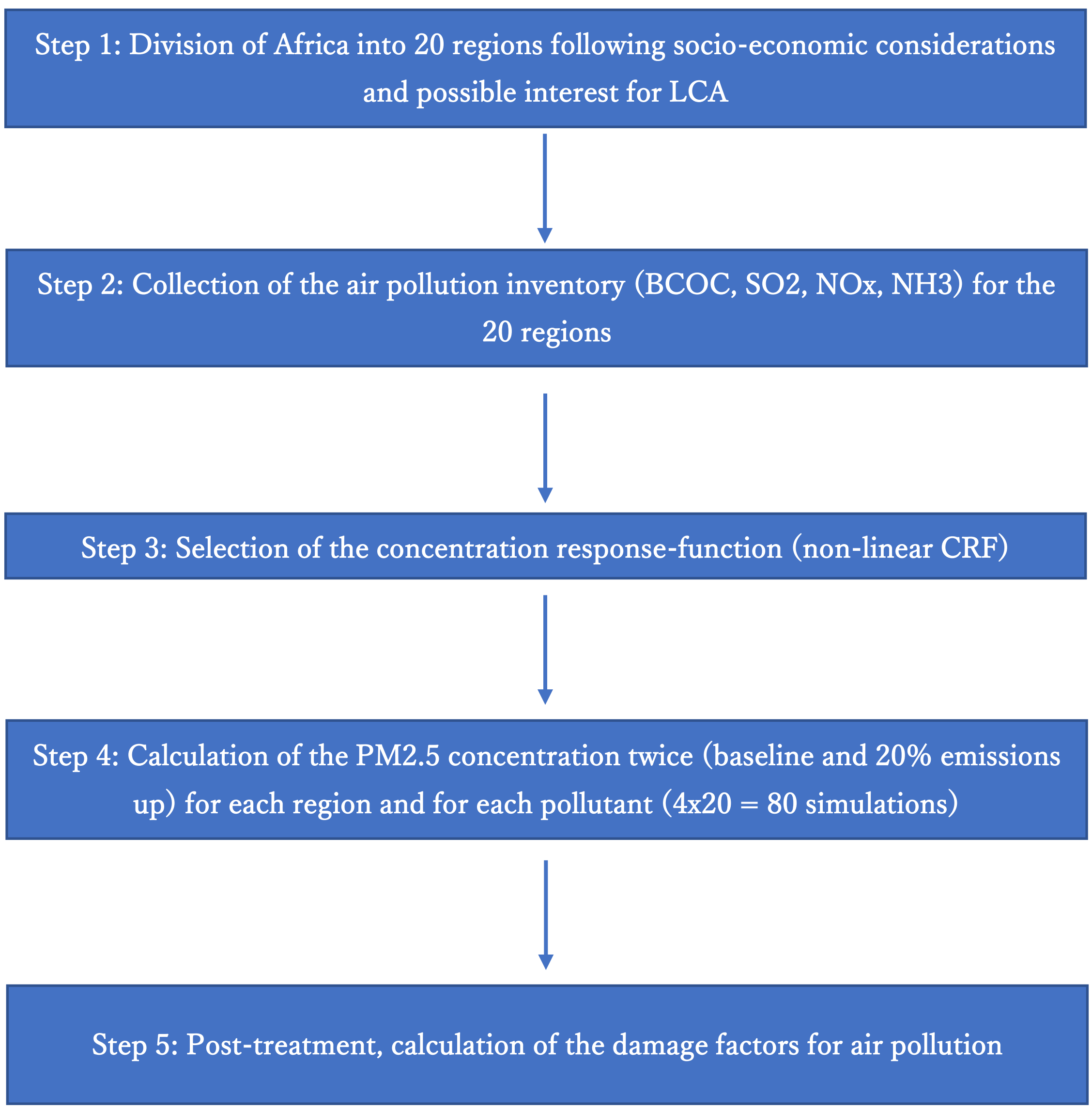


Figure 3. 1 Procedure to obtain the damage factor for air pollution in Africa

3.1 Procedure

3.1.1 Description of African division in this study

The calculation time is one of the limitations to run a simulation based on a chemical transport model. To limit this calculation time, it was decided to divide Africa into 20 regions. This division is based on several considerations: As shown in Table **3.1**, there exist several disparities between the African countries:

- Some countries have a very high population, such as Nigeria, Egypt, or Ethiopia
- Some countries have a very small population, such as Capo Verde or Sao Tome
- The economy of North African countries is mostly superior to Sub-Saharan countries
- It is difficult to group the countries into large regions as their situations really differ

In addition, as shown in Section **1.1.3** not all of them have research groups focusing on LCA. Therefore, it was decided to divide Africa into 20 regions with the priority given to African most advanced economies and countries with a higher number of LCA researchers.

The division is shown in Figure **3.2**:

- ALG: Algeria
- ANC: Angola, RD Congo
- BUR: Burundi, Rwanda, Uganda
- CGS: Cameroon, Central African Republic, Congo, Equa. Guinea, Gabon, Sao Tome
- EAF: Eritrea, Djibouti, Somalia
- EGY: Egypt
- ETH: Ethiopia
- KEN: Kenya
- MAMA: Mali, Mauritania
- MOR: Morocco
- NAB: Botswana, Namibia
- NGA: Nigeria
- NICH: Chad, Niger
- RSA: Lesotho, South Africa, Swaziland
- SEA: Comoros, Madagascar, Malawi, Mozambique, Zambia, Zimbabwe
- SUD: South Sudan, Sudan,
- TULI: Libya, Tunisia
- TZA: Tanzania
- WESE: Benin, Burkina Faso, Cote d'Ivoire, Ghana, Togo
- WESW: Cabo Verde, Gambia, Guinea, Guinea-Bissau, Liberia, Senegal, Sierra Leone

Table 3.1 Demographic and economic situation of African countries in 2019

Country	GDP (bil $)	Population	GDP per capita
Algeria	183.687	43,000,420	4,272
Angola	92.191	24,383,301	3,781
Benin	11.184	10,008,749	1,117
Botswana	19.651	2,024,904	9,705
Burkina Faso	14.882	18,450,494	807
Burundi	3.573	9,823,828	364
Cameroon	39.219	21,917,602	1,789
Cape Verde	2.042	491,875	4,151
Central African Republic	2.285	3,859,139	592
Chad	11.372	11,039,873	1,030
Congo	11.162	3,697,490	3,019
Comoros	0.726	806,200	901
Democratic Republic of the Congo	48.458	89,561,403	541
Djibouti	2.392	864,618	2,767
Egypt	299.589	102,334,404	2,928
Equatorial Guinea	12.432	1,222,442	10,170
Eritrea	7.718	6,536,000	1,181
Eswatini	4.662	1,119,375	4,165
Ethiopia	105	114,963,588	913
Gabon	16.709	1,802,278	9,271
Gambia	1.741	1,882,450	925
Ghana	68.258	31,072,940	2,197
Guinea	12.623	10,628,972	1,188
Guinea-Bissau	1.538	1,530,673	1,005
Ivory Coast	45.252	22,671,331	1,996
Kenya	109.246	53,714,296	2,034
Lesotho	2.811	1,894,194	1,484
Liberia	3.221	3,476,608	926
Libya	44.964	5,298,152	8,487
Madagascar	12.734	22,434,363	568
Malawi	7.436	16,832,900	442
Mali	17.833	14,528,662	1,227
Mauritania	5.569	3,718,678	1,498
Mauritius	14.812	1,261,208	11,744
Morocco	121.35	35,795,289	3,390
Mozambique	15.372	28,013,000	549
Namibia	13.961	2,280,700	6,121
Niger	9.724	17,138,707	567
Nigeria	444.916	206,139,589	2,158
Rwanda	10.211	10,515,973	971
São Tomé and Príncipe	0.477	201,784	2,364
Senegal	25.32	14,354,690	1,764
Seychelles	1.654	90,945	18,187
Sierra Leone	3.998	6,348,350	630
Somalia	7.903	22,316,895	354
South Africa	371.298	59,622,350	6,227
South Sudan	3.151	8,260,490	381
Sudan	31.468	42,268,269	744
Tanzania	61.032	59,734,218	1,022
Togo	5.592	6,191,155	903
Tunisia	36.204	10,982,754	3,296
Uganda	33.569	45,741,007	734
Zambia	24.615	15,473,905	1,591
Zimbabwe	22.29	13,061,239	1,707

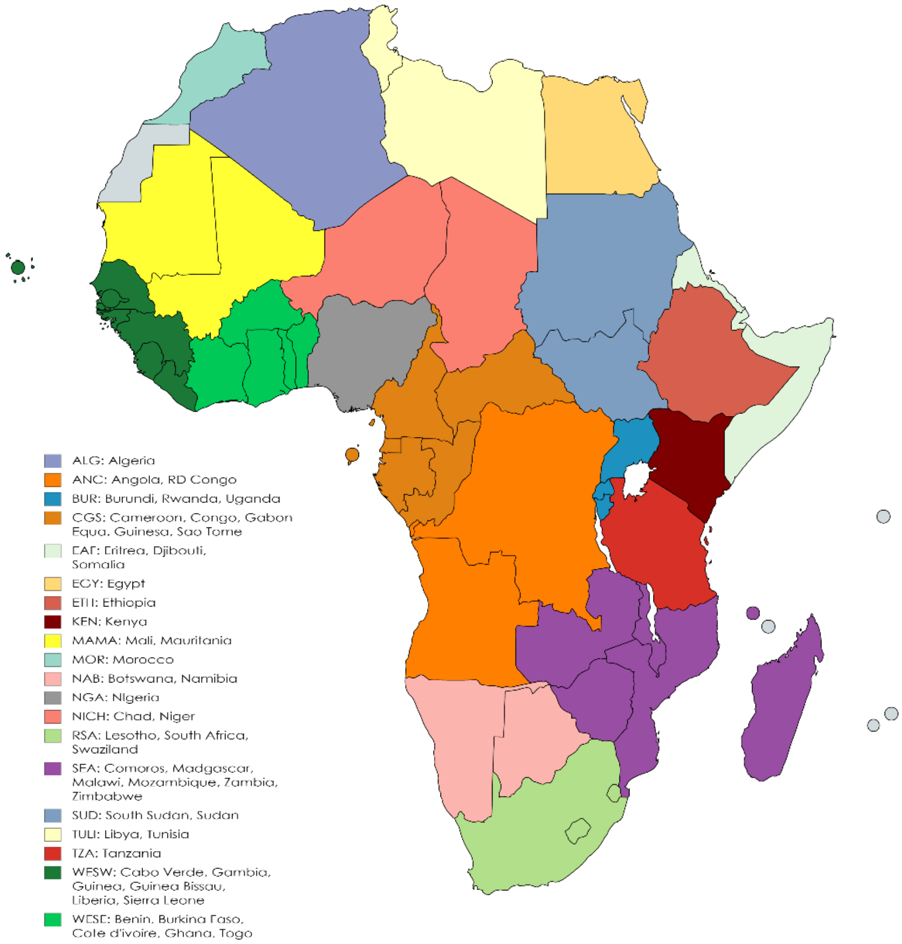


Figure 3. 2 Regions/countries division in this study

3.1.2 Description of chemical transport model: MIROC

Simulations in our study are made using MIROC-ESM-CHEM [1] based on the aerosol module Sprintars coupled with chemistry model CHASER [2]. The chemistry model can calculate the concentration of 92 chemical species with 262 chemical reactions, while the aerosol module evaluates the transport of tropospheric aerosols such as carbonaceous (BCOC) as well as their deposition. An overview of the model is given in Figure 3.3.

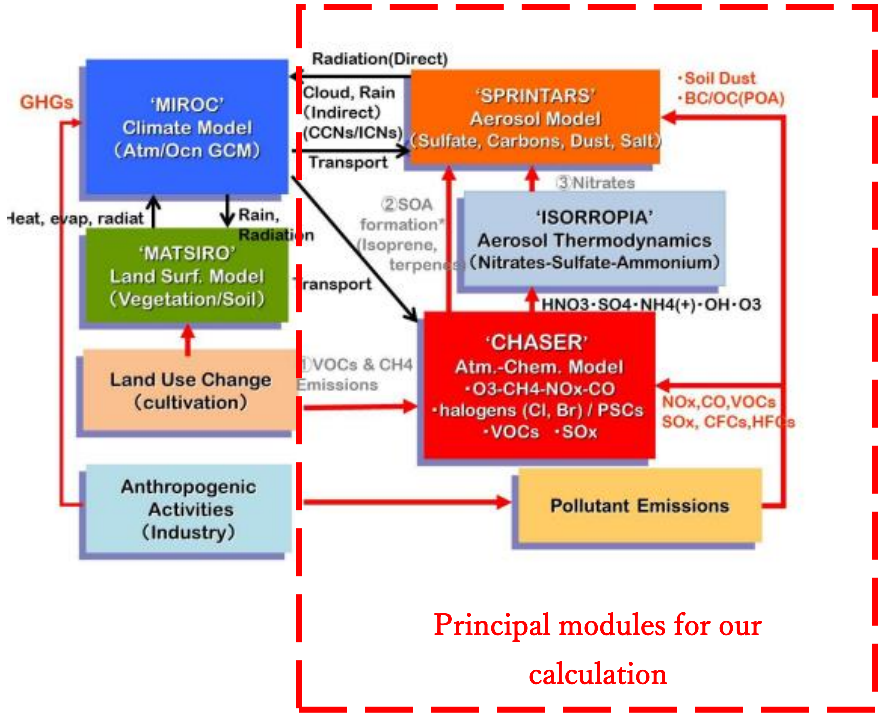


Figure 3. 3 Overview of the CHASER and SPRINTARS models

The CTM can evaluate the change of PM2.5 concentration following a change in one of the precursors (BCOC, SO2, NOX, NH3). The atmospheric conditions largely impact the change of concentrations at the emission location (temperature, humidity, pressure, wind speed). An example of chemical reactions for secondary sources of particulate matter is given in Figure 3.4.
In order to perform a simulation using MIROC-ESM CHEM, an inventory of pollutants is needed for each region, data were collected from HTAP v2 project [3], data are presented in Table 3.2

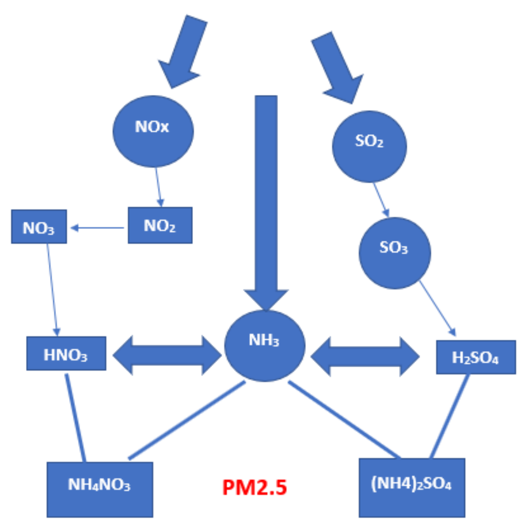


Figure 3. 4 Chemical reactions for secondary source of PM2.5

Table 3.2 Emissions for each substance and each region

	BCOC	NOx	SO2	NH3
ALG	6.7	336.1	85.7	57.2
ANC	269.2	166.2	98.5	91.3
BUR	195.0	70.4	45.2	97.2
CGS	79.5	84.0	31.6	102.1
EAF	49.8	35.2	25.7	81.7
EGY	17.3	544.9	664.9	384.9
ETH	328.3	134.9	61.6	357.9
KEN	118.1	124.7	92.6	196.8
MAMA	31.2	44.1	20.3	100.4
MOR	9.0	196.3	286.7	114.2
NAB	9.2	44.8	191.8	43.0
NGA	906.5	535.8	164.9	259.6
NICH	63.4	28.2	15.9	124.9
RSA	234.6	1322.7	2365.1	264.1
SEA	264.9	155.7	420.7	245.0
SUD	76.4	135.7	69.9	366.3
TULI	19.9	381.0	457.8	76.7
TZA	160.2	81.2	25.4	163.7
WESE	207.2	182.7	65.6	222.4
WESW	85.6	76.7	56.5	88.6

3.1.3 Summary of the epidemiological studies for air pollution

The effects of air pollution on human health have already been highlighted since the 70s ([4]). The research has been accelerated in the last 20 years, with several studies trying to quantify ambient air pollution's impacts on human health. In the first decade of the 20th-century, studies mainly focus on developing linear concentration response-function (=the function linking the concentration of particulate matter 2.5 and the damage to air pollution). In linear concentration-response function, the damages are constant, following the increase of PM2.5 concentration (e.g., 6% of increased mortality risk due to cardiopulmonary disease for 10µg/m3 concentration increase [5]). Most of these studies were conducted in North America (Canada, USA) [4]. The mean relative risk for the studies was found as follows: 1.08 (95% CI = 1.06–1.11) for all-cause mortality, 1.11 (1.08–1.14) for cardiopulmonary mortality, and 1.13 (1.07–1.20) for lung cancer mortality. It has to be noted that differences could be observed between the regions (e.g., Europe vs. Asia), and no well-known study has been conducted in Africa. The subjects' age is also a key parameter influencing the impact with higher relative risks for young children under five years old and elderly people. A summary of the principal linear cohort studies is given in Table 3.3.

Table 3.3 Summary of the main linear cohort studies focusing on air pollution impacts (RR per 10µg/m3)

Authors (Year)	Location	Summary
Dockery et al (1993)	USA	RR=1.18 for cardiopulmonary RR=1.18 for Lung Cancers
Pope et al (1995)	USA	RR=1.19 for cardiopulmonary RR=1.01 for Lung Cancers
Krewski et al (2000)	USA	RR=1.19 for cardiopulmonary RR=1.00 for Lung Cancers
Pope et al (2002)	USA	RR=1.09 for cardiopulmonary RR=1.14 for Lung Cancers
Pope et al (2004)	USA	RR=1.12 for cardiopulmonary
Jerrett et al (2009)	USA	RR=1.15 for cardiopulmonary
Krewski et al (2009)	USA	RR=1.09 for cardiopulmonary RR=1.09 for Lung Cancers
Smith et al (2009)	USA	RR=1.14 for cardiopulmonary
Bentayeb et al (2015)	France	RR=1.16 for cardiopulmonary
Fischer et al (2015)	Netherlands	RR=1.09 for cardiopulmonary RR=1.41 for Lung Cancers
Pope et al (2015)	USA	RR=1.21 for cardiopulmonary RR=1.01 for Lung Cancers
Wong et al (2015)	Hong Kong	RR=1.22 for cardiopulmonary RR=1.14 for Lung Cancers
Turner et al (2016)	USA	RR=1.12 for cardiopulmonary
Jerrett et al (2017)	USA	RR=1.14 for cardiopulmonary
Yin et al (2017)	China	RR=1.09 for cardiopulmonary RR=1.12 for Lung Cancers
Pope et al (2019)	USA	RR=1.23 for cardiopulmonary RR=1.13 for Lung Cancers

Since 2010, non-linear concentration-response functions have been developed where air pollution impacts do not increase anymore above a certain value (Figure 3.5) [6]. Using a meta-analysis approach based on several cohort studies from all around the world, Burnett et al. (2014) demonstrated that the PM2.5-mortality association was non-linear and more complex than a simple linear relationship His approach has been adopted by both the WHO [7] and the global burden of disease (GBD) [6] to avoid any over-estimation of air pollution-related mortality. As shown in the figure, five types of disease are considered: Stroke, Ischemic Heart Disease, Lung Cancer, and Acute lower respiratory infections (ALRI). This approach was also used in our study to keep the consistency with the consensus on concentration response function. An example of the results obtained for some African regions is added on the figure.

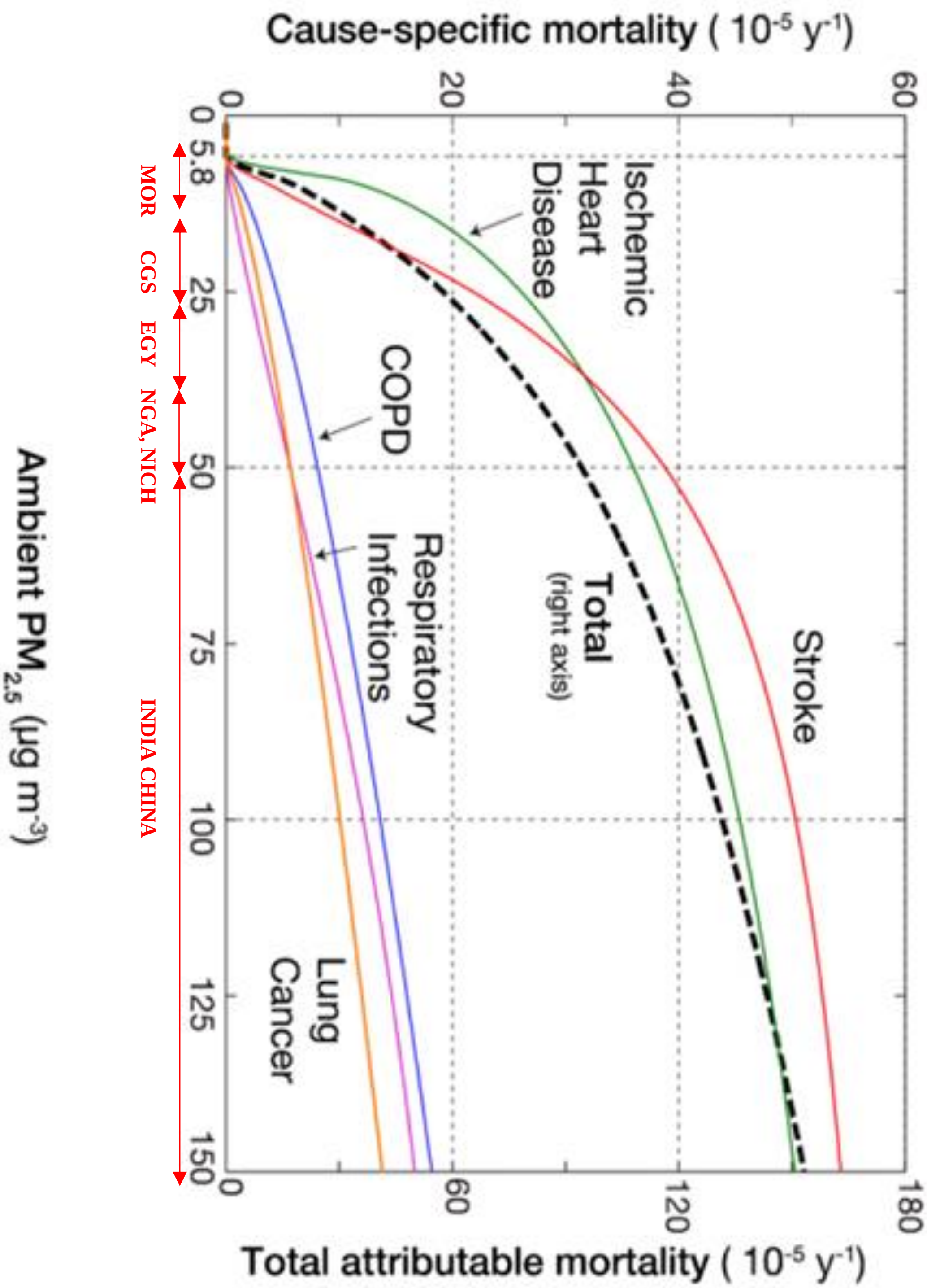


Figure 3. 5 Example of a non-linear concentration response function with results obtained for some African regions

The curve used in this thesis is provided in Figure 3.6, it shows the importance of considering a non-linear response function as the damage caused by air pollution do not not increase above a certain value.

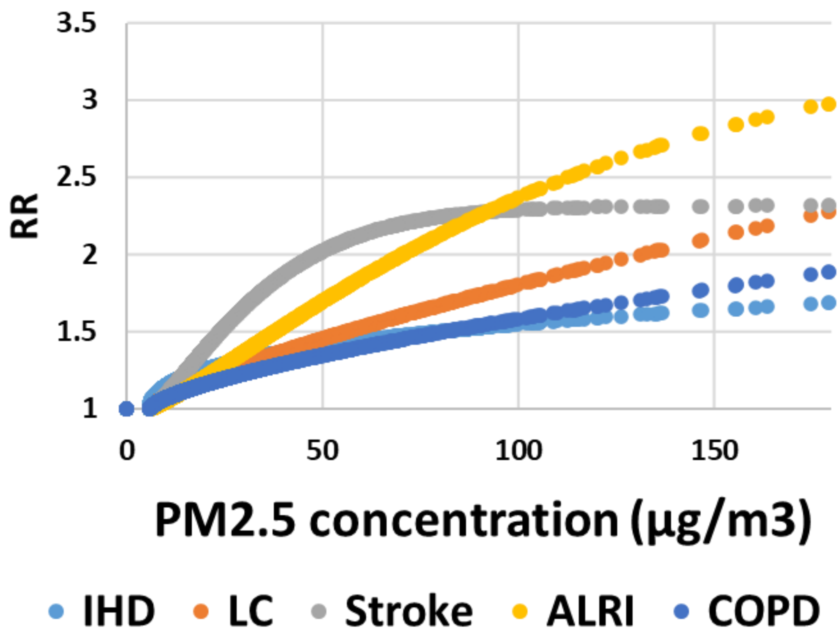
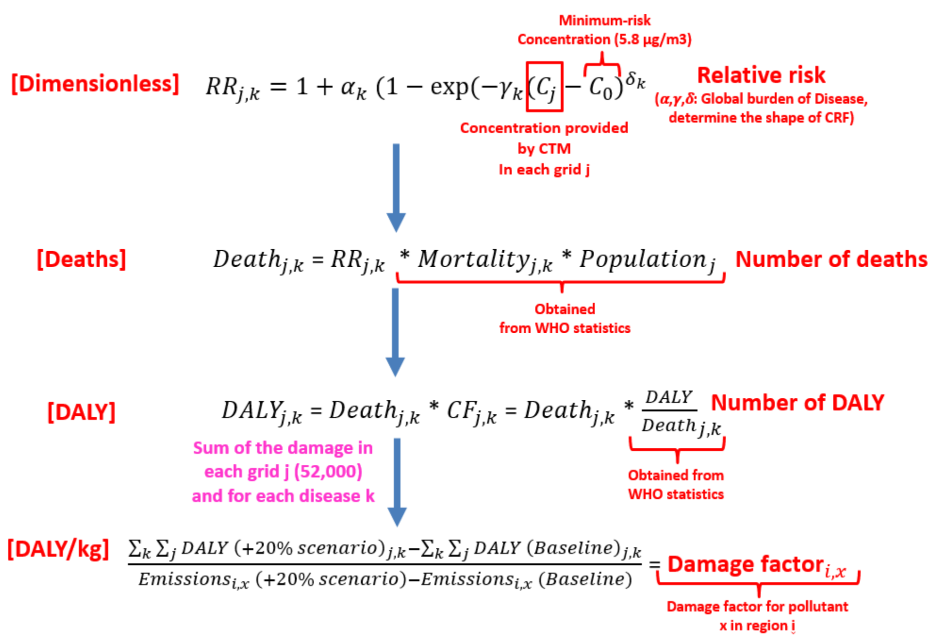


Figure 3. 6 Non-linear concentration response function used in this study

Therefore, the damage from air pollution were calculated using the output of the chemical transport model (the background PM2.5 concentration), and the relationship between the concentration and the relative risk as following:

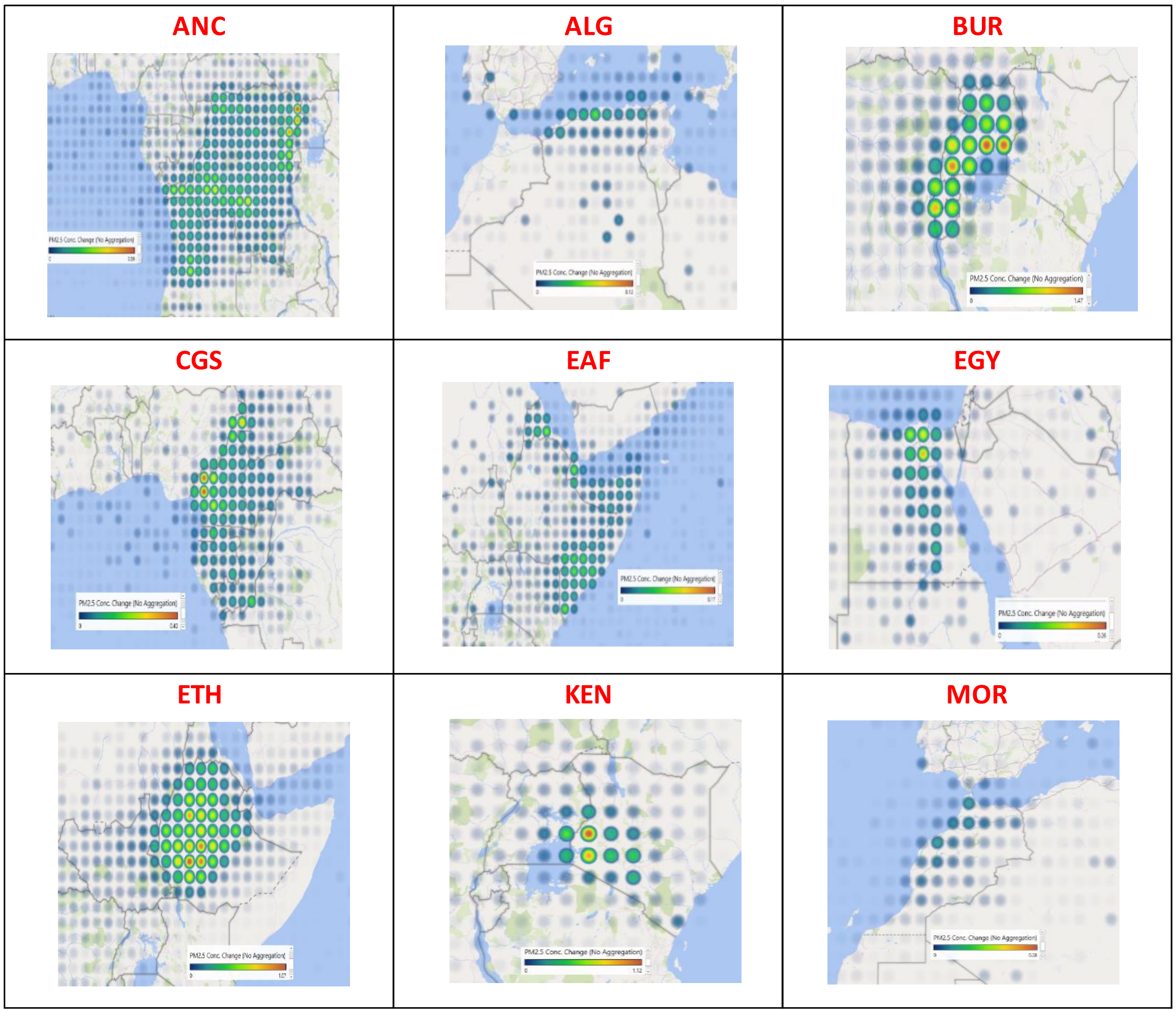


3.2 Results

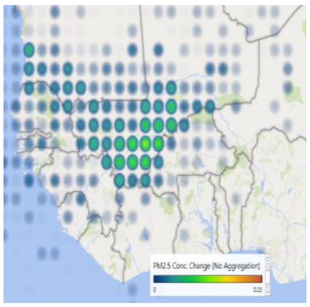
3.2.1 Fate analysis

3.2.1.1 BCOC

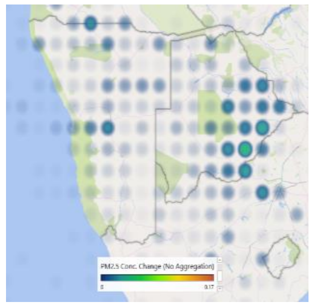
The first calculation was made for BCOC, the results for each simulation (one for each region) are presented in Figure 3.7.



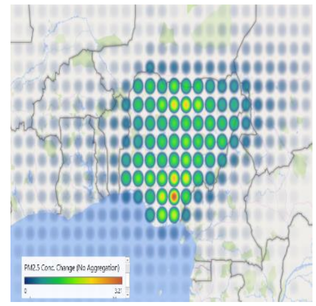
MAMA



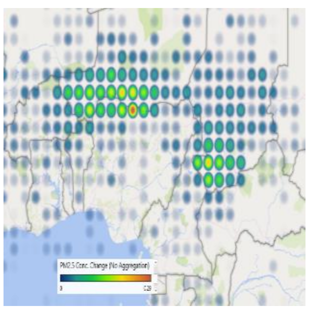
NAB



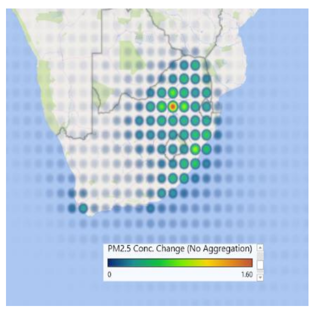
NGA



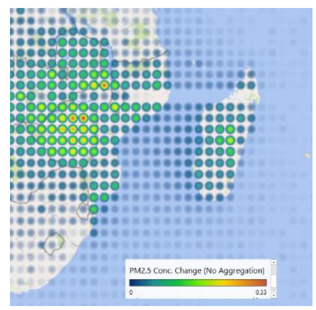
NICH



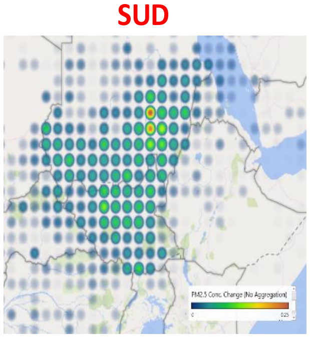
RSA



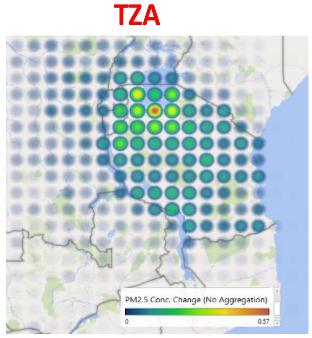
SEA



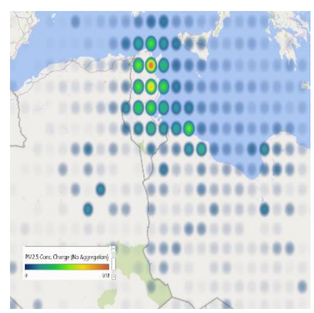
SUD



TZA



TULI



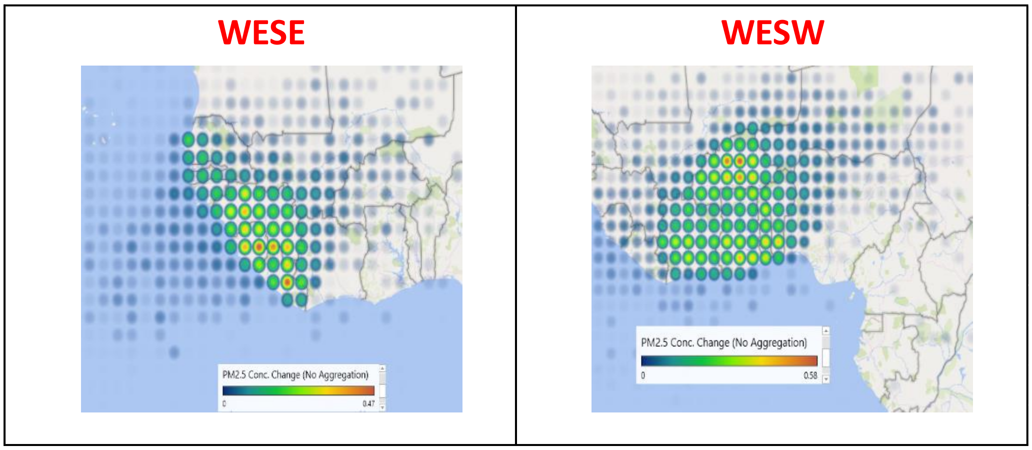


Figure 3. 7 Output of the simulation for each region, change of yearly global average PM2.5 concentration per grid following the change of BCOC emissions

As it can be seen in the figure, the change is of the PM2.5 concentration is directly linked to the location of the emissions, the dispersion is relatively low. The dispersion in higher in the northern part of Africa due to the higher wind speed. Overall, BCOC as a primary component of particulate matter is the substance contributing the most to the change of concentration.

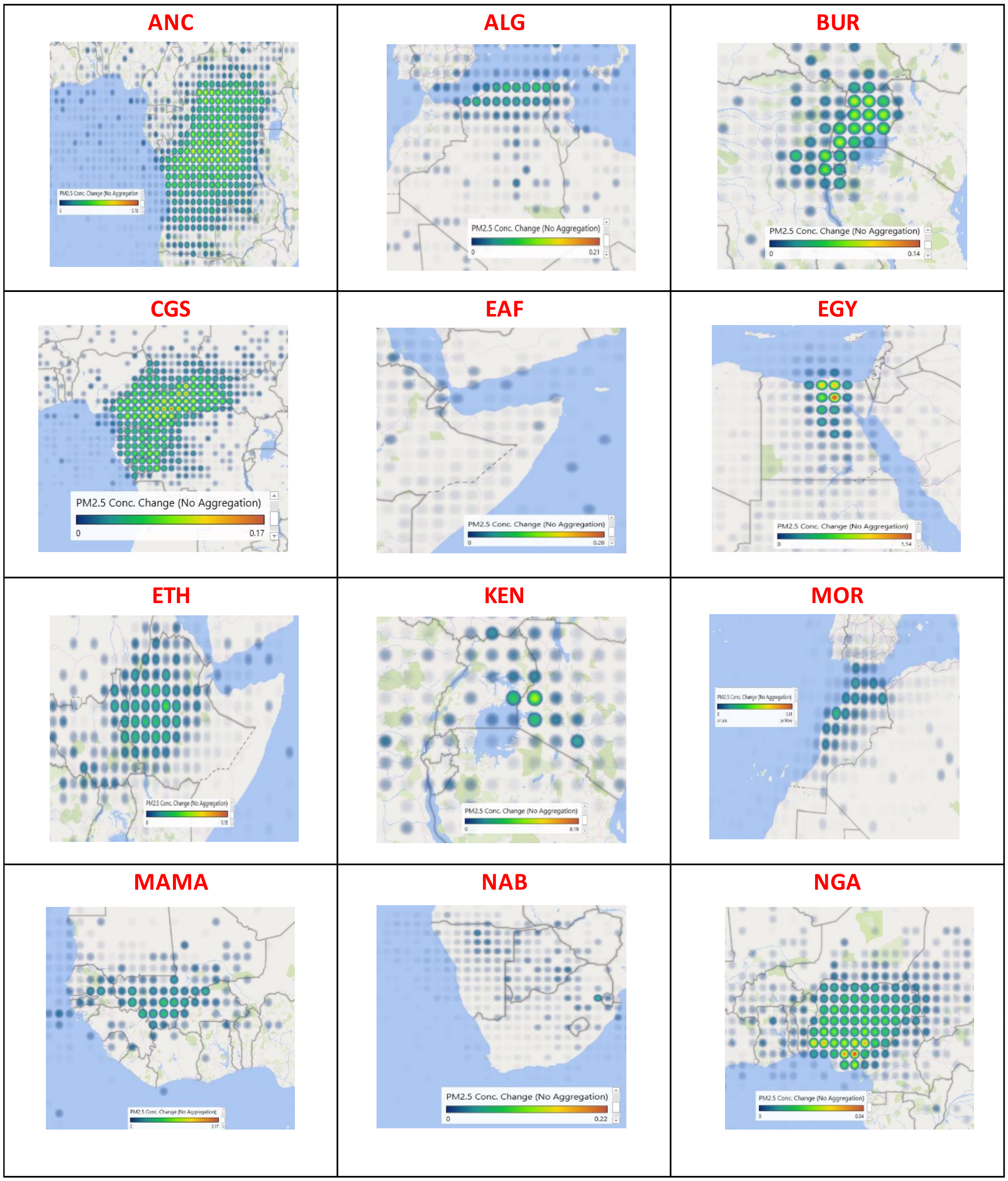
Table 3.4 summarizes the change of average PM2.5 concentration inside each region.

Table 3.4 Change of PM2.5 concentration inside each region following the change of BCOC emissions

Region	Change of emissions (kton)	Average change of PM2.5 concentration inside the region (ug/m3)	Average change of population-weighted PM2.5 concentration inside the region (ug/m3)
ALG	1.3	0.003	0.018
ANC	53.8	0.121	0.173
BUR	39	0.754	1.202
CGS	15.9	0.072	0.144
EAF	10	0.037	0.048
EGY	3.5	0.028	0.109
ETH	65.7	0.348	0.642
KEN	23.6	0.137	0.380
MAMA	6.2	0.02	0.067
MOR	1.8	0.013	0.036
NAB	1.8	0.007	0.018
NGA	181.3	1.325	1.532
NICH	12.7	0.036	0.111
RSA	46.9	0.249	0.696
SEA	53	0.108	0.162
SUD	15.3	0.042	0.112
TULI	4	0.01	0.070
TZA	32	0.147	0.236
WESE	41.4	0.284	0.325
WESW	17.1	0.201	0.228

3.2.1.2 NOx

The second calculation was made for Nitrogen Oxide (NOx), the results for each simulation (one for each region) are presented in Figure 3.8.



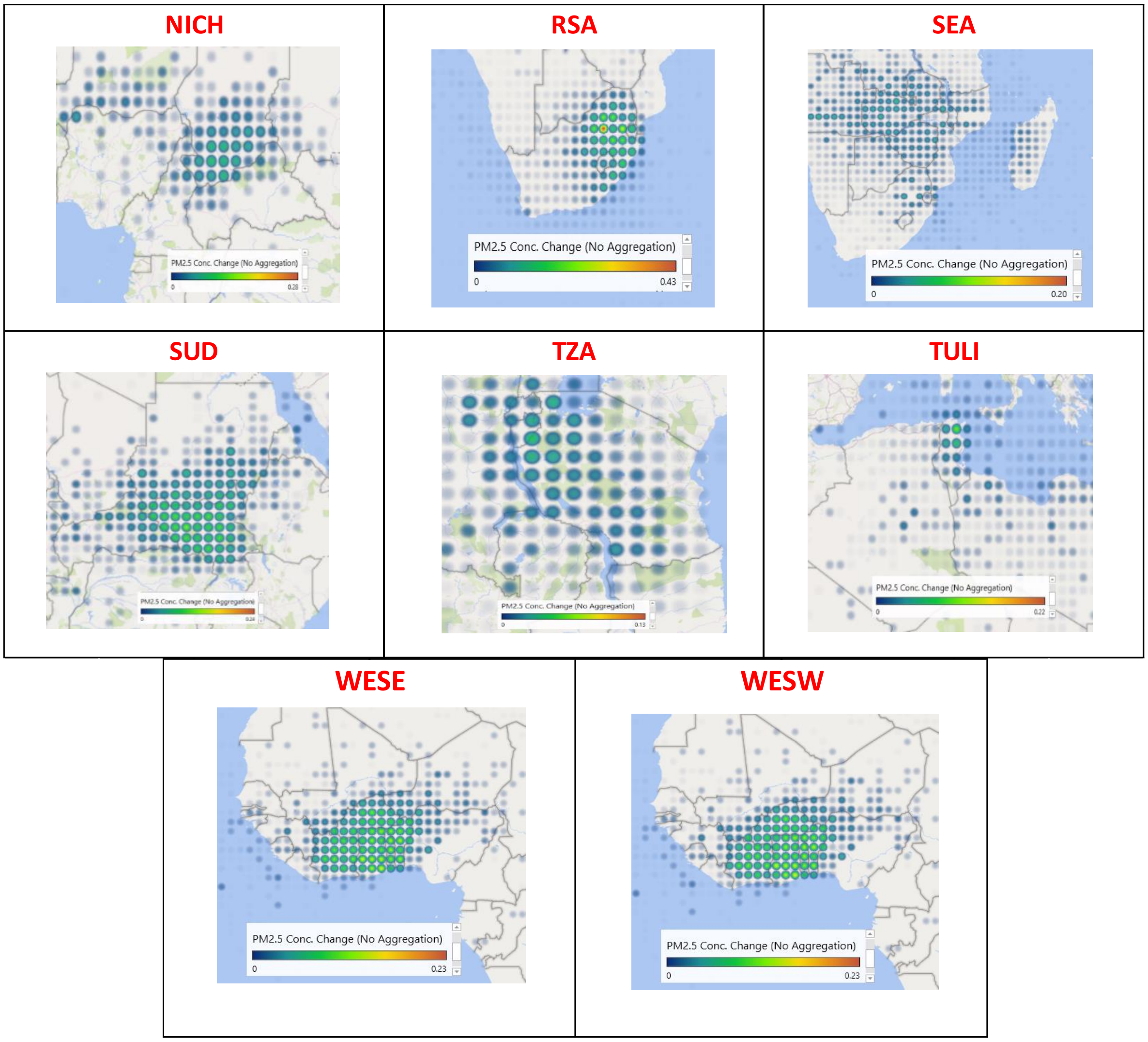


Figure 3. 8 Output of the simulation for each region, change of yearly global average PM2.5 concentration per grid following the change of NOx emissions

Similar to BCOC, the dispersion of NOx was not very important in Africa, the change of PM2.5 concentration mainly occur inside the region of emissions, NOx contributes far less than BCOC to the change of PM2.5 concentration, it contributes nearly equally to NH3 and less than SO2.Table 3.5 summurizes the change of average PM2.5 concentration inside each region.

Table 3.5 Change of PM2.5 concentration inside each region following the change of NOx emissions

Region	Change of emissions (kton)	Average change of PM2.5 concentration inside the region (ug/m3)	Average change of population-weighted PM2.5 concentration inside the region (ug/m3)
ALG	67.2	0.008	0.039
ANC	32.6	0.064	0.050
BUR	14	0.057	0.071
CGS	16.4	0.085	0.075
EAF	6.9	0.004	0.007
EGY	109	0.111	0.560
ETH	26.7	0.021	0.034
KEN	24.7	0.012	0.032
MAMA	8.6	0.007	0.020
MOR	39.3	0.024	0.064
NAB	8.7	0.008	0.011
NGA	106.9	0.133	0.148
NICH	5.3	0.013	0.029
RSA	263.4	0.064	0.174
SEA	30.7	0.019	0.023
SUD	26.7	0.031	0.042
TULI	76.2	0.01	0.042
TZA	16.1	0.014	0.014
WESE	36.3	0.087	0.087
WESW	15.2	0.046	0.048

From the table it can be confirm that the change of PM2.5 is correlated with the amount of change of NOx emissions. Despite their lower emissions, ANC, BUR and, CGS show a moderate-high increase of the average PM2.5 concentration as the sources of emissions are spread all over the territory, not only in a single area.

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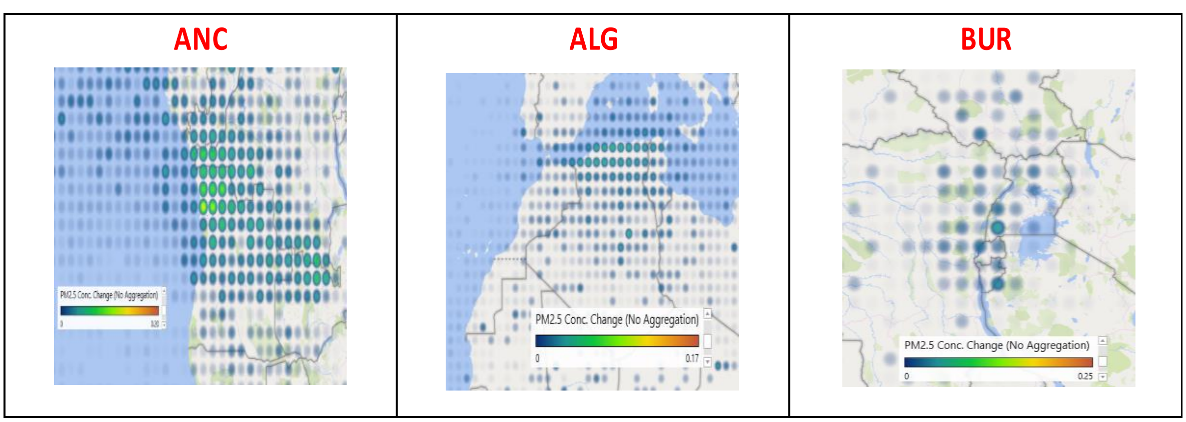
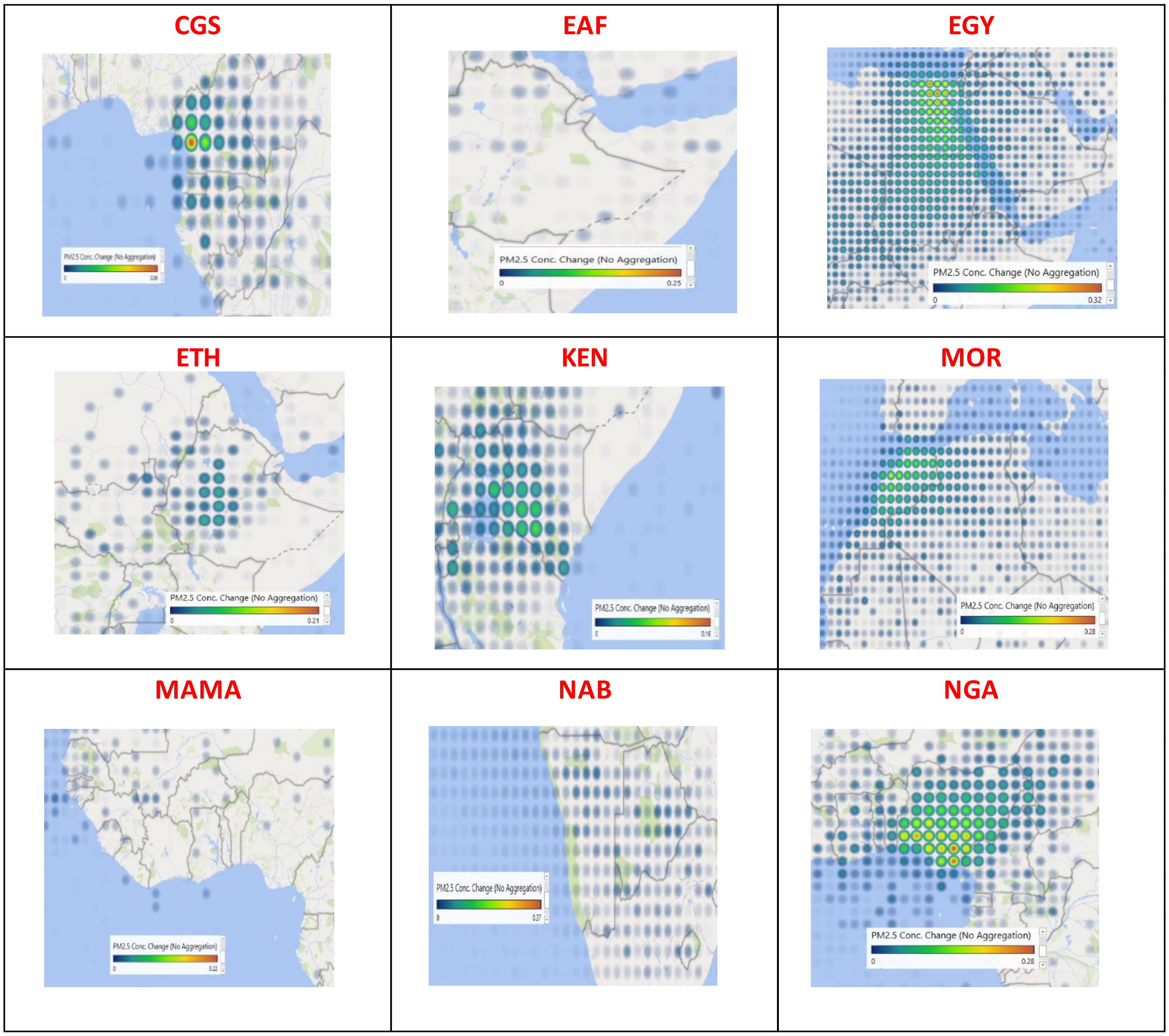
3.2.1.3 SO2

The third calculation was made for Sulfur Dioxide (SO2), the results for each simulation (one for each region) are presented in Figure 3.9




CGS
EAF
PM2.5 Conc. Change (No Aggregation)
0
0.25
EGY
PM2.5 Conc. Change (No Aggregation)
0
0.32
ETH
PM2.5 Conc. Change (No Aggregation)
0
0.21
KEN
MOR
PM2.5 Conc. Change (No Aggregation)
0
0.28
MAMA
NAB
NGA
PM2.5 Conc. Change (No Aggregation)
0
0.28

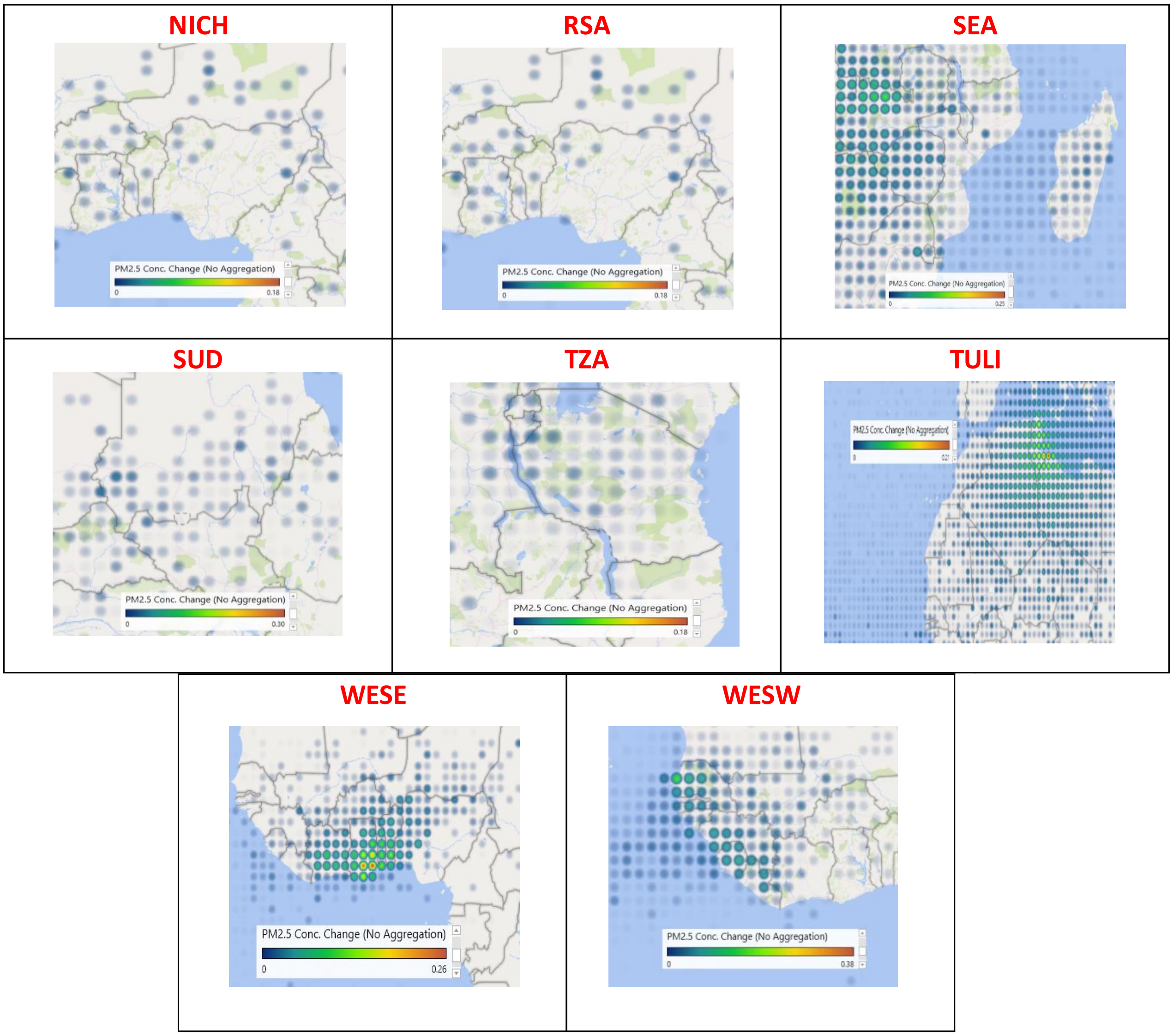


Figure 3. 9 Output of the simulation for each region, change of yearly global average PM2.5 concentration per grid following the change of SO2 emissions

Table 3.6 summarizes the change of average PM2.5 concentration inside each region.

The dispersion of SO2 is relatively higher than the other substances. After BCOC, SO2 is the substance contributing the most to the change of PM2.5:

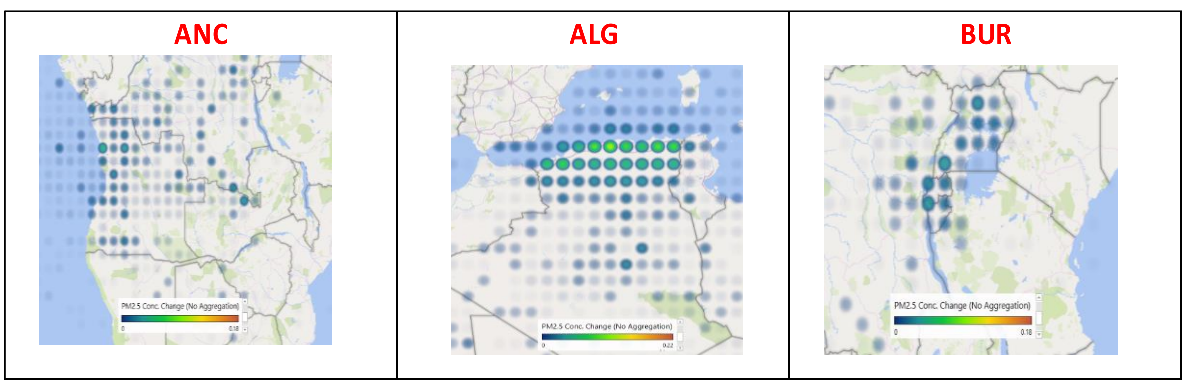
From the table, it can be confirmed that the change of PM2.5 is correlated with the amount of change of SO2 emissions. For NGA, the greater change of PM2.5 concentration can be explained due to the high emissions of NH3 in the baseline scenarios; SO2 reacts with NH3 to form H2SO4, contributing to increasing the contribution to particulate matter formation. A similar observation can be made for WESE.

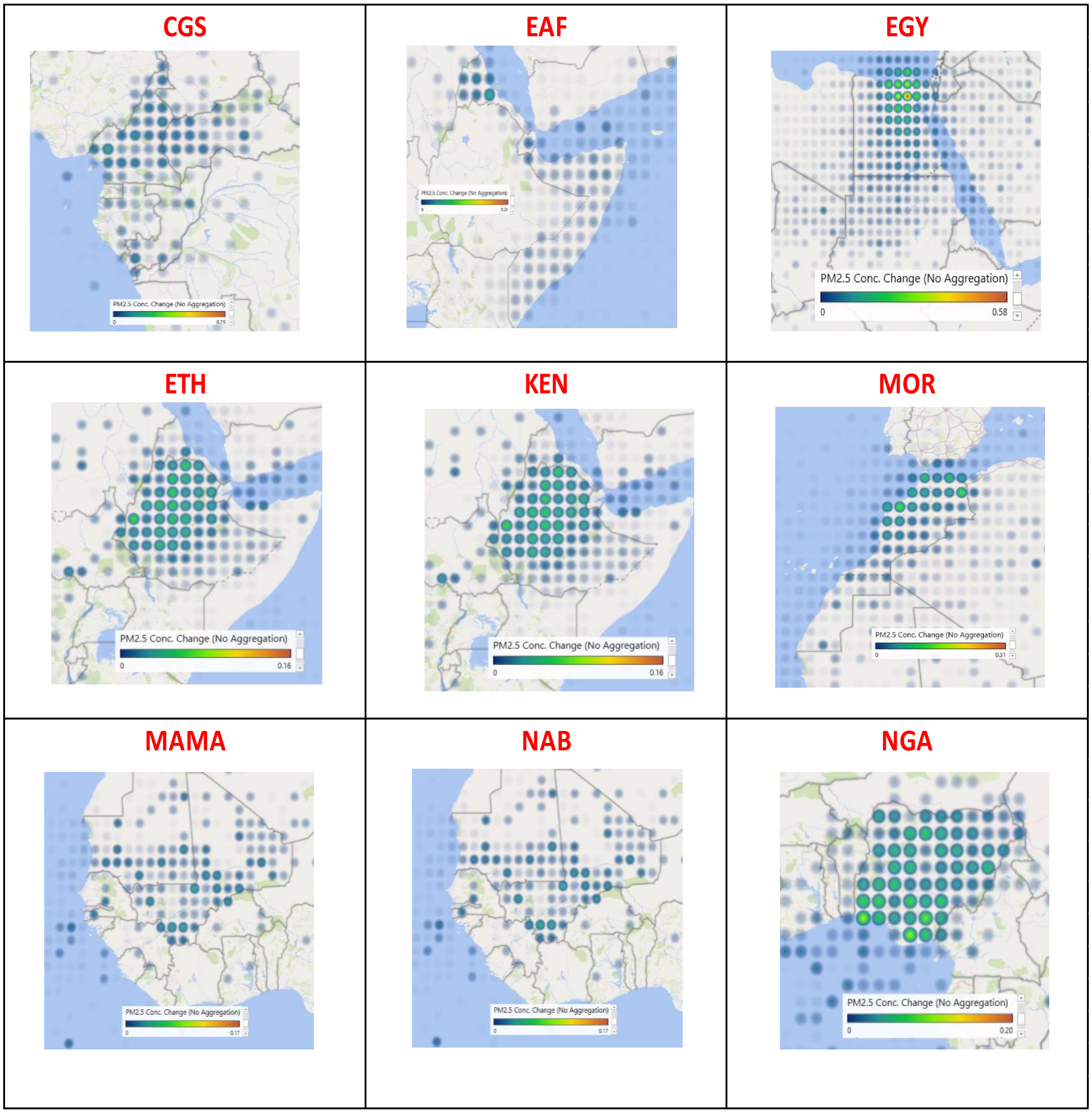
Table 3.6 Change of PM2.5 concentration inside each region following the change of SO2. emissions

Region	Change of emissions (kton)	Average change of PM2.5 concentration inside the region (ug/m3)	Average change of population-weighted PM2.5 concentration inside the region (ug/m3)
ALG	17.1	0.011	0.028
ANC	19.6	0.021	0.040
BUR	9	0.013	0.009
CGS	6.3	0.023	0.115
EAF	5.1	0.002	0.006
EGY	133	0.142	0.241
ETH	12.3	0.01	0.022
KEN	18.5	0.021	0.050
MAMA	4	0.002	0.002
MOR	57.3	0.071	0.124
NAB	7.1	0.019	0.022
NGA	33	0.106	0.149
NICH	3.1	0.001	0.001
RSA	472.9	0.313	0.548
SEA	84.1	0.019	0.023
SUD	13.9	0.005	0.009
TULI	91.6	0.044	0.088
TZA	5.1	0.005	0.004
WESE	13.1	0.053	0.074
WESW	11.3	0.049	0.071

3.2.1.4 NH3

The fourth and last calculation was made for Ammonia (NH3), the results for each simulation (one for each region) are presented in Figure 3.10.




CGS
EAF
EGY
PM2.5 Conc. Change (No Aggregation)
0
0.58
ETH
PM2.5 Conc. Change (No Aggregation)
0
0.16
KEN
PM2.5 Conc. Change (No Aggregation)
0
0.16
MOR
MAMA
NAB
NGA
PM2.5 Conc. Change (No Aggregation)
0
0.20

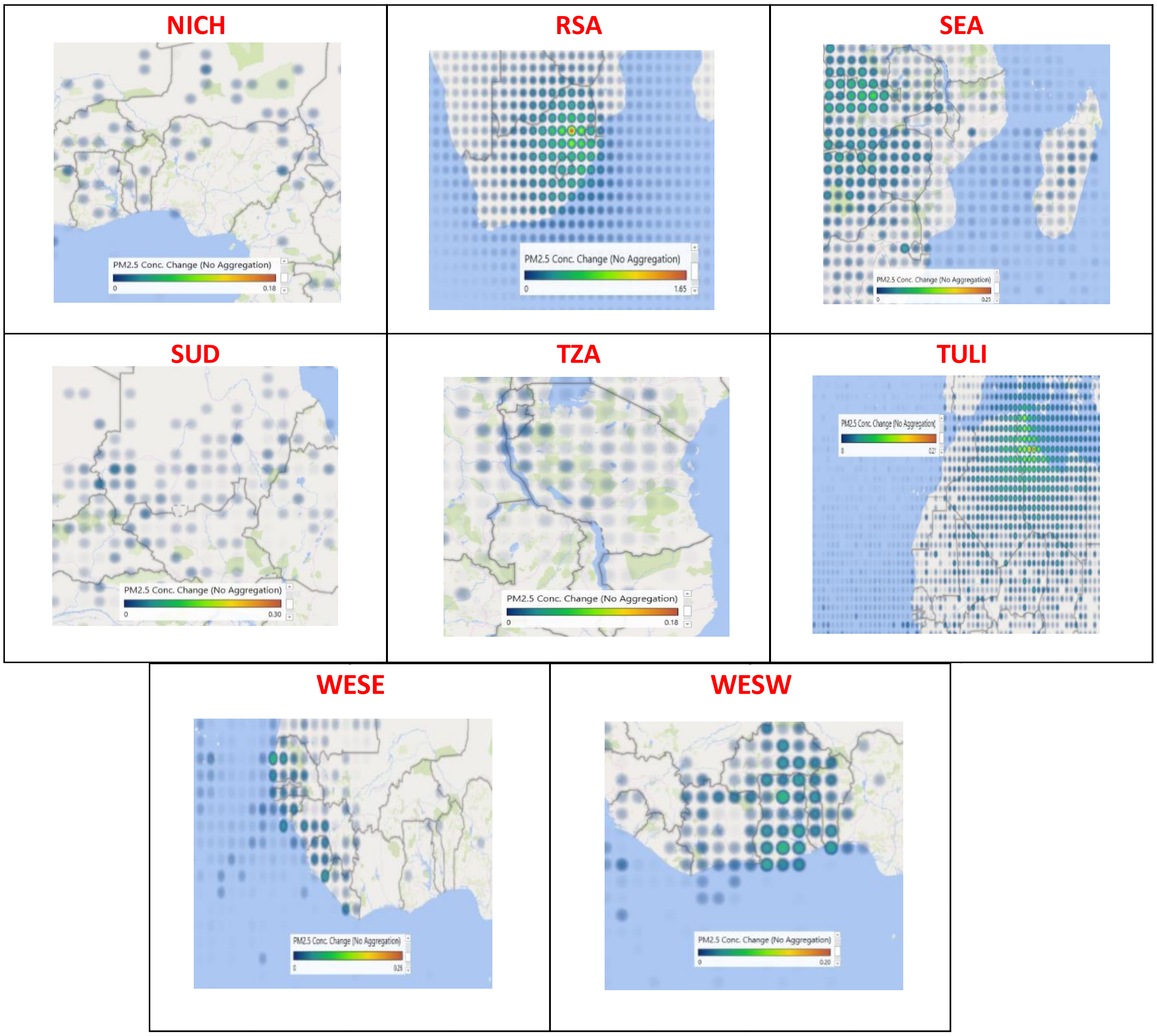


Figure 3. 10 Output of the simulation for each region, change of yearly global average PM2.5 concentration per grid following the change of NH3 emissions

As it can be seen in Figure 3.11, similarly to NOx, the emissions of NH3 does not contribute a lot to the PM2.5 concentration.

Table 3.7 summarizes the change of average PM2.5 concentration inside each region.

Table 3.7 Change of PM2.5 concentration inside each region following the change of NH3 emissions

Region	Change of emissions (kton)	Average change of PM2.5 concentration inside the region (ug/m3)	Average change of population-weighted PM2.5 concentration inside the region (ug/m3)
ALG	11.4	0.013	0.054
ANC	18.3	0.006	0.010
BUR	19.4	0.015	0.019
CGS	20.4	0.016	0.026
EAF	16.3	0.014	0.023
EGY	77	0.097	0.256
ETH	71.6	0.024	0.035
KEN	39.4	0.008	0.017
MAMA	25.6	0.008	0.006
MOR	20.1	0.035	0.072
NAB	22.8	0.009	0.013
NGA	51.9	0.041	0.060
NICH	25	0.011	0.019
RSA	52.8	0.137	0.450
SEA	49	0.011	0.021
SUD	73.3	0.022	0.033
TULI	15.3	0.019	0.064
TZA	32.7	0.008	0.008
WESE	44.5	0.02	0.023
WESW	17.7	0.02	0.030

For NH3 also, the change of PM2.5 concentration is correlated with the amount of emissions change. For RSA, the higher change of PM2.5 concentration can be explained due to the high emissions of SO2 in the baseline scenarios, NH3 reacts with SO2 & NOx to form H2SO4, H2NO3 contributing to increase the contribution to particulate matter formation. A similar observation can be made for EGY.

3.2.2 Damage results by country & disease

Damage Factors for air pollution are shown in Figure 3.10. BCOC, showing higher values with results between 103 and 2211 DALY/kg. Similarly to previous studies [9,10], the values for SO2 and NOx damage factors were shown in the same range (respectively 16-353 and 23-1130) while the damage factors for NH3 were shown the lowest (15-396). For northern Africa (MOR, ALG, TULI, and EGY), Ischemic heart disease was shown to have the highest responsibility for the damage. For sub-Saharan Africa, acute lower respiratory disease was shown to have the highest damage. These observations can be explained due to the different population range in the two areas, much younger in sub-Sahara area than in northern Africa. Overall, Nigeria and Egypt showed the highest results due to their high population number and high population density. This latter is also responsible for the high damage in Burundi, Rwanda and Uganda (BUR).

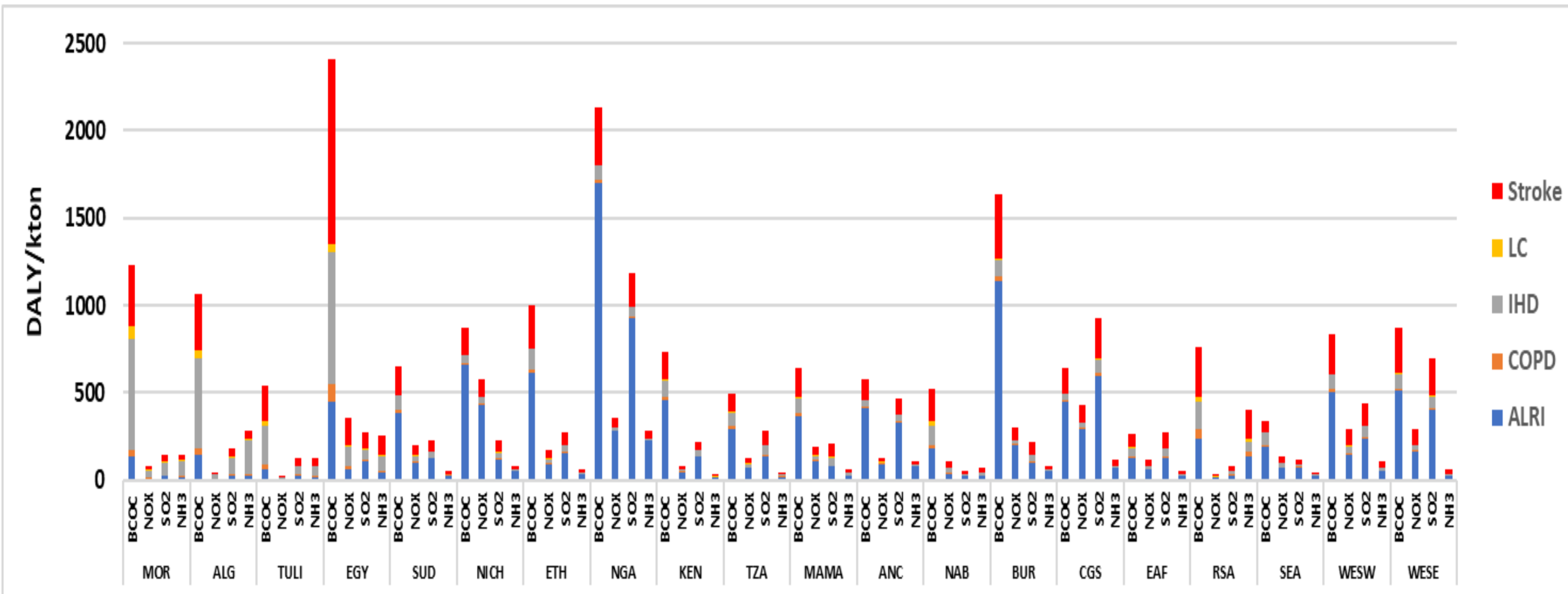


Figure 3. 11 Damage factors of BCOC, NOx, SO2 and NH3 for the 20 African regions including breakdown of diseases

3.2.3 Importance of the transboundary effect

As the transboundary effect was also considered, the damage of air pollution is occurring in the region of the emissions source and the surrounding regions, as shown in Figure 3.12.

Due to its high dispersion, SO2 was shown to have a more considerable impact outside the region of emission. In contrast, for BCOC, the impacts are more or less associated with the number of populations living in the area of emissions. Some results can be highlighted

For MOR, 25% of the impact of BCOC occur outside Africa, especially in southern Europe. For NOx the dispersion is lower and 83% of the impact occur in the region. For SO2 as the dispersion is higher, ALG (9%) and EGY (5%) are more affected.

For ALG, 29% of the impact of BCOC occur outside Africa, especially in southern Europe. As the population of the country is mostly located in the north of the country (low-population density), with the dispersion, the share of impacts of NOx and SO2 are shown higher in surrounding regions than for MOR. The same observations can be done for TULI.

For EGY, the population density is very high in the center of the country (around Cairo area), in addition, outside the Nile river area, the country and the other surroundings countries (Libya. Saudi Arabia) are relatively empty. Therefore except for SO2 the impacts mostly happen in the region (more than 80% for BCOC, NOx and NH3). For SO2 the dispersion is higher and there the change of PM2.5 concentration is observed in some remote areas (SUD, Middle East).

For SUD, observations like ALG can be done (low population density, mostly concentrated in the same area). Therefore, the impacts of pollutants is shown high in the surrounding regions.

For NICH, the impacts of the pollutants are shown high outside the region due to the proximity of Nigeria (12-23% of the impacts happen in Nigeria).

For ETH, similar observations as Egypt can be done (high population density in a restricted area)

For NGA, due to the very high population density and number, the impacts of all pollutants is shown high in the region (>80%)

For KEN, the situation is like NICH, the impacts are shown high in BUR (27% for BCOC), due to the high population density and number of latter one. The situation is similar for TZA.

For MAMA, 8-20% of the impact happen in surrounding area (Western Africa: NGA, WESW, WESE).

For ANC, the surrounding countries have a low number of populations, therefore the impacts mostly happen in the region (60-70%)

For NAB and EAF, as the population of both regions is relatively small, the share of the impacts outside the regions is higher than inside the region.

For BUR, similar for NGA, except for SO2 (due to the dispersion), 60-90% of the impacts occur inside the region due to the population number and density.

For CGS, except ANC and NGA, the surroundings regions are mainly empty, so the impact mainly occur inside the region.

For RSA, similar to NGA and BUR, the impacts of all pollutants is shown high in the region (>80%).

For SEA, due to the proximity of ANC and RSA, the impacts are shared between these three regions.

For WESW and WESE, the population density being high in both regions, the impacts occur (mainly above 50%) except for SO2 due to the dispersion.

Overall, the emissions in North-Africa have a higher responsibility for the damage outside Africa (about 20%) due to Europe's proximity.

It can be confirmed that it is important to consider the transboundary effect (which can be up to 80% for EAF) as the share of the damage outside the region of emissions can be important, especially in emitting regions with a low population or a low density or regions located next a region with a high population density.

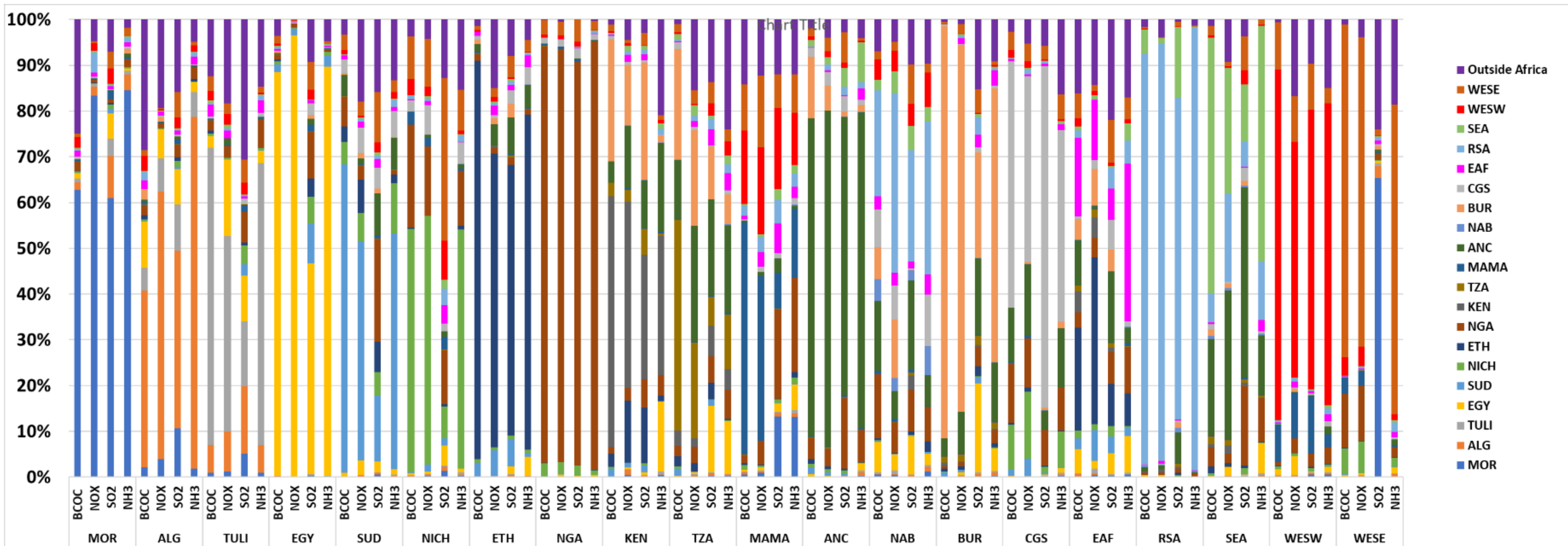


Figure 3. 12 Ratio of damage for each affected region caused by one source region for BCOC, NOx, SO2 and NH3

3.3 Discussion

3.3.1 Comparison with the previous methods

For the first time, damage factors for Africa were developed; we can compare our results with previous methods that considered Africa with a low resolution (e.g., the whole continent only). As stated previously, mainly three models have been developed, each of them belonging to a global LCIA method (LIME3, Recipe2016, Impact World+).

It is difficult to compare our results with LIME3 and Impact world+ as the resolution for these two methods is relatively low; however, these two methods give very interesting indications.
Several areas in Africa being empty, when considering the impact at a low resolution (e.g., whole continent), this low resolution might influence the damage factors. There is an important difference for the damage factors in Urban Area and Rural area in ImpactWorld+ method (Figure 3.13). This can explain why the damage factors for Africa in LIME3 also show lower results.

When comparing our results with Ono (Edahiro) et al. 2018 [11] (the only existing study using the same methodology) our hypothesis is confirmed. In Ono et al. 2018: Algeria, Egypt, Libya, Morocco and Tunisia were considered as one region (NAF). In our research, these countries are allocated to 4 regions: MOR, ALG, TULI, EGY. While the damage in EGY are larger in our study than in Ono et al. (2414 vs. 1100), the damages for MOR & ALG show similar values (about 1100). However, the damages for Tunisia show a lower value in our research (536 vs. 1100).

To sum up, the damage factor provided for NAF in Ono et al. 2018 is more or less an average of the four damage factors provided for north African countries in our research (ALG, EGY, MOR, TULI).

Finally, the comparison with Recipe2016 (6 regions considered) can also be interesting, although ALRI is not considered in this method. Our research proposes a similar definition for Egypt & South Africa, if we withdraw damages caused by ALRI, our results are nearly identical (1964 vs. 2200 for Egypt; 529 vs. 320 for South Africa)

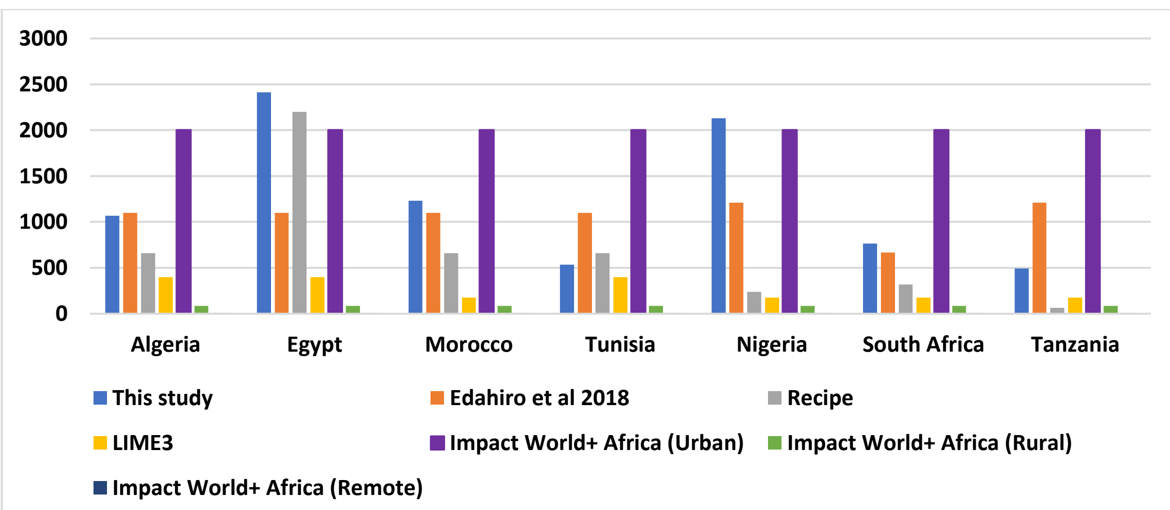


Figure 3. 13 Comparison of the damage factors for BCOC with previous studies (DALY/kton)

The advantages of each LCIA method containing information concerning African countries were compared in Table 3.8. The 3 main global LCIA method were compared with our study. To sum up, following the scale of the inventory each method has disadvantages and advantages, our study chose an approach that is the closest to the recent LCA trend ("regionalization"). The next step would be to go further and develop method at a prefecture-level or grid-level.

Table 3.8 Advantages and disasadvantages of each LCIA method to assess African country

	LIME3	Impact World+	Recipe	This study
Number of regions considered	2	3	6	20
Advantages	In case the inventory is limited (Africa continent inventory), it is still possible to calculate the impact	If the inventory is obtained at the same scale (e.g, emissions of vehicles in African urban area	Can be used to assess specific African regions (North, West, South. East)	Higher resolution/ Consideration of the damage caused by air pollution on younger population/Non-linear response function
Disadvantages	Do not differentiate the countries/ Do not take into account younger population	Do not differentiate the countries/ Do not take into account younger population	The regional scale is still a limitation (e.g, Nigeria vs other Western African countries)/ Do not take into account younger population	Do not differentiate urban and rural area

Best utilization following the scale of inventory

Inventory at continental-level (for example "Africa's total emissions" without any precise information on the location)

Inventory at country-level (for example "Nigeria's total emission")

3.3.2 Comparison with the WHO estimations

A comparison was also made with the estimations of the WHO for the damage of ambient air pollution. Our results were multiplied with the latest global inventory available for 2015 (EDGAR v5.0 published in April 2020 [12]). The comparison is shown in Figure 3.14. Even though the trend observed is similar, with Nigeria and Egypt having the highest impacts due to air pollution, the damages are estimated lower in our study. This could be explained by the observations made in the previous section: to obtain closer values to the WHO estimations, it would be needed to estimate damage factors at a grid-level. However, to do so, the required calculation time would be too important; several supercomputers would be required. Moreover, the current chemical transport model's accuracy is still uncertain when calculating at such a high resolution. Our results are closer to the WHO estimations compared with previous LCIA method Recipe, a total of 5.5 Million DALYs is observed.

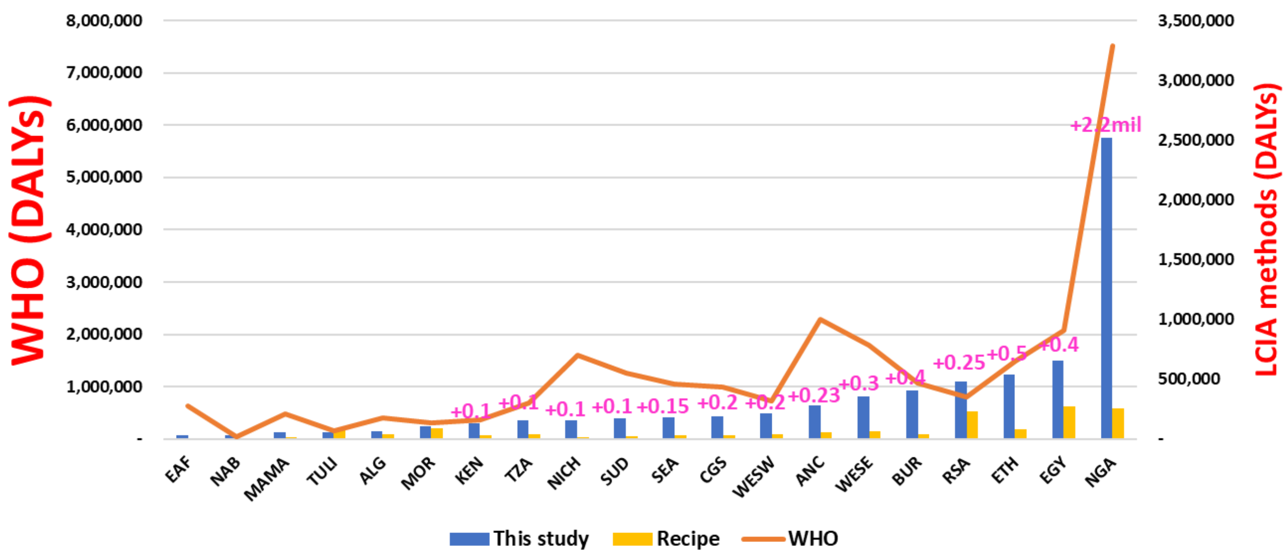
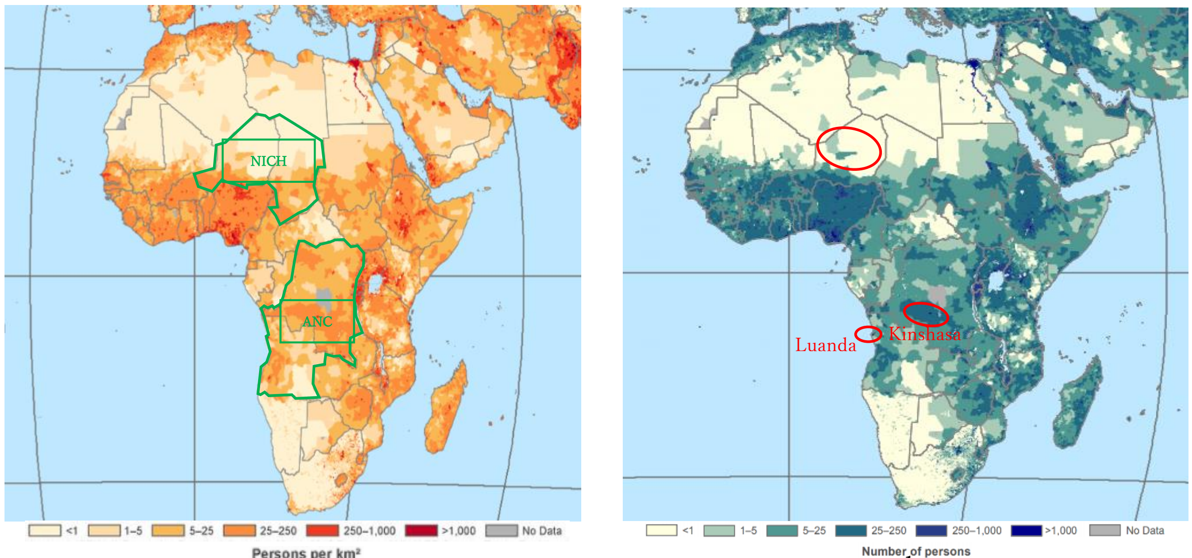


Figure 3. 14 Comparison of the damage obtained in this study with WHO 2016 estimations

3.4 Limitations

As Shown in the section 3.3.2, there are some limitations in our study. At first in the definition of the regions the accuracy has been greatly improved compared with previous studies. However due to the limitation of calculation time, only 20 regions could be considered. It was shown that for example for ANC (Angola, Congo) and NICH (Niger, Chad) in Figure 3.15, our results did not follow the trend of the WHO. This is due to the to the spread of the population in the territory. In the case of Niger and Chad, the country is mostly empty except the southern part. For the case of Angola and Congo, the population is mainly in two very dense urban area of over 10 million inhabitants respectively Luanda and Kinshasa.



a b

Figure 3. 15 a) 2015 gridded population density b) 2015 gridded population number (1km^2) [13]

Another point has to be raised, the data from the WHO (e.g, Death/case of disease, DALY/Death) are collected at country-level and not grid-level. The difference between health systems in urban and rural inside the same country was therefore not considered.

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Chapter 4: Application of the damage factors to the African sectors of activity

4.1 Procedure

4.1.1 General principles

Input-Output (IO) LCA enables to solve the limitations of processed-based LCA (for example, lack of primary data, unknown system boundaries) by integrating both direct and indirect emissions along the supply chain. It is based on the economic input-output tables provided by each country. Unlike process-based LCA, which uses physical flows, IO LCA uses the monetary flows between different sectors of activity. An example of an input-output table structure is given in Figure 4.1.

	Using Industries					Industrial Use		Consumers & Governments		
Transaction matrix	Ind. 1	Ind. 2	Ind. 3	Ind. 4	Ind. 5	Total Intermediate input	+	Final Demand	=	Total Industrial Output
Supplying Industries	$	$	$	$	$	$		$		$
Industry 1	1	2	3	4	5	15		1		16
Industry 2	1	2	3	4	5	15		15		30
Industry 3	1	2	3	4	5	15		30		45
Industry 4	1	2	3	4	5	15		45		60
Industry 5	1	2	3	4	5	15		60		75
Total intermediate input	5	10	15	20	25	Ax	+	y	=	x
+										
Value added	11	20	30	40	50					
=										
Total industrial input	16	30	45	60	75					

Figure 4. 1 Simplified structure of an IO table

In Figure 4.1, "A" is the economic matrix, composed with input-output coefficients (representing the monetary output from sector i required to produce $1 of output from sector j). "x" is the total monetary amount (e.g., in $) of goods and services required in each sector to meet the final demand "y". Direct purchase from sector j requires indirect investments from the sectors that serve j, calculated by multiplying the IO matrix A by y. To account for the entire supply chain, we need to add this to the output due to second-tier suppliers, Ay, and all preceding suppliers, which gives:

$$x = (I + A + A^2 + A^3 + \ldots)y = (I - A)^{-1} y$$

With "I" the identity matrix. To obtain the environment impacts "u", x is multiplied with an environment matrix B (composed with emissions per sectors):

$$\mathbf{u} = \mathbf{B\,x} = \mathbf{B\,(I - A)^{-1}\,y}$$

The transaction matrix is available in several countries (e.g., Japan [1], USA [2]), even though the level of details is different for each country (for example 42 for Switzerland [3] or 500 in the USA). Multiregional input–output (MRIO) tables such as EORA (Section 4.1.2) gather economic I/O matrices from several countries, they are used to assess the global supply-chain.

4.1.2 Multi-regional input-output table (MRIO): EORA

There exist several MRIO tables, mainly four are commonly used: EXIOBASE [4], WIOD [5], GTAP [6], and EORA [7]. Their main characteristics relative to African countries is shown in Table 4.1.

Table 4.1 Main characteristics of MRIO relative to African countries

Name (release version)	Latest available information (Year)	African countries data characteristics
Exiobase (v3)	**2011**	**South Africa represented as a single country, other African countries as "Rest of the World Africa"**
WIOD (2016)	**2014**	**Africa represented inside "Rest of the World" category**
GTAP (GTAP 10)	**2014**	**31 African countries with Western Africa and Central Africa defined as regions**
EORA (2015)	**2015**	**51 African countries including both monetary and air pollution data**

As it can be seen in the Table 4.1, EORA has the highest level of detail concerning African countries. Information concerning 15,909 sectors among 190 countries is detailed. 2720 environmental indicators are also provided, including, for example, GHG and air pollution emissions. The latest version is available for the year 2015. EORA does not present a harmonized format, in the way that countries do not have the same number of sectors. EORA was chosen to estimate the environmental burden from air pollution in Africa as it has the highest detailed information for 51 African countries. Compared with the other MRIO tables, it is also usually updated to match with the latest trade information. A simplified structure of EORA is provided in Figure 4.2.

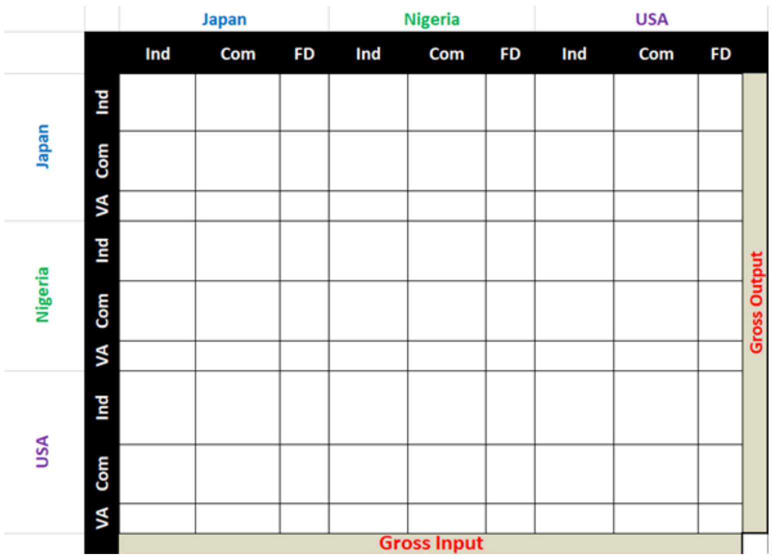


Figure 4. 2 EORA simplified structure (Com= Commodities, FD= Final Demand, Ind= Industrial, VA= Added Value)

Two approaches were chosen in our research. The production-based approach where the emissions are allocated to the location of the emissions. The second approach is the consumption-based approach, which tracks each country's responsibility for global emissions. In this approach, a focus is done on the imports of each country. An overview of these two approaches is presented in Figure 4.3.

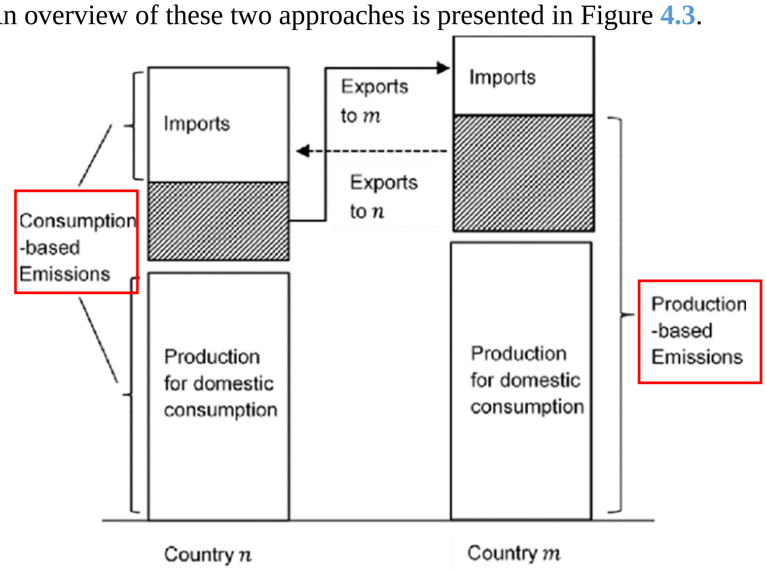


Figure 4. 3 Overview of production-based and consumption-based approaches [8]

It is then possible to evaluate the responsibility of each African country in its own emissions but also the responsibility of each country located outside Africa in the impacts of air pollution within Africa.

The inventory inside the satellite matrix in EORA contains the following emissions shown in Table 4.2. According to this inventory, the emissions in DR Congo, Ghana, Guinea, Nigeria, and South Africa are overall the highest in Africa due to several sources:

- For NOx: Road transportation, Savanna burning, grassland fires and electricity generation (only for South Africa)
- For BCOC: Savanna burning, grassland fires and residential sector
- For SO2: Savanna burning, Road transportation and electricity generation (only for South Africa)
- For NH3: Manure and Savanna burning

Table 4.2 Emissions for African countries in EORA

	NOx	BCOC	SO2	NH3
Algeria	415	135	227	200
Angola	208	138	162	182
Benin	238	279	152	186
Botswana	164	90	204	154
Burkina Faso	192	229	145	231
Burundi	494	831	188	312
Cameroon	134	86	132	134
Cape Verde	134	133	134	132
Chad	532	981	189	330
Congo	165	142	136	168
Cote d'ivoire	206	215	154	191
DR Congo	999	2103	281	440
Djibouti	146	86	151	134
Egypt	752	178	750	541
Eritrea	147	102	141	146
Ethiopia	715	1327	228	588
Gabon	159	104	151	137
Gambia	144	108	135	138
Ghana	781	1400	283	379
Guinea	701	1336	220	369
Kenya	393	338	327	435
Lesotho	135	93	134	139
Liberia	149	134	140	142
Libya	438	96	471	153
Madagascar	167	145	143	229
Malawi	174	172	139	191
Mali	314	472	159	262
Mauritania	169	94	153	160
Morocco	313	120	473	236
Mozambique	170	147	146	158
Namibia	153	90	263	161
Niger	151	130	140	162
Nigeria	1343	1802	325	609
Rwanda	141	107	138	148
Sao Tome	134	132	133	133
Senegal	272	315	190	208
Sierra Leone	244	333	154	180
Somalia	152	140	139	206
South Africa	2077	869	2747	756
Swaziland	135	91	134	139
Togo	240	295	150	179
Tunisia	218	102	254	171
Uganda	487	906	190	331
Tanzania	218	224	146	282
Zambia	161	134	486	168
Zimbabwe	185	160	227	177

As the amount of data is important in EORA (14839x14839 sectors), a software is needed to analyze it. Therefore Matlab [9] is used to operate the calculation, the Matlab code to obtain the emissions in both production based and consumption based approaches is provided in Appendix 4.1.

4.1.3 Calculation procedure

The procedure to obtain the emissions in both consumption and production based approaches is the following:

Step 1: Diagonalize the final demand Y:

Y'= diag (Y)

Y' is a diagonal matrix, with the final demand of each country sector in the diagonal.

Step 2: Sum the coefficient of the transaction matrix T (rows) and diagonalize the sum:

T'= sum(T,2)
T''= diag (T')

T'' is a diagonal matrix, with the total intermediate input of each country sector in the diagonal.

Step 3: Add the final demand matrix Y' with the total input matrix T'' to obtain the gross input X (also called total industrial output)

X= Y' + T''

X is a diagonal matrix, with the gross input of each country sector in the diagonal.

Step 4: Multiply the transaction matrix T with the inverse of matrix X to obtain the economic matrix A, composed with input-output coefficients

A= T * inv(X)

A is economic matrix, composed with input-output coefficients (representing the monetary output from sector i required to produce $1 of output from sector j)

Step 5: A is withdrawn to the identity matrix I and then inverted to create the matrix $(I-A)^{-1}$

IA= (I-A)
IA'= inv (IA) =$(I-A)^{-1}$

Step 6: The satellite accounts Q which provide the air pollution emissions for each sector is divided by the gross input X in order to obtain the emission per monetary unit

dair= Q/X

With dair a row matrix with the emissions of each sector per gross input

Step 7: dair is diagonalized and multiplied by $(I-A)^{-1}y$ to obtain a matrix u with the emissions caused by each using industry in the supplying industries.

$$\mathbf{u = dair * (I\text{-}A)^{-1}y}$$

u is matrix with the with the emissions caused by each using industries in the supplying industries as shown in Figure 4.4

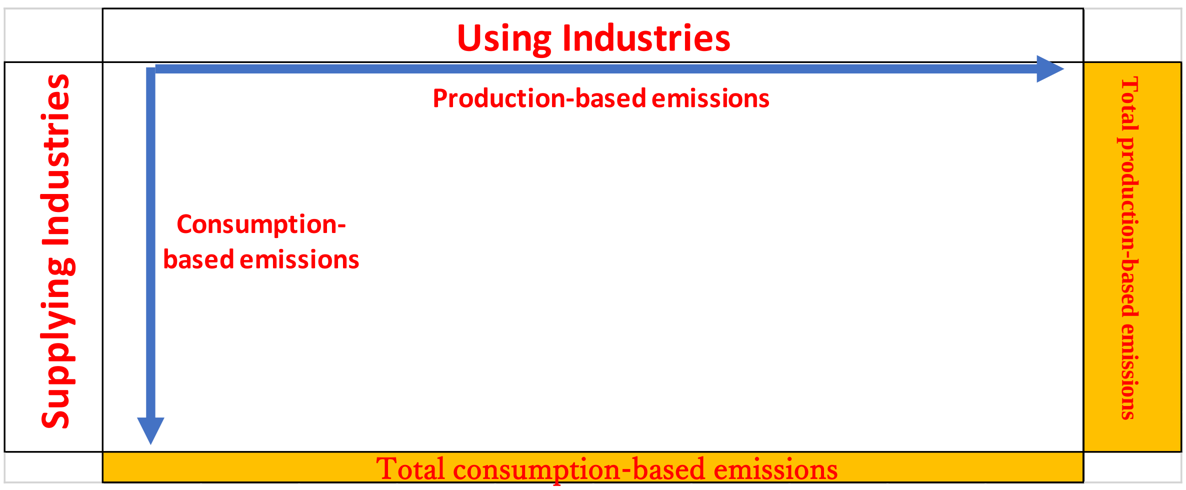


Figure 4. 4 Description of the u matrix

4.2 Results

4.2.1 Production-based & Consumption-based impacts of African sectors of activity

4.2.1.1 Production-based impacts of African sectors of activity

By multiplying the emissions in the production-based emissions by each country damage factors (developed in section 3):

$$Yearly\ Impact\ (DALY) = PBE_{NOx} * DF_{NOx} + PBE_{SO2} * DF_{SO2} + PBE_{NH3} * DF_{NH3} + PBE_{BCOC} * DF_{BCOC}$$

With PBE, the production-based emissions and DF the damage factor for each substance. Using, EORA it is possible to quantify each country's responsibility for the emissions happening inside its territory. The results are shown in Table 4.3 and Figure 4.5. In addition, total export values were also collected [10, 11]:

Table 4.3 Production-based impact & responsibility in the impact

	Production-based Impact	Responsibility in production-based impact	Exports value (In Billion USD)
Algeria	258,747	67%	37.9
Angola	200,760	76%	16.9
Benin	427,887	91%	1.16
Botswana	87,141	93%	6.3
Burkina Faso	369,275	92%	3.6
Burundi	272,769	91%	0.1
Cameroon	950,729	64%	5.04
Cape Verde	182,798	88%	0.07
Chad	1,227,326	64%	2.16
Congo	305,434	73%	6.32
Cote d'ivoire	364,401	70%	12.8
DR Congo	1,511,220	89%	6.22
Djibouti	86,862	88%	#N/A
Egypt	1,036,773	87%	27.8
Eritrea	88,873	90%	0.4
Gabon	289,166	82%	5.43
Gambia	205,552	89%	0.1
Ghana	1,662,553	51%	11.2
Guinea	1,450,489	79%	2.67
Kenya	363,720	80%	5.41
Lesotho	141,894	88%	0.6
Liberia	230,959	68%	1.01
Libya	140,312	63%	10.3
Madagascar	97,210	83%	2.65
Malawi	105,061	75%	1.33
Mali	412,145	84%	3.56
Mauritania	133,718	78%	1.95
Morocco	272,133	82%	36.9
Mozambique	95,396	92%	6.24
Namibia	89,747	86%	4.6
Niger	244,769	93%	1.45
Nigeria	4,870,922	86%	49.8
Rwanda	257,873	94%	0.8
Senegal	446,162	80%	2.85
Sierra Leone	434,042	90%	0.6
Somalia	101,834	94%	0.7
South Africa	1,250,943	76%	111
Swaziland	140,097	84%	1.70
Togo	440,789	75%	1.89
Tunisia	113,780	81%	15.8
Uganda	1,691,986	85%	2.43
Tanzania	191,950	76%	7.36

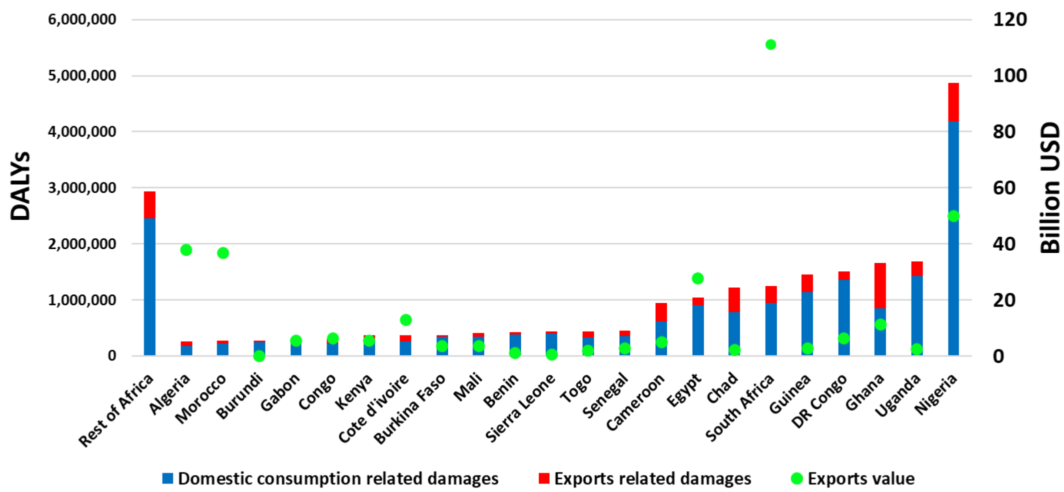


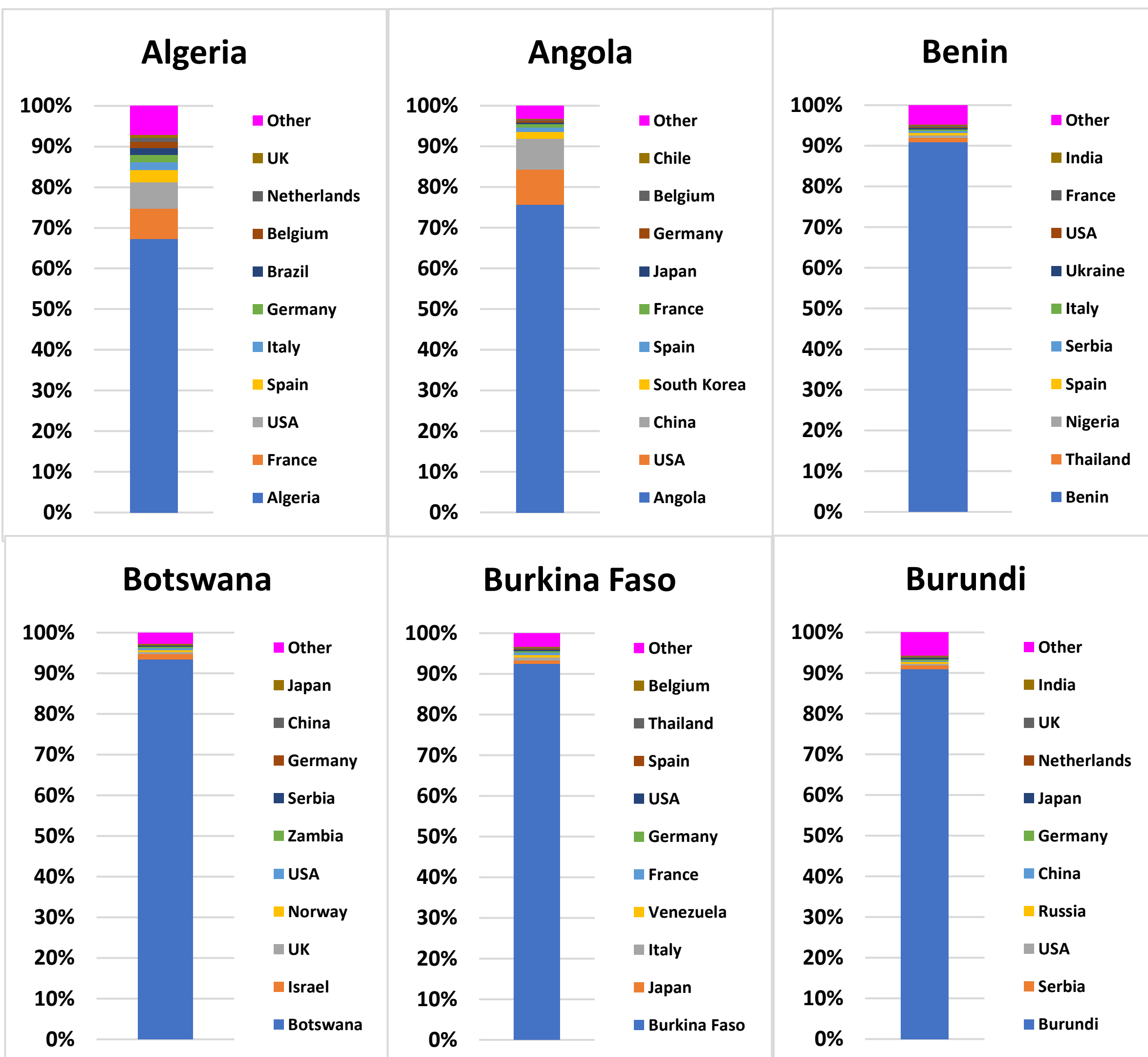
Figure 4. 5 Production-based impact and exports value

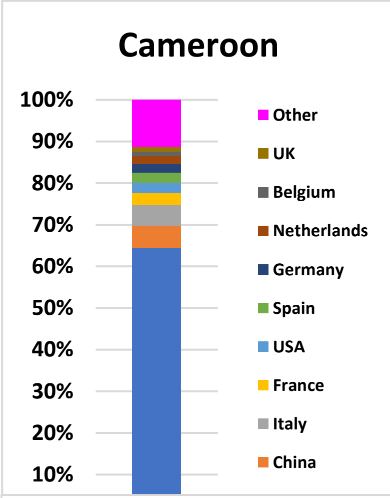
The responsibility of African countries in the production-based impact is, on average, around 80%. It can be explained in general by the low economic dependence of African countries on exports.

Some comments can be done for some countries that a show a lower responsibility in the production-based impact as they are more connected to developed economies:

- For Algeria, the exports of oil and natural gas especially to Europe (more than 50%) explain the higher share of exports impact (23%)
- For Angola, the exports of oil to Asia (more than 50%, with more than 40% to China) explain the higher share of exports impact (24%)
- For Cameroon, the exports of wood and cocoa, explain the higher share of exports impact (36%)
- For Chad, the exports of Arabic gum, explain the higher share of exports impact (36%)
- For Congo, the exports of oil to Asia, explain the higher share of exports impact (27%)
- For Cote D'Ivoire, the exports of cocoa especially to Europe (more than 50%), explain the higher share of exports impact (30%)
- For Ghana, the exports of cocoa (about 3 billion USD) especially to Europe (more than 50%), explain the higher share of exports impact (49%)
- For Liberia, the exports of Iron ore and rubber, to Germany and the USA, respectively, explain the higher share of exports impact (32%)
- For Libya, the exports of oils, especially to Europe (more than 50%), explain the higher share of exports impact (37%)
- For Malawi, the exports of tobacco and coffee, explain the higher share of exports impact (25%)
- For South Africa, the exports of mining products to China, India, the USA, Germany and Japan explain the higher share of exports impact (24%)
- For Togo, the exports of coffee and cocoa to France, Italy and Netherlands explain the higher share of impacts (25%)
- For Tanzania, the exports of mining products to China, coffee and sesamum seeds to Japan, coffee to the USA, explain the higher share of exports impact (24%)

The results agree with the WHO observations. Overall, the production-based damage is higher in Nigeria, with more than 4.5 million DALYs. The detailed results are provided in Figure 4.6. Overall, the trade between African countries is not having an important influence on the results. An explanation could be that trade volume between African countries is small, about 60 billion dollars (nearly 10% of African countries exports). Only the impact from G20 countries can be noticed, it is further explained in Section 4.2.2.

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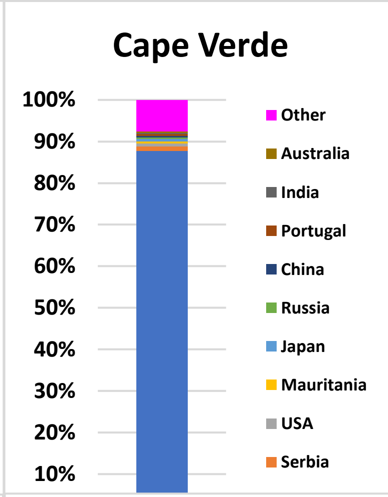
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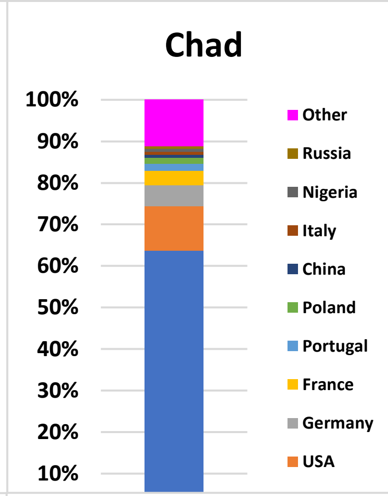
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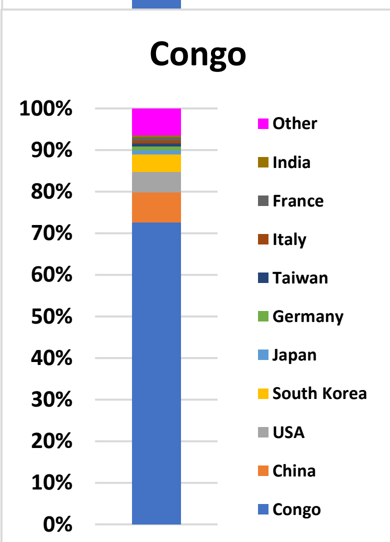
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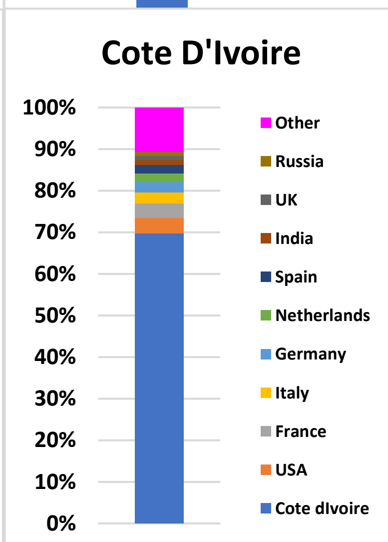
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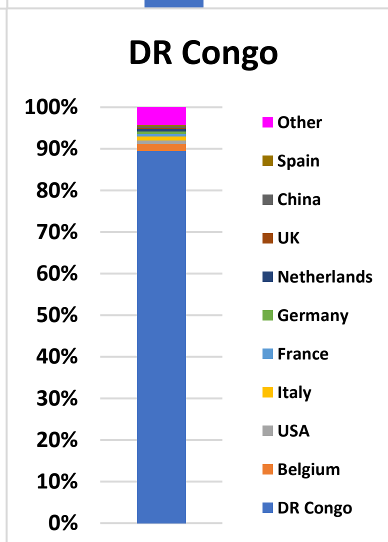
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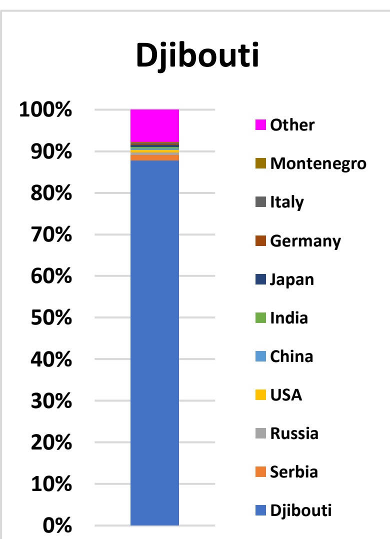
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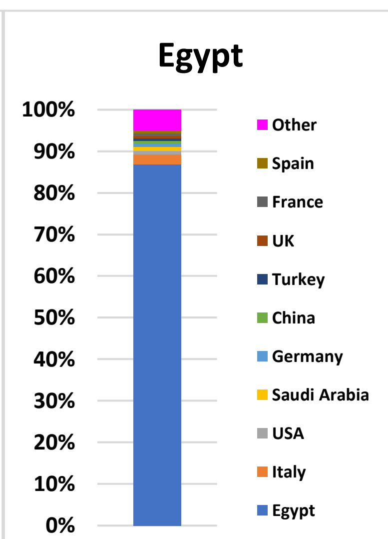
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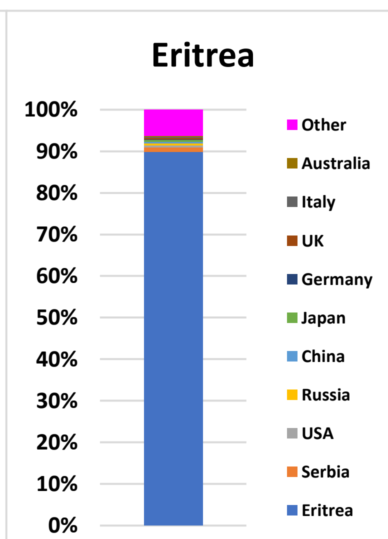
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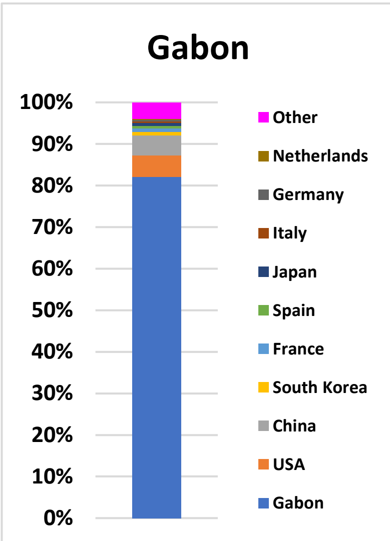
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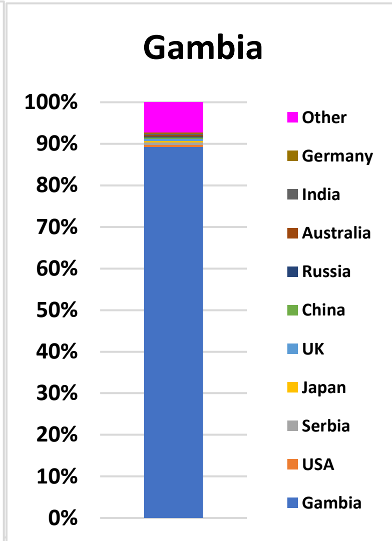
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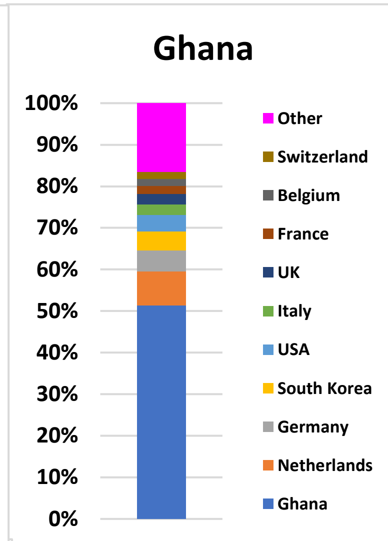
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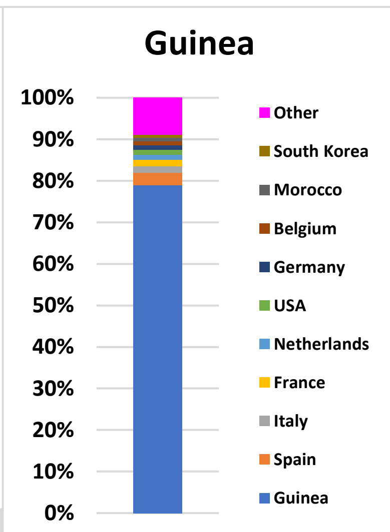
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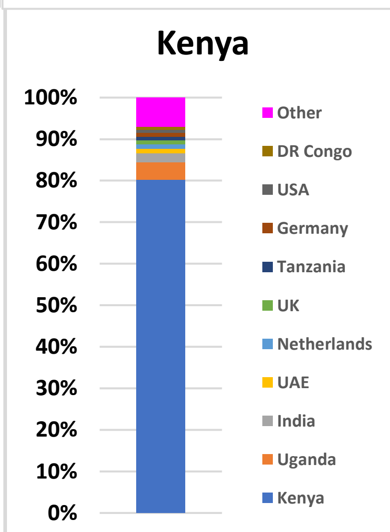
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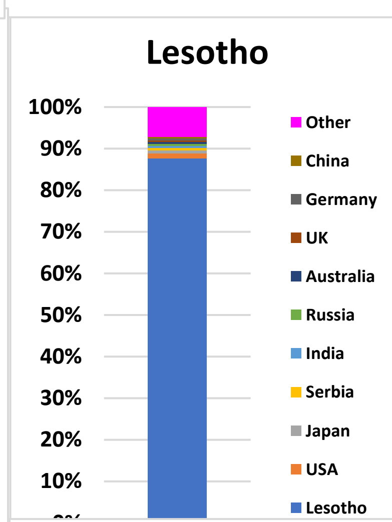
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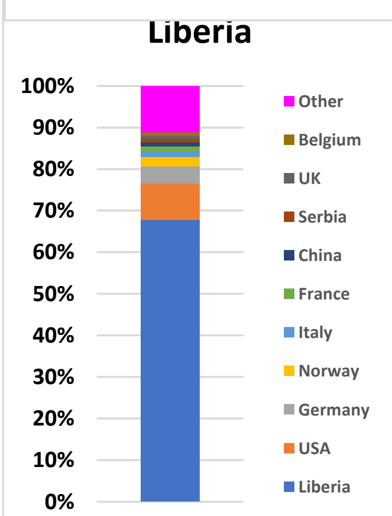
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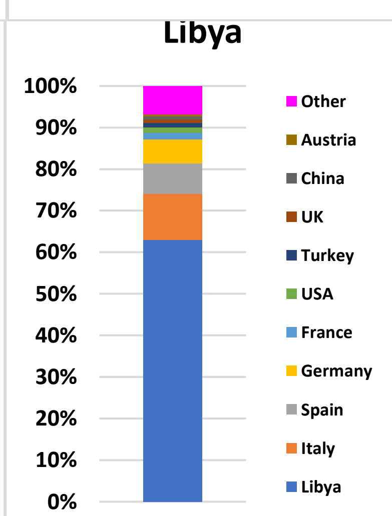
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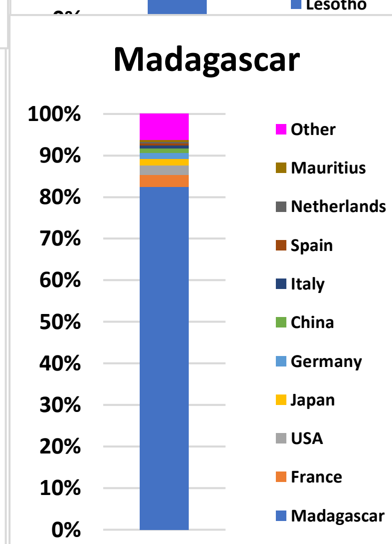
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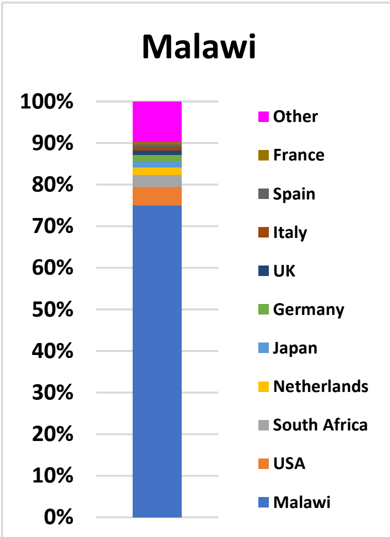
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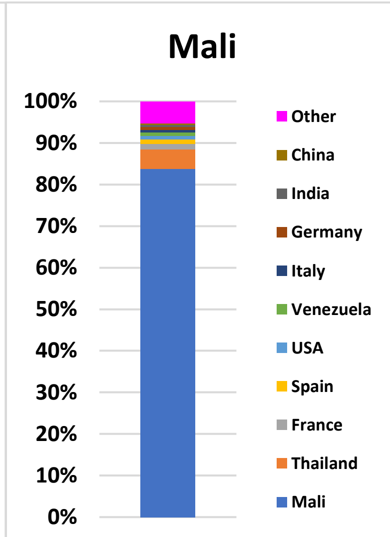
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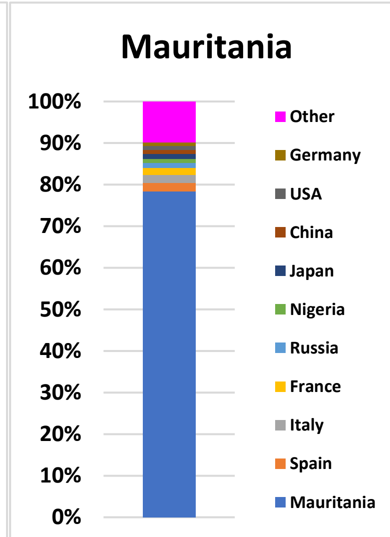
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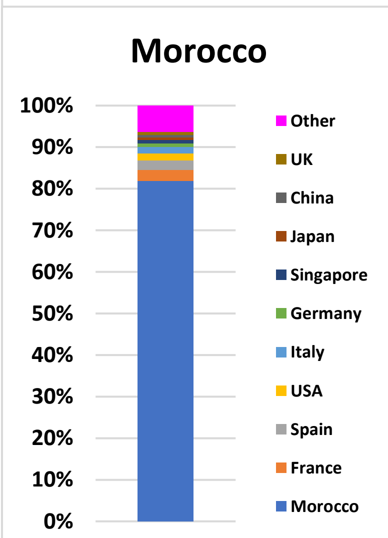
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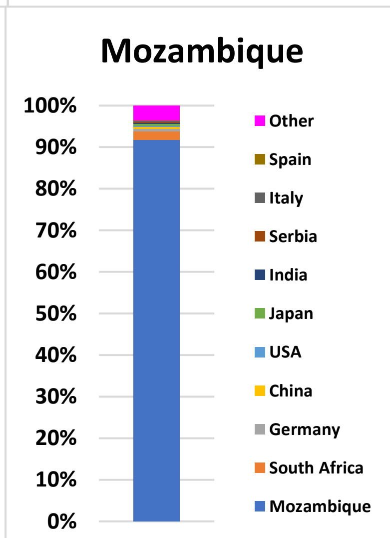
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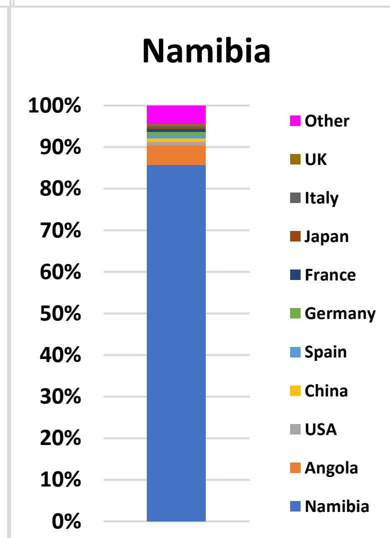
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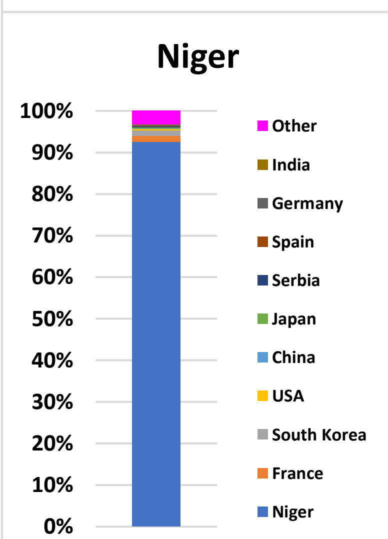
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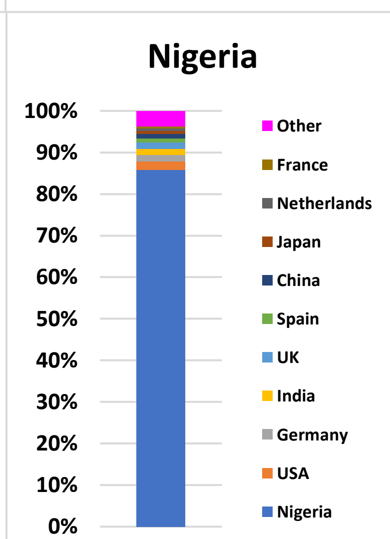
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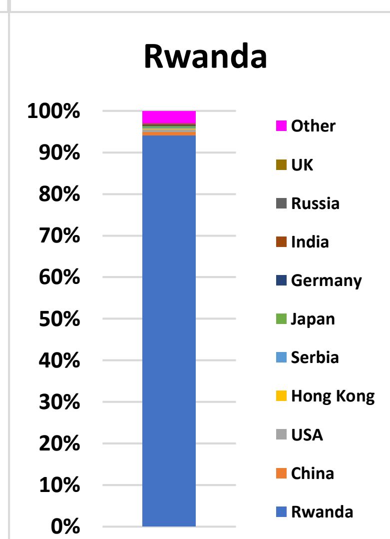
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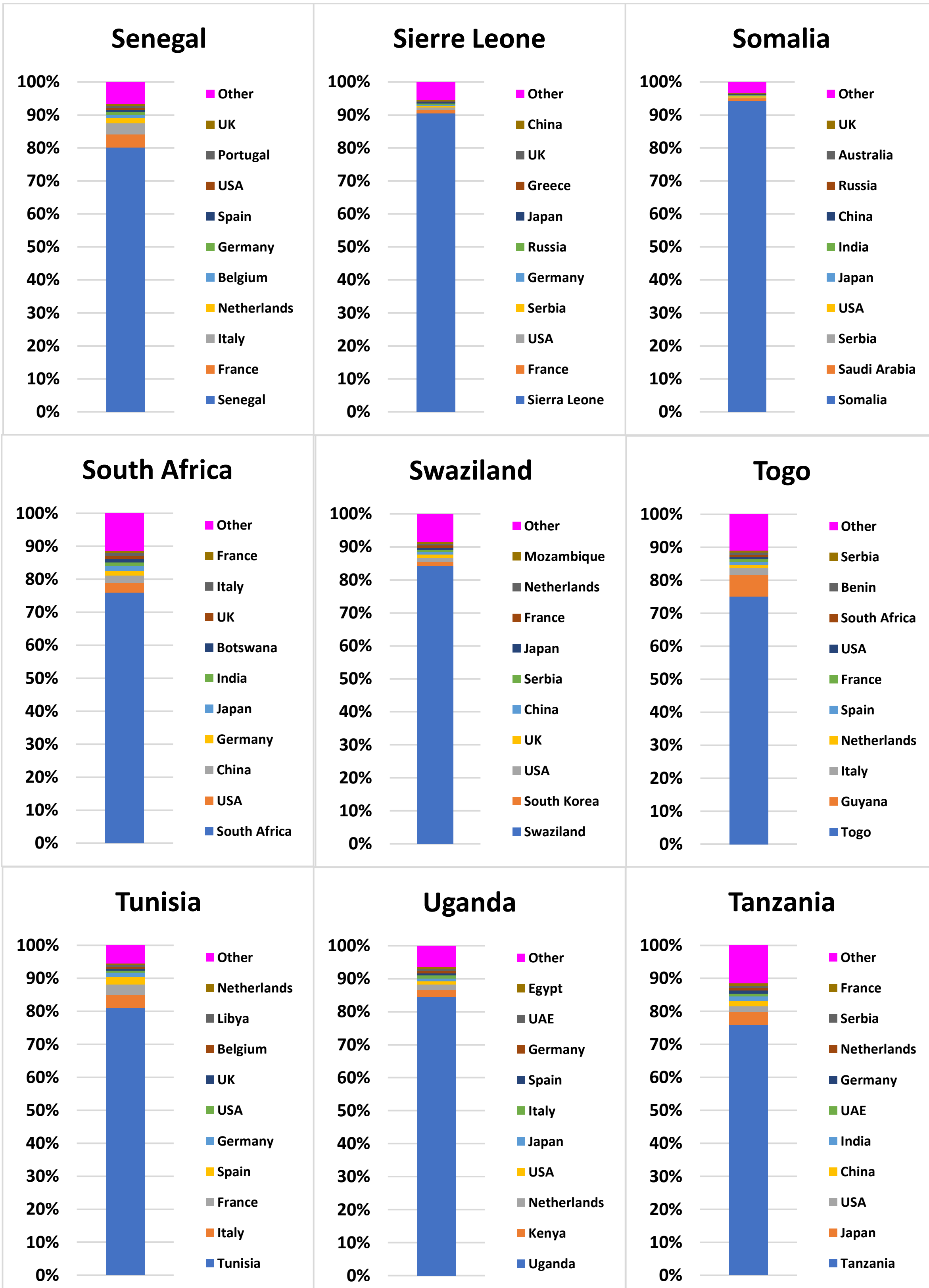


Figure 4. 6 Responsibility for production-based impact in each African country

When looking at the sectors having the African sectors having the highest impacts (Table 4.4), it can be clearly understood that Agriculture is the sector having mostly impacts in Africa with nearly 13 million DALYs annually (more than 50% of the total impact in Africa). Then the transport sector is the second with more than 900,000 DALYs followed by Electricity, Gas and Water with more than 500,000 DALYs. The latter one is shown lower than in other developing countries as the total annual electricity generation in Africa is under 800 TWh (around the electricity generation of a G20 country such as Korea, representing about 3% of the global production). Moreover, more than 50% of this electricity is produced from Natural gas (39%), renewables (20%), and nuclear (10%), respectively. The results for each African sector are provided in Appendix 4.2.

The damages in each African country are explained by the following substances (a summary is provided in Figure 4.6):

- Algeria:
  BCOC (143,646 DALYs especially due to Mining and Quarrying, Petroleum, Chemical and Non-Metallic Mineral Products, Transport & Agriculture)
  NH3 (55,674 especially due to Agriculture)
  SO2 (40,259 especially due to Transport, Petroleum, Chemical and Non-Metallic Mineral Products & Mining and Quarrying)
  NOx (19,167 especially due to Transport & Electricity, Gas and Water)
- Angola:
  BCOC (78,858 DALYs especially due to Mining and Quarrying & Agriculture)
  SO2 (75,081 DALYs especially due to Electricity, Gas and Water & Transport)
  NOx (26,821 DALYs especially due to Transport)
  NH3 (20,000 DALYs especially due to Agriculture & Mining and Quarrying)
- Benin:
  BCOC (242,420 DALYs especially due to Agriculture)
  SO2 (105,029 especially due to Agriculture)
  NOx (68,997 especially due to Agriculture)
  NH3 (11,441 especially due to Agriculture)
- Botswana
  BCOC (47,002 DALYs, various sectors)
  NOx (18,215 especially due to Transport)
  SO2 (10,989 especially due to Metal Products & Electricity, Gas and Water)
  NH3 (10,935 especially due to Agriculture)
- Burkina Faso:
  BCOC (198,715 DALYs especially due to Agriculture)
  NOx (100,714 especially due to Agriculture)
  SO2 (55,663 especially due to Agriculture & Electricity, Gas and Water)
  NH3 (14,184 especially due to Agriculture)
- Burundi
  BCOC (188,828 DALYs especially due to Transport)
  NOx (42,202 especially due to Agriculture)
  SO2 (29,975, various)
  NH3 (11,764 especially due to Mining and Quarrying & Agriculture)

- Cameroon
  BCOC (529,944 DALYs especially due to Agriculture)
  NOx (211,301 especially due to Agriculture)
  SO2 (173,813 especially due to Agriculture)
  NH3 (35,671 especially due to Agriculture)
- Cape Verde
  BCOC (72,007 DALYs, various)
  SO2 (57,988, various)
  NOx (38,627, various)
  NH3 (14,176, various)
- Chad
  BCOC (851,492 DALYs especially due to Agriculture)
  NOx (306,386 especially due to Agriculture)
  SO2 (43,360 especially due to Agriculture)
  NH3 (26,089 especially due to Agriculture)
- Congo
  SO2 (125,231, various)
  BCOC (90,293 DALYs especially due to Agriculture)
  NOx (70,747 especially due to Agriculture & Transport)
  NH3 (19,163 especially due to Agriculture & Mining and Quarrying)
- Cote D'Ivoire
  BCOC (186,612 DALYs especially due to Agriculture)
  SO2 (106,491 especially due to Agriculture & Transport)
  NOx (59,566 especially due to Agriculture & Transport)
  NH3 (11,732 especially due to Agriculture & Mining and Quarrying)
- DR Congo
  BCOC (1,203,653 DALYs especially due to Agriculture)
  SO2 (130,509 especially due to Agriculture)
  NOx (128,565 especially due to Agriculture)
  NH3 (48,493 especially due to Agriculture)
- Djibouti
  SO2 (40,845 DALYs especially due to Electricity, Gas and Water)
  BCOC (22,859, various)
  NOx (16,605 especially due to Electricity, Gas and Water & Transport)
  NH3 (6,553, various)
- Egypt
  BCOC (428,955 DALYs especially due to Petroleum, Chemical and Non-Metallic Mineral Products, Mining and Quarrying & Transport)
  NOx (268,771 especially due to Transport)
  SO2 (202,366 especially due to Electricity, Gas and Water)
  NH3 (136,681 especially due to Agriculture)
- Eritrea
  SO2 (38,090 especially due to Electricity, Gas and Water)
  BCOC (26,996 DALYs, various)
  NOx (16,685 especially due to Electricity, Gas and Water & Transport)
  NH3 (7,101 especially due to Agriculture)

- Gabon
  SO2 (139,527, various)
  NOx (68,000 DALYs especially due to Transport, Agriculture & Electricity, Gas and Water)
  BCOC (66,008 especially due to Agriculture)
  NH3 (15,631 especially due to Agriculture)
- Gambia
  BCOC (90,342 DALYs especially due to Agriculture)
  SO2 (59,207, various)
  NOx (41,440 especially due to Agriculture)
  NH3 (14,563 especially due to Agriculture)
- Ghana
  BCOC (1.216,741 DALYs especially due to Agriculture)
  SO2 (226,018 especially due to Agriculture & Electricity, Gas and Water)
  NOx (196,501 especially due to Agriculture)
  NH3 (23,293 especially due to Agriculture)
- Guinea
  BCOC (1,112,891 DALYs especially due to Agriculture)
  SO2 (202,188 especially due to Agriculture)
  NOx (96,491 especially due to Agriculture)
  NH3 (38,819 especially due to Agriculture)
- Kenya
  BCOC (249,209 DALYs especially due to Quarrying and Mining & Transport)
  SO2 (71,372 especially due to Electricity)
  NOx (30,554 especially due to Electricity & Transport)
  NH3 (12,585 especially due to Quarrying)
- Lesotho
  BCOC (71,514 DALYs, various)
  NH3 (55,328 especially due to Agriculture)
  SO2 (10,542, various)
  NOx (4,511, various)
- Liberia
  BCOC (111,749 DALYs especially due to Agriculture)
  SO2 (61,183, various)
  NOx (43,013 especially due to Agriculture)
  NH3 (15,014 especially due to Agriculture & Mining and Quarrying)
- Libya
  SO2 (58,100 DALYs especially due to Electricity, Gas and Water)
  BCOC (51,418, various)
  NH3 (19,712 especially due to Agriculture)
  NOx (11,081 especially due to Transport & Electricity, Gas and Water)
- Madagascar
  BCOC (48,731 DALYs especially due to Mining and Quarrying & Agriculture)
  NOx (22,019 especially due to Transport & Agriculture)
  SO2 (16,261 especially due to Electricity, Gas and Water)
  NH3 (10,199 especially due to Agriculture)

- Malawi
  BCOC (57,898 DALYs especially due to Agriculture)
  NOx (22,939 especially due to Agriculture)
  SO2 (15,735, various)
  NNH3 (8,489 especially due to Agriculture)
- Mali
  BCOC (303,463 DALYs especially due to Agriculture)
  NOx (60,070 especially due to Agriculture)
  SO2 (32,401 especially due to Agriculture)
  NH3 (16,212 especially due to Agriculture)
- Mauritania
  BCOC (60,399 DALYs, various)
  NOx (32,300 especially due to Transport& Electricity, Gas and Water)
  SO2 (31,119 especially due to Electricity, Gas and Water)
  NH3 (9,900 especially due to Agriculture)
- Morocco
  BCOC (148,085 DALYs especially due to Electricity, Gas and Water)
  SO2 (66,405 especially due to Electricity, Gas and Water)
  NH3 (33,925 especially due to Agriculture)
  NOx (23,717 especially due to Transport)
- Mozambique
  BCOC (49,362 DALYs especially due to Agriculture & Transport)
  NOx (22,475 especially due to Transport)
  SO2 (16,534 especially due to Transport & Metal Products)
  NH3 (7,025 especially due to Agriculture)
- Namibia
  BCOC (47,037 DALYs especially due to Agriculture)
  NOx (17,052 especially due to Transport)
  SO2 (14,176 especially due to Metal Products)
  NH3 (11,482 especially due to Agriculture)
- Niger
  BCOC (111,862 DALYs especially due to Agriculture & Mining and Quarrying)
  NOx (87,006 especially due to Agriculture & Transport)
  SO2 (32,076 especially due to Electricity, Gas and Water)
  NH3 (12,825 especially due to Agriculture)
- Nigeria
  BCOC (3,840,255 DALYs especially due to Agriculture)
  NOx (473,860 especially due to Agriculture & Transport)
  SO2 (384,0767 especially due to Agriculture)
  NH3 (172,732 especially due to Agriculture)
- Rwanda
  BCOC (174,203 DALYs, various)
  NOx (41,967, various)
  SO2 (29,449, various)
  NH3 (12,253 especially due to Agriculture & Mining and Quarrying)

- Senegal
  BCOC (262,210 DALYs especially due to Agriculture)
  SO2 (83,477 especially due to Electricity, Gas and Water)
  NOx (78,552 especially due to Agriculture)
  NH3 (21,293 especially due to Agriculture)
- Sierra Leone
  BCOC (277,158 DALYs especially due to Agriculture)
  NOx (70,365 especially due to Agriculture)
  SO2 (67,506 especially due to Agriculture)
  NH3 (19,103 especially due to Agriculture)
- Somalia
  BCOC (37,396 DALYs especially due to Mining and Quarrying)
  NOx (37,085 especially due to Agriculture & Transport)
  SO2 (17,317, various)
  NH3 (10,034 especially due to Agriculture)
- South Africa
  BCOC (664,971 DALYs due to Agriculture & Electricity)
  NH3 (300,642 due to Agriculture)
  SO2 (215,754 due to Electricity)
  NOx (69,576 due especially to Electricity & Transport)
- Swaziland
  BCOC (69,588 DALYs, various)
  NH3 (55,459 especially due to Agriculture)
  SO2 (10,514, various)
  NOx (4,537, various)
- Tanzania
  BCOC (110,505 DALYs especially due to Agriculture)
  SO2 (57,988, various)
  NOx (38,627 especially due to Transport & Agriculture)
  NH3 (14,176 especially due to Agriculture)
- Togo
  BCOC (256,342 DALYs especially due to Agriculture)
  SO2 (103,980 especially due to Agriculture)
  NOx (69,444 especially due to Agriculture & Transport)
  NH3 (11,023 especially due to Agriculture)
- Tunisia
  BCOC (54,861 DALYs, various)
  SO2 (31,334 especially due to Petroleum, Chemical and Non-Metallic Mineral Products & Electricity, Gas and Water)
  NH3 (22,075 especially due to Agriculture)
  NOx (5,511 especially due to Transport & Electricity)
- Uganda
  BCOC (1,479,298 DALYs especially due to Agriculture)
  NOx (144,723 especially due to Agriculture)
  SO2 (40,616 especially due to Agriculture)
  NH3 (27,349 especially due to Agriculture)

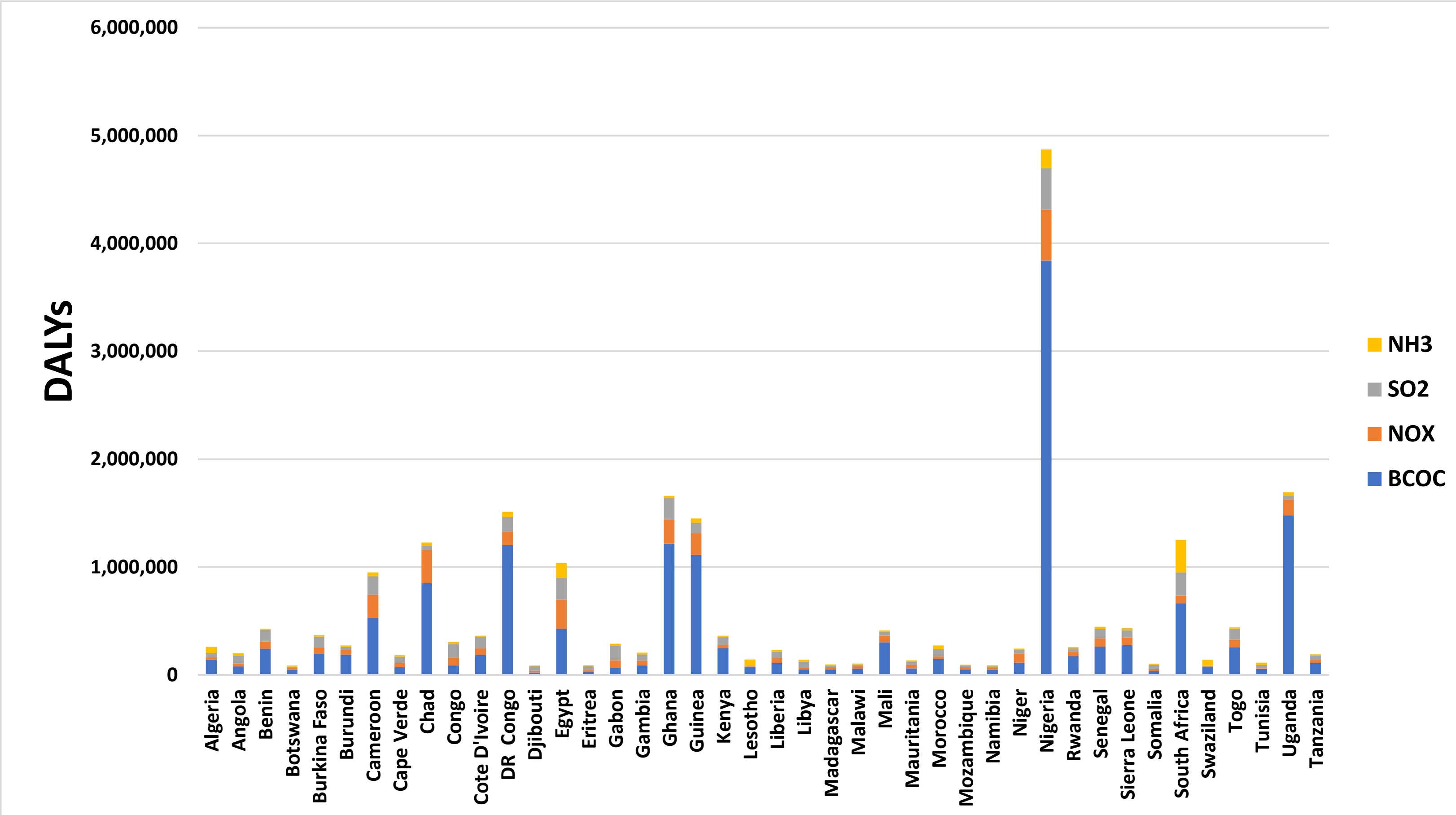


Figure 4. 7 Annual impact (DALYs) per substance

Table 4.4 Top 5 sectors with the highest impact per country (number of DALYs)

	Top1	Top2	Top3	Top4	Top5
Algeria	Agriculture (27,999)	Transport (24,130)	Mining and Quarrying (22,920)	PCNMMP (18,209)	Electricity, G&W(11,612)
Angola	Mining and Quarrying (17,779)	Transport (16,286)	Agriculture (16,064)	Electricity, G&W(11,110)	FIBA (11,021)
Benin	Agriculture (190,478)	Transport (18,444)	FIBA (13,967)	Mining and Quarrying (11,536)	Education H&OS (11,499)
Botswana	Metal Products (5,972)	Transport (5.494)	Agriculture (4,813)	Electricity, G&W(4,538)	Mining and Quarrying (3,697)
Burkina Faso	Agriculture (102,039)	Transport (17,264)	Mining and Quarrying (16,539)	Public Administration (15,924)	Wholesale Trade (13,619)
Burundi	Agriculture (18,417)	Mining and Quarrying (16,249)	Transport (13,840)	Education H&OS (13,699)	Public Administration (13,521)
Cameroon	Agriculture (663,528)	Transport (24,310)	FIBA (16,916)	Electricity, G&W(16,378)	Mining and Quarrying (13,125)
Cape Verde	Electricity, G&W(7,410)	Education H&OS (7,396)	Public Administration (7,392)	Wholesale Trade (7,382)	Retail Trade (7,381)
Chad	Agriculture (1,007,666)	FIBA (14,621)	Mining and Quarrying (13,067)	Education H&OS (11,201)	Public Administration (11,122)
Congo	Agriculture (46,898)	Mining and Quarrying (18,030)	Transport (16,289)	FIBA (11,488)	Education H&OS (10,655)
Cote D'Ivoire	Agriculture (98,737)	Transport (23,476)	Mining and Quarrying (23,129)	FIBA (13,075)	Education H&OS (12,062)
DR Congo	Agriculture (1,212,281)	FIBA (54,492)	Transport (28,430)	Education H&OS (26,563)	Public Administration (17,152)
Djibouti	Electricity, G&W(7,496)	Transport (3,909)	FIBA (3,609)	Mining and Quarrying (3,393)	Electrical and Machinery (3,361)
Egypt	Transport (189,711)	Electricity, G&W(160,057)	Agriculture (140,224)	PCNMMP (85,968)	Mining and Quarrying (66,510)
Eritrea	Electricity, G&W(5,728)	Agriculture (4,240)	Transport (4,166)	FIBA (4,153)	Education H&OS (3,847)
Gabon	Agriculture (23,703)	Electricity, G&W(16,346)	Transport (14,440)	FIBA (13,623)	Mining and Quarrying (12,932)
Gambia	Agriculture (27,260)	Mining and Quarrying (8,012)	FIBA (7,982)	Education H&OS (7,661)	Transport (7,655)
Ghana	Agriculture (1,327,005)	Electricity, G&W(52,770)	Transport (36,383)	Mining and Quarrying (18,341)	Wholesale Trade (17,339)
Guinea	Agriculture (1,239,293)	Transport (12,574)	Electricity, G&W(12,142)	Mining and Quarrying (12,089)	FIBA (11,464)
Kenya	Quarrying and Mining (36,288)	Transport (28,353)	Electricity (14,789)	Maize (13,489)	Tea (12,418)
Lesotho	Agriculture (7,462)	Mining and Quarrying (6,918)	Public Administration (6,052)	Education H&OS (5,956)	FIBA (5,830)
Liberia	Agriculture (29,942)	FIBA (11,158)	Transport (10,862)	Mining and Quarrying (10,345)	Education H&OS (10,070)
Libya	Electricity, G&W(42,196)	Transport (12,728)	PCNMMP (6,223)	Agriculture (5,770)	Mining and Quarrying (4,766)
Madagascar	Agriculture (11,830)	Mining and Quarrying (8,360)	Transport (6,162)	FIBA (6,048)	Education H&OS (4,347)
Malawi	Agriculture (30,427)	Mining and Quarrying (5,263)	FIBA (4,506)	Transport (4,093)	Education H&OS (3,629)
Mali	Agriculture (285,781)	FIBA (7,844)	Education H&OS (6,398)	Transport (6,373)	Public Administration (5,975)
Mauritania	Electricity, G&W(10,254)	Transport (8,405)	Agriculture (7,235)	Mining and Quarrying (6,687)	Public Administration (5,281)
Morocco	Electricity, G&W(66,336)	Agriculture (27,721)	Transport (20,231)	PCNMMP (14,335)	Metal Products (8,584)
Mozambique	Transport (8,964)	Agriculture (7,783)	Mining and Quarrying (5,214)	Education H&OS (4,581)	Public Administration (4,450)
Namibia	Metal Products (9,752)	Agriculture (6,813)	Transport (4,918)	Mining and Quarrying (3,498)	Public Administration (3,143)
Niger	Agriculture (23,282)	Mining and Quarrying (15,510)	Transport (14,020)	Electricity, G&W(11,183)	Public Administration (10,935)
Nigeria	Agriculture (3,854,674)	Transport (226,864)	Mining and Quarrying (81,033)	Electricity, G&W(76,263)	Retail Trade (51,338)
Rwanda	Mining and Quarrying (15,005)	FIBA (14,964)	Agriculture (13,540)	Education H&OS (12,426)	Transport (12,406)
Senegal	Agriculture (216,961)	Electricity, G&W(27,311)	Transport (19,636)	Mining and Quarrying (14,125)	FIBA (9.542)
Sierra Leone	Agriculture (231,641)	Wholesale Trade (14,651)	Mining and Quarrying (12,225)	Electricity, G&W(10,197)	Transport (10,032)
Somalia	Agriculture (9,328)	Mining and Quarrying (7,331)	FIBA (6,089)	Education H&OS (4,842)	Transport (4,758)
South Africa	Electricity (290,061)	Agriculture (283,941)	Transportservices (57,594)	Other mining (57,954)	Trade (16,287)
Swaziland	Agriculture (7,888)	Electricity, G&W(6,809)	Mining and Quarrying (5,944)	FIBA (5,733)	Education H&OS (5,656)
Tanzania	Agriculture (31,507)	Transport (16,126)	Mining and Quarrying (16,097)	FIBA (13,964)	Education H&OS (10,136)
Togo	Agriculture (194,596)	Transport (18,774)	Mining and Quarrying (15,812)	FIBA (14,844)	Education H&OS (12,129)
Tunisia	PCNMMP (11,003)	Electricity, G&W(9,976)	Agriculture (9,174)	Transport (6,740)	Mining and Quarrying (5,543)
Uganda	Agriculture (1,275,924)	FIBA (60,189)	Transport (35,331)	Education H&OS (34,990)	Mining and Quarrying (31,222)

*Education H&OS = Education, Health and Other Services, *Electricity G&W= Electricity, Gas and Water, *FIBA= Financial Intermediation and Business Activities, *PCNMMP= Petroleum, Chemical and Non-Metallic Mineral Products

4.2.1.2 Consumption-based impacts of African sectors of activity

In the consumption-based approach, the responsibility is on the consuming sectors. For example, the sectors consuming electricity or the sectors importing products from other. Therefore, the impact is not only occurring within the border of the consumer country but also in the producer of the imports. As our study only develops damage factors for African countries, the damage factors from Ono et al. [12] were used for the regions located outside Africa.

The results are shown in Table 4.5 and Figure X.X, in addition imports values were also collected [10, 11]:

Table 4.5 Consumption-based impact & responsibility in the impact

	Consumption-based Impact	Responsibility in consumption-based impact	Imports value (In Billion USD)
Algeria	215,004	81%	52.70
Angola	182,173	83%	35.30
Benin	398,402	98%	5.76
Botswana	99,836	82%	7.60
Burkina Faso	352,850	97%	3.17
Burundi	505,984	99%	0.56
Cameroon	623,915	98%	6.36
Cape Verde	164,060	98%	0.60
Chad	785,685	100%	0.90
Congo	231,246	96%	5.23
Cote d'ivoire	262,579	97%	9.52
DR Congo	1,376,570	98%	5.88
Djibouti	78,715	97%	#N/A
Egypt	968,605	93%	77.30
Eritrea	82,057	97%	0.40
Gabon	249,118	95%	2.72
Gambia	185,316	99%	1.00
Ghana	869,292	98%	14.30
Guinea	1,149,201	100%	3.25
Kenya	367,957	79%	18.60
Lesotho	132,165	94%	1.41
Liberia	159,243	98%	5.92
Libya	107,830	82%	12.90
Madagascar	86,073	93%	2.94
Malawi	85,093	93%	2.30
Mali	354,078	98%	2.95
Mauritania	231,249	95%	2.65
Morocco	262,342	85%	27.00
Mozambique	95,504	92%	9.02
Namibia	89,373	86%	0.00
Niger	240,049	94%	2.50
Nigeria	4,269,158	98%	40.30
Rwanda	256,403	95%	1.90
Senegal	370,969	96%	6.59
Sierra Leone	399,338	98%	1.95
Somalia	97,763	98%	2.70
South Africa	1,084,270	88%	82.10
Swaziland	124,417	95%	0.00
Togo	338,158	98%	9.04
Tunisia	116,291	79%	21.20
Uganda	1,457,568	98%	6.29
Tanzania	164,642	89%	15.00

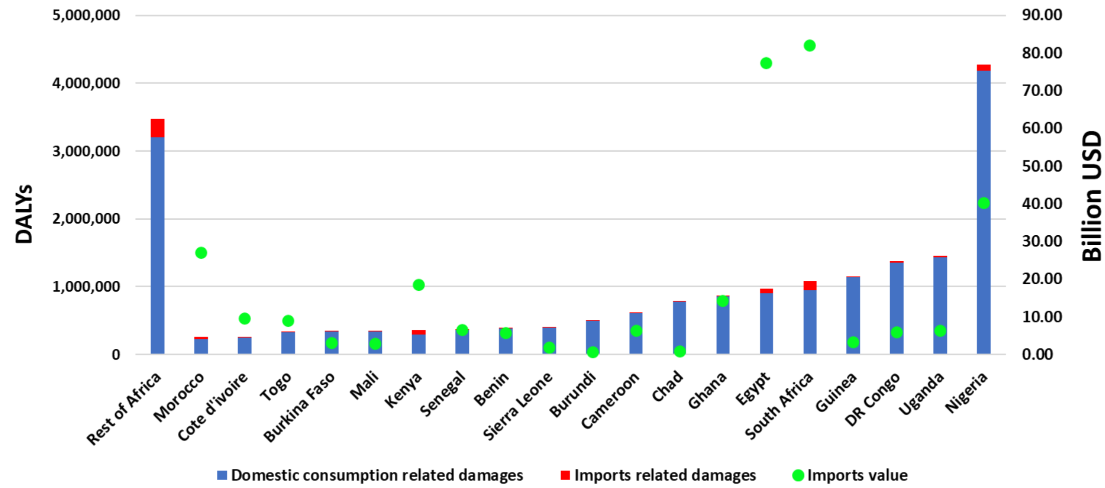
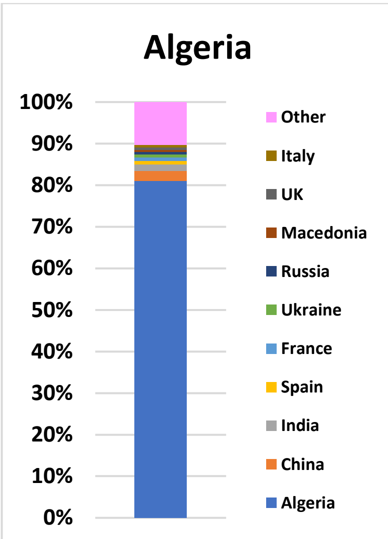


Figure 4. 8 Consumption-based impacts and exports values

As reported in the table, for African countries, consumption-based impacts mainly occur within their borders. It is mainly explained by the low volume of imports and the low added value of these imports (Mainly raw materials and fuels). The trend is opposed to developed countries (especially G20 countries, see Section 4.2.2). Northern Africa (Algeria, Morocco, Libya, Tunisia) being more connected to global economies, the impact occurring outside the borders is shown higher (about 20%). These countries especially import products from China and India (mainly electronic products). The detailed results are provided in Figure 4.7.

Some comments can be done for some countries that a show a higher responsibility in the consumption-based impact:

- For Algeria, the imports of machinery equipment and vehicles from China, India and Spain explain the higher share of imports impact (19%)
- For Angola, the imports of machinery equipment from Portugal and machinery products and Food products from South Africa explain the higher share of imports impact (17%)
- For Botswana, the imports of machinery equipment and food products from South Africa explain the higher share of imports impact (18%)
- For Kenya, the imports of food products from Uganda and oil from India explain the higher share of imports impact (21%)
- For Libya, the imports of textile and machinery products explain partly the higher share of imports impact (18%)
- For Morocco, the imports of coffee from Guinea and machinery products from India explain the higher share of imports impact (18%)
- For Tunisia, the imports of machinery products from India and China explain the higher share of imports impact (18%)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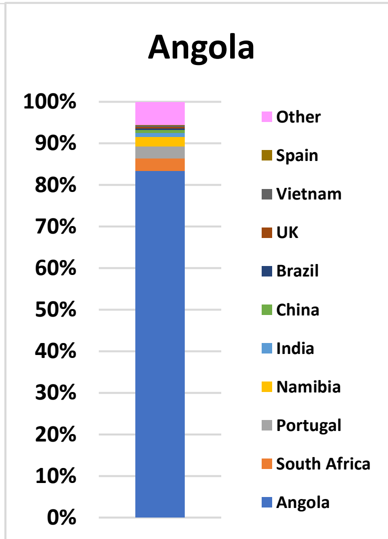
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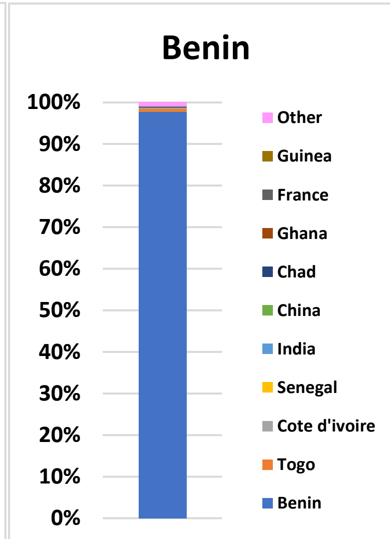
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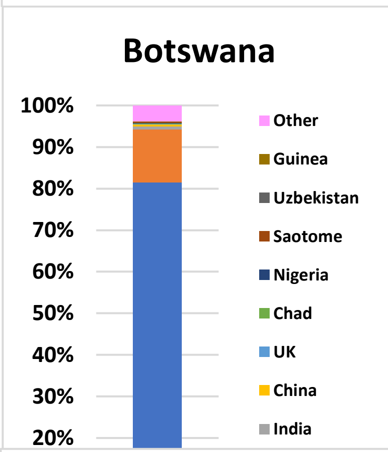
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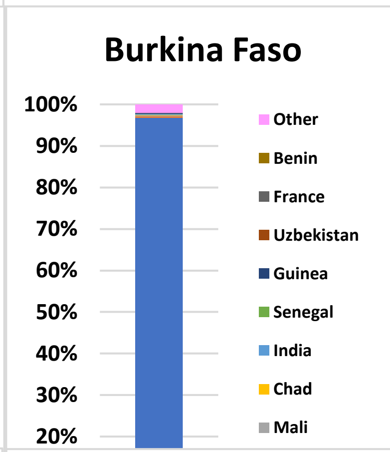
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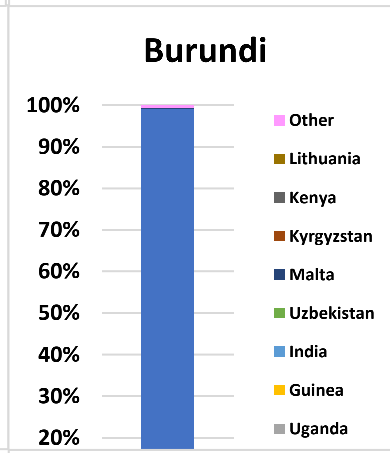
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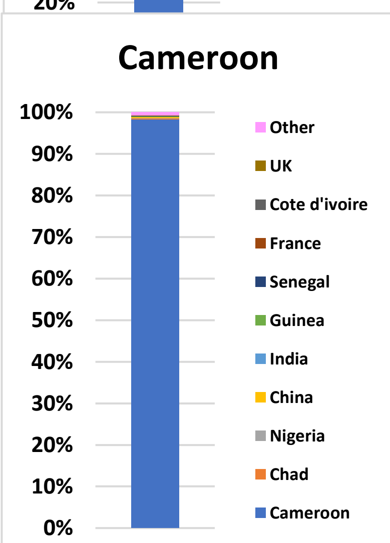
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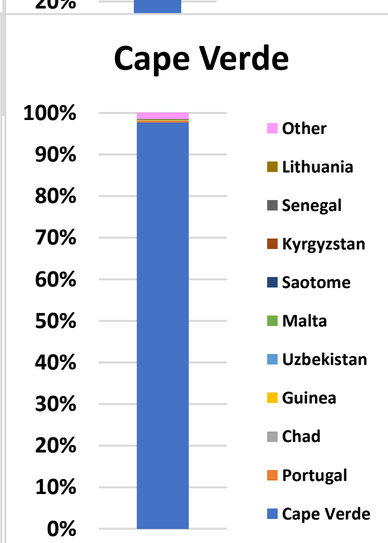
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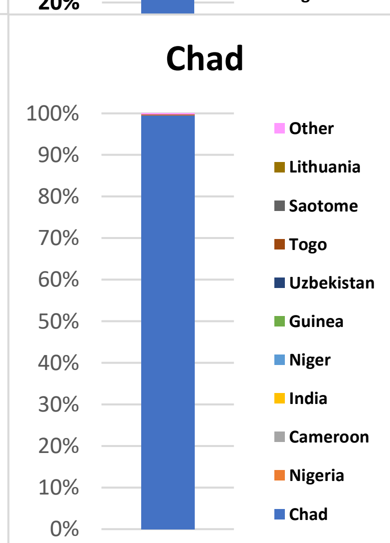
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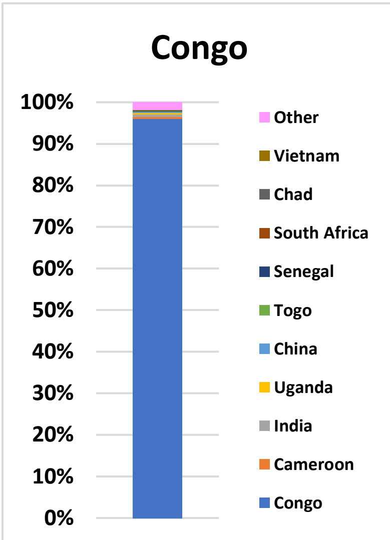
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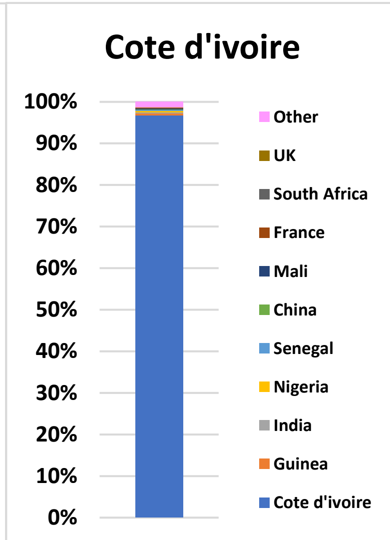
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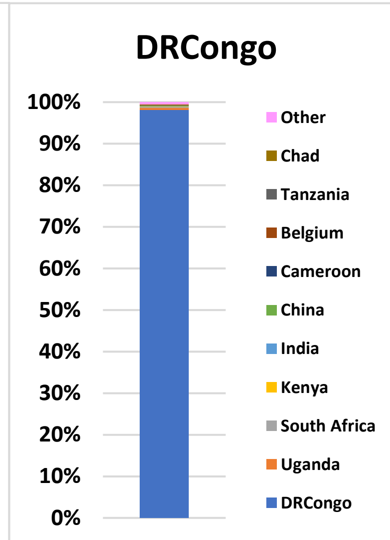
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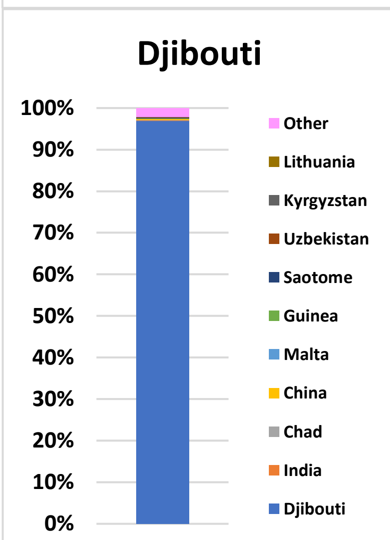
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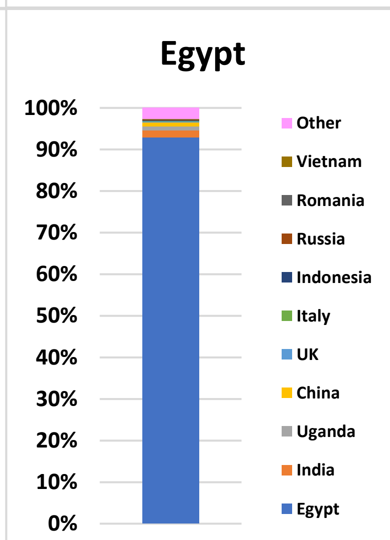
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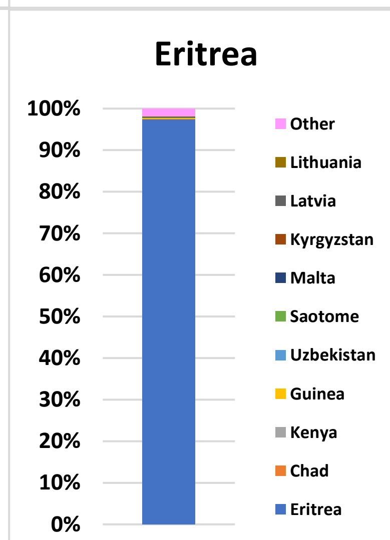
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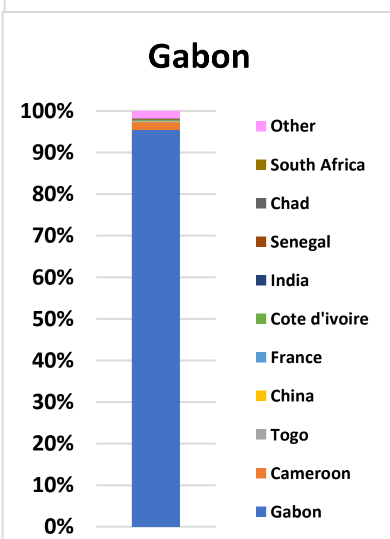
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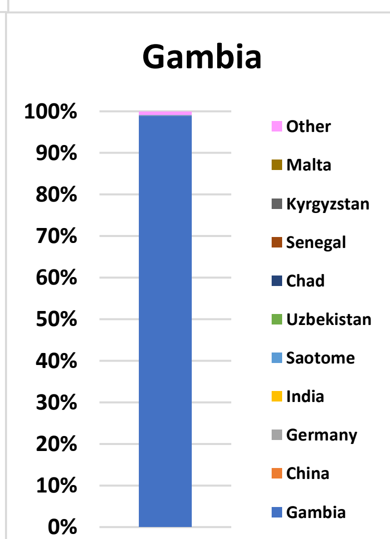
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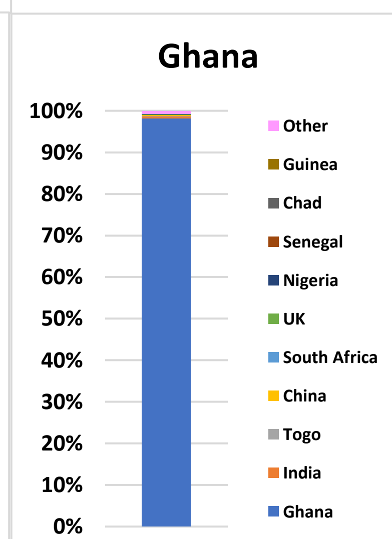
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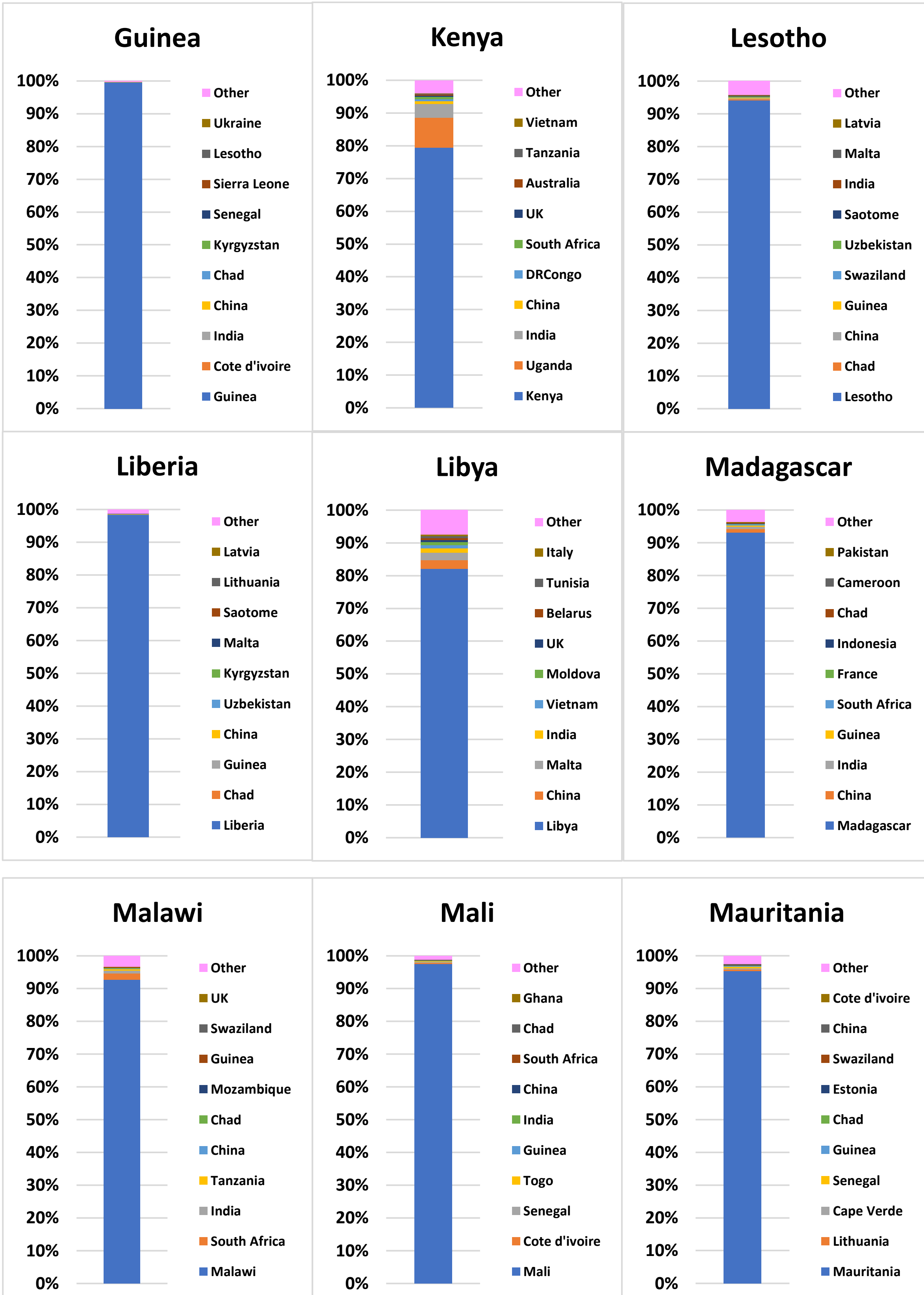
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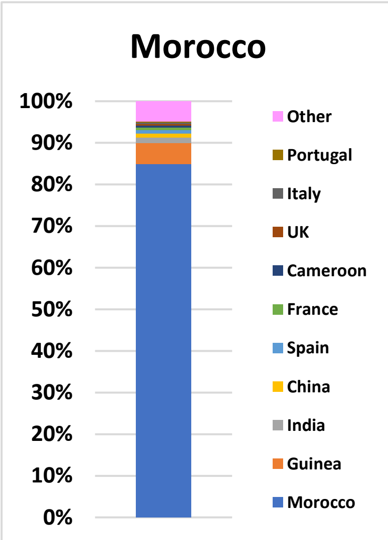
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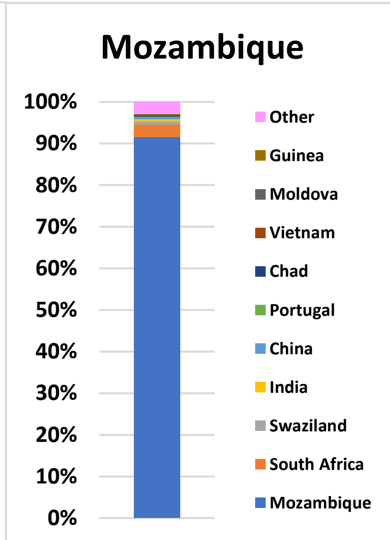
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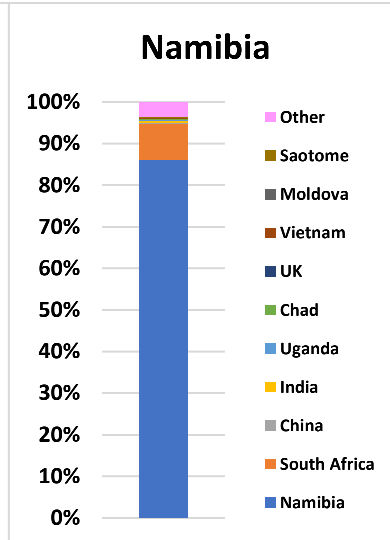
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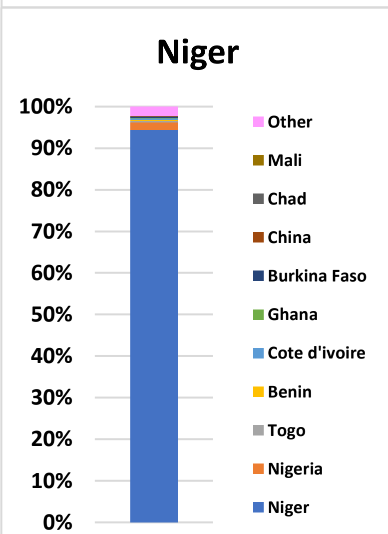
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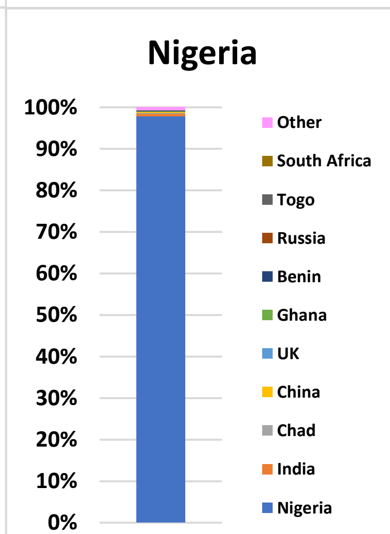
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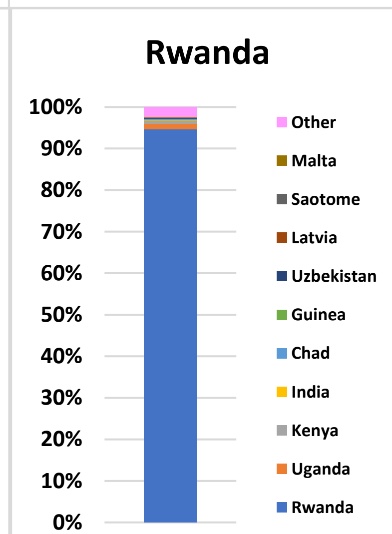
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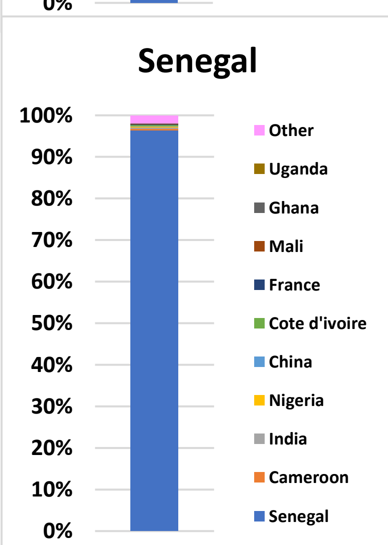
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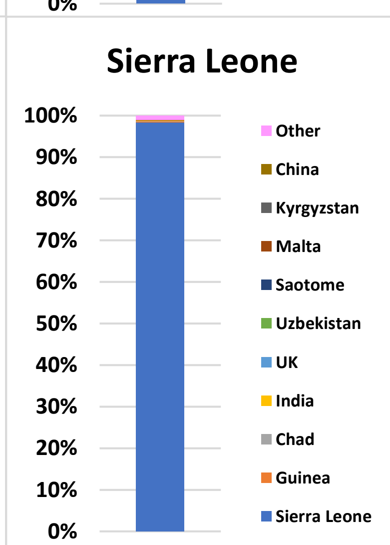
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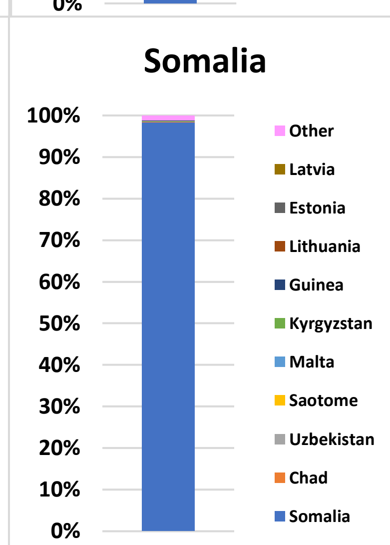
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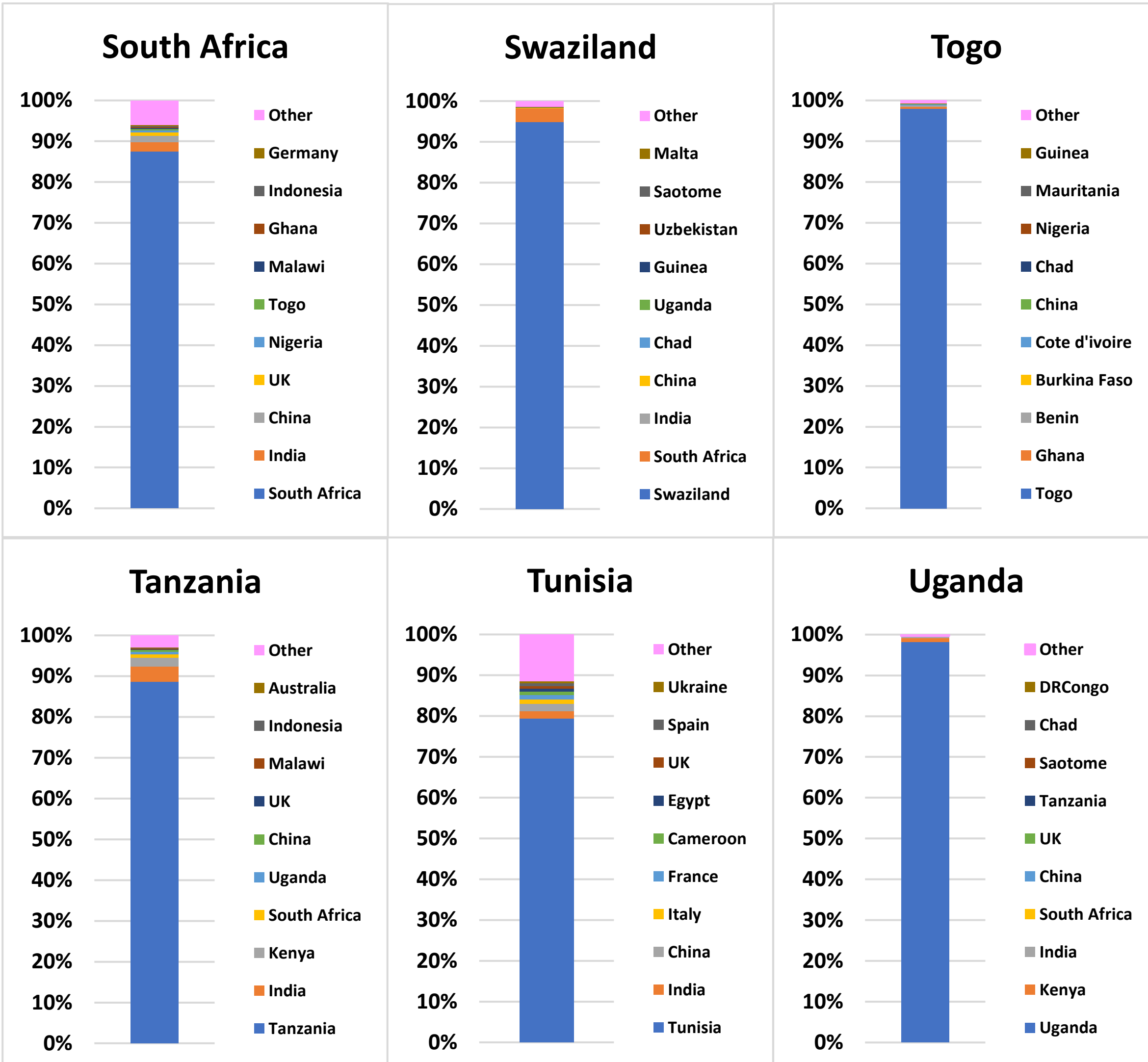


Figure 4. 9 Responsibility for consumption-based impact in each African country

When looking at the sectors having the African sectors having the highest impacts (Table 4.6) it can be clearly understood that sectors in a relationship with agriculture (food & beverages, hotels and restaurants) have mostly impacts in Africa. The impact of public administration and education, health and other services sectors have also to be noticed (about 2 million DALYs in total). The results for each African sector are provided in Appendix 4.3.

Table 4.6 Top 5 sectors with the highest impact per country (number of DALYs)

	Top1	Top2	Top3	Top4	Top5
Algeria	Public Administration(26,425)	Construction(21091)	Food & Beverages(19803)	Education H&OS(13845)	Hotels and Restraurants(12903)
Angola	Public Administration(25,598)	Education H&OS(23063)	Food & Beverages(16879)	Construction(15722)	Hotels and Restraurants(12275)
Benin	Food & Beverages(84,166)	Agriculture(45878)	Education H&OS(35207)	Hotels and Restraurants(29728)	Construction(26649)
Botswana	Public Administration(13,075)	Construction(15772)	Food & Beverages(6186)	Education H&OS(6579)	Hotels and Restraurants(6039)
Burkina Faso	Food & Beverages(49,125)	Public Administration(37978)	Agriculture(30413)	Hotels and Restraurants(29331)	Construction(24434)
Burundi	Public Administration(30,162)	Construction(22967)	Food & Beverages(18567)	Education H&OS(26272)	Hotels and Restraurants(19311)
Cameroon	Agriculture(176839)	Food & Beverages(135502)	Education H&OS(38980)	Hotels and Restraurants(36534)	Construction(32011)
Cape Verde	Education H&OS(20427)	Public Administration(19646)	Construction(15539)	FIBA(12401)	Food & Beverages(11474)
Chad	Agriculture(216815)	Food & Beverages(159730)	Public Administration(82131)	Education H&OS(74840)	Construction(51806)
Congo	Construction(25474)	Food & Beverages(25222)	Public Administration(22205)	Education H&OS(21875)	Hotels and Restraurants(19515)
Cote d'ivoire	Agriculture(38258)	Food & Beverages(25472)	Public Administration(21593)	Education H&OS(19438)	Construction(17082)
DR Congo	Food & Beverages(440074)	Agriculture(280017)	Hotels and Restraurants(128223)	Education H&OS(109402)	FIBA(84580)
Djibouti	Education H&OS(9917)	Public Administration(9298)	Food & Beverages(6304)	Construction(5780)	FIBA(5701)
Egypt	Food & Beverages(107024)	Transport(100813)	Electricity, Gas and Water(97674)	Education H&OS(65058)	Construction(63107)
Eritrea	Public Administration(10781)	Construction(5258)	Food & Beverages(6236)	Education H&OS(10583)	Hotels and Restraurants(4768)
Gabon	Public Administration(25866)	Construction(28863)	Food & Beverages(21915)	Education H&OS(25046)	Hotels and Restraurants(14251)
Gambia	Education H&OS(26125)	FIBA(19801)	Public Administration(19779)	Food & Beverages(15702)	Construction(14822)
Ghana	Agriculture(395133)	Food & Beverages(138668)	Hotels and Restraurants(42846)	Public Administration(37993)	Construction(34447)
Guinea	Food & Beverages(433603)	Agriculture(314524)	Hotels and Restraurants(72284)	Education H&OS(59822)	Construction(44685)
Kenya	Grain Milling(44955)	Transport(34163)	Building and Construction(27817)	Beverages and tobacco(15951)	Meat and dairy processing(13490)
Lesotho	Public Administration(16085)	Construction(13946)	Education H&OS(13107)	Hotels and Restraurants(9471)	Food & Beverages(9300)
Liberia	Education H&OS(23573)	Public Administration(19174)	FIBA(13170)	Hotels and Restraurants(12951)	Food & Beverages(11953)
Libya	Public Administration(13631)	Education H&OS(11497)	Electricity, Gas and Water(10053)	Construction(7971)	Food & Beverages(7907)
Madagascar	Education H&OS(8976)	FIBA(6901)	Food & Beverages(6517)	Public Administration(6224)	Construction(6122)
Malawi	Agriculture(8969)	Education H&OS(8645)	Food & Beverages(8054)	Public Administration(6035)	FIBA(6018)
Mali	Food & Beverages(95747)	Agriculture(69225)	Education H&OS(28398)	Hotels and Restraurants(26211)	Public Administration(22602)
Mauritania	Public Administration(13767)	Construction(8868)	Food & Beverages(13569)	Education H&OS(8686)	Hotels and Restraurants(7488)
Morocco	Food & Beverages(31286)	Construction(26701)	Electricity, Gas and Water(25411)	Public Administration(23992)	Textiles and Wearing Apparel(18631)
Mozambique	Public Administration(9886)	Construction(8822)	Education H&OS(8529)	Food & Beverages(7962)	Hotels and Restraurants(6002)
Namibia	Food & Beverages(9886)	Public Administration(9532)	Construction(8811)	Education H&OS(8064)	Hotels and Restraurants(5237)
Niger	Food & Beverages(23935)	Education H&OS(23617)	Public Administration(22816)	Construction(20366)	Hotels and Restraurants(17823)
Nigeria	Agriculture(1880978)	Food & Beverages(980693)	Hotels and Restraurants(376157)	Retail Trade(163358)	Transport(152194)
Rwanda	Education H&OS(29585)	Public Administration(23157)	Food & Beverages(21295)	FIBA(19622)	Hotels and Restraurants(18388)
Senegal	Food & Beverages(88041)	Agriculture(50948)	Construction(25942)	Hotels and Restraurants(23456)	Education H&OS(21594)
Sierra Leone	Food & Beverages(83369)	Hotels and Restraurants(56112)	Education H&OS(39652)	Agriculture(38638)	Public Administration(30695)
Somalia	Education H&OS(13123)	Public Administration(11066)	FIBA(8654)	Construction(8367)	Food & Beverages(7507)
South Africa	Electricity(110304)	Agricultural products(104215)	General Government services(57756)	Meat products(54955)	Other constructions(47703)
Swaziland	Education H&OS(13476)	Public Administration(11267)	Food & Beverages(10331)	Construction(9239)	Hotels and Restraurants(8527)
Togo	Food & Beverages(55416)	Agriculture(46262)	Education H&OS(35110)	Public Administration(26371)	FIBA(22801)
Tunisia	Public Administration(11895)	Construction(10922)	Food & Beverages(9697)	Textiles and Wearing Apparel(9691)	Education H&OS(9017)
Uganda	Agriculture(539583)	Food & Beverages(330882)	Education H&OS(90956)	Hotels and Restraurants(88318)	FIBA(72032)
Tanzania	Education H&OS(20697)	Public Administration(16881)	Food & Beverages(12942)	FIBA(11660)	Hotels and Restraurants(10915)

*Education H&OS = Education, Health and Other Services, *FIBA= Financial Intermediation and Business Activities

4.2.2 Comparison with developed countries

When comparing African countries with other developed countries, especially G20 countries, several differences can be observed, as shown in Table 4.7. For African countries, as stated previously, the impact in the production-based approach is higher than in the consumption-based impact. Especially for G20 countries, the impact of consumption is much higher than production.

Table 4.7 Comparison of production-based & consumption-based impact between G20 countries and African countries (G20 countries indicated with a yellow flag)

	Production-based Impact	Consumption-based Impact	Difference Production-Consumption
Algeria	258,747	215,004	43,743
Angola	200,760	182,173	18,587
Benin	427,887	398,402	29,484
Botswana	87,141	99,836	-12,695
Burkina Faso	369,275	352,850	16,425
Burundi	272,769	505,984	-233,216
Cameroon	950,729	623,915	326,814
Cape Verde	182,798	164,060	18,738
Chad	1,227,326	785,685	441,641
Congo	305,434	231,246	74,189
Cote d'ivoire	364,401	262,579	101,822
DR Congo	1,511,220	1,376,570	134,650
Djibouti	86,862	78,715	8,147
Egypt	1,036,773	968,605	68,168
Eritrea	88,873	82,057	6,816
Gabon	289,166	249,118	40,047
Gambia	205,552	185,316	20,236
Ghana	1,662,553	869,292	793,261
Guinea	1,450,489	1,149,201	301,288
Kenya	363,720	367,957	-4,236
Lesotho	141,894	132,165	9,729
Liberia	230,959	159,243	71,717
Libya	140,312	107,830	32,482
Madagascar	97,210	86,073	11,137
Malawi	105,061	85,093	19,967
Mali	412,145	354,078	58,067
Mauritania	133,718	231,249	-97,531
Morocco	272,133	262,342	9,791
Mozambique	95,396	95,504	-108
Namibia	89,747	89,373	374
Niger	244,769	240,049	4,720
Nigeria	4,870,922	4,269,158	601,764
Rwanda	257,873	256,403	1,470
Senegal	446,162	370,969	75,193
Sierra Leone	434,042	399,338	34,704
Somalia	101,834	97,763	4,071
South Africa	1,250,943	1,084,270	166,673
Swaziland	140,097	124,417	15,680
Togo	440,789	338,158	102,631
Tunisia	113,780	116,291	-2,510
Uganda	1,691,986	1,457,568	234,418
Tanzania	191,950	164,642	27,307
Argentina	317,919	339,523	-21,605
Australia	858,353	984,173	-125,819
Brazil	1,342,134	1,533,938	-191,804
Canada	243,394	593,852	-350,458
China	24,611,254	23,198,633	1,412,620
France	1,002,240	1,762,159	-759,918
Germany	1,228,419	2,616,321	-1,387,902
India	22,017,541	19,975,135	2,042,406
Indonesia	5,401,339	4,858,804	542,535
Italy	1,089,937	2,005,059	-915,122
Japan	2,997,885	3,871,756	-873,871
Mexico	506,986	724,540	-217,554
Russia	2,438,727	2,682,975	-244,248
Saudi Arabia	594,462	715,393	-120,931
South Korea	1,291,042	1,805,132	-514,090
Turkey	1,007,434	1,379,828	-372,394
UK	3,265,347	3,359,265	-93,918
USA	3,193,452	6,446,259	-3,252,807

As the consumption-based impacts are mostly higher than production-based impacts for G20 countries, it was decided to calculate the responsibility of each G20 country in the impact in Africa (Figure 4.8). The USA has the highest impact, with more than 500,000 DALYs mainly due to the imports of oil from Chad and Nigeria. Then China, France, Germany and Italy impacts are shown around 300,000 DALYs due also to the imports of agriculture products from Chad and Nigeria but also imports from Ghana (mainly oil and cocoa).

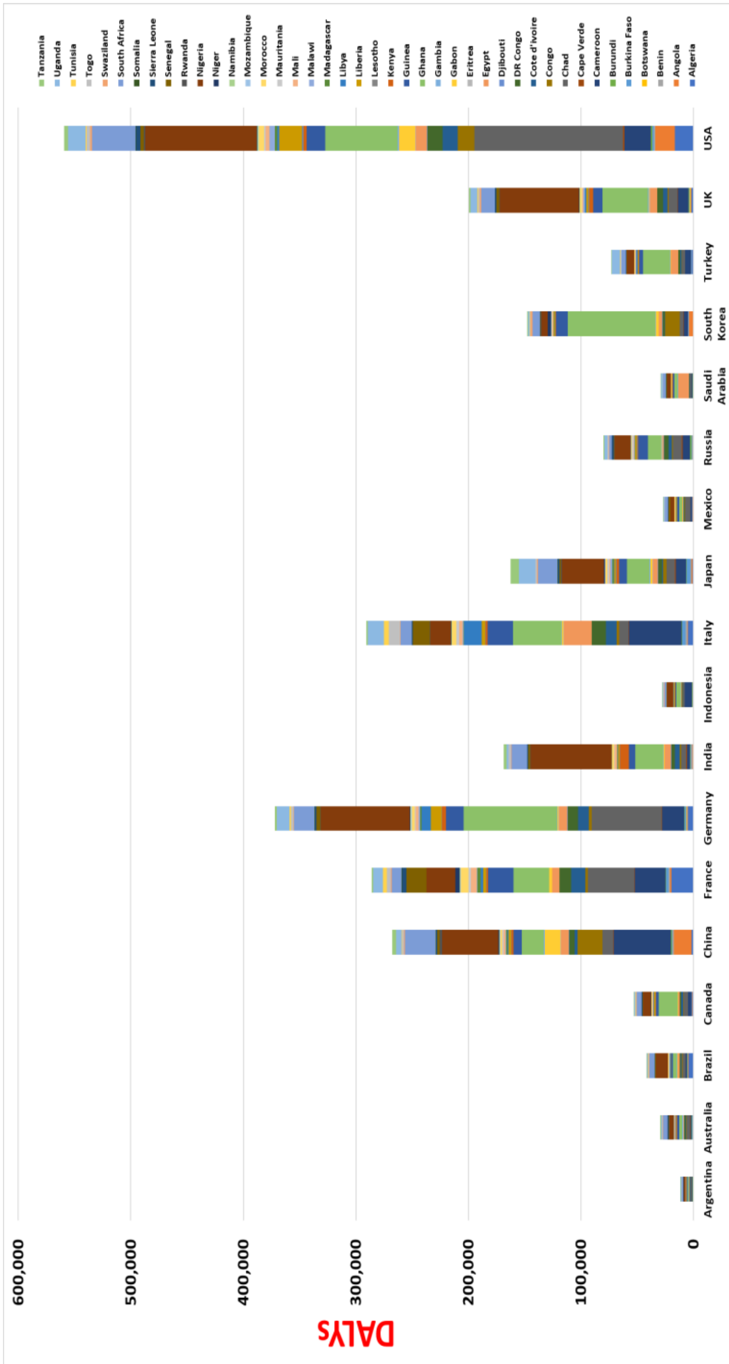


Figure 4. 10 Impact of G20 countries imports on African countries

4.3 Discussion

4.3.1 Agriculture

As shown in Section 4.2.2.1, the impacts of Agriculture are particularly high, with more than 13,000,000 DALYs due to poor agriculture practices. To confirm the impact of each crop, it was chosen to collect several information, especially from FAOSTAT database [13]. The main crops produced in each country are detailed in Table 4.8, a reason is provided for the importance of the impacts.

Table 4.8 Overview of African agriculture production (2015)

	Impact from Agriculture (DALYs)	Production of crop (MT)	Value of production (Bil $)	Main crop cultivated	Production of Cassava (MT)	Production of Palm oil (MT)	Possible reasons for the impact
Algeria	27,999	22.4	28.3	Potatoes, Wheat, Watermelons	0.0	0.0	Small impact
Angola	16,064	19.3	5.3	Cassava, Bananas, Sweet Potatoes	7.7	0.3	Small impact
Benin	190,478	11.2	3.6	Cassava, Yams, Maize	4.0	0.6	Biomass burned before cassava planting
Botswana	4,813	0.2	0.1	Roots & tubers, Vegetables, Sorghum	0.0	0.0	Small impact
Burkina Faso	102,039	7.6	3.1	Maize, Sorghum, Millet	0.0	0.0	Biomass burned before cassava planting
Burundi	18,417	5.9	2.0	Cassava, Bananas, Sweet Potatoes	2.8	0.1	Small impact
Cameroon	663,528	26.8	9.5	Cassava, Plantains, Oil palm fruit	5.2	2.8	Biomass burned before cassava planting
Cape Verde	7,290	#N/A	#N/A	Sugar Cane, Tomatoes, Bananas	0.0	0.0	Small impact
Chad	1,007,666	5.4	5.4	Sorghum, Groundnuts, Millet	0.1	0.0	Burning savanna
Congo	46,898	2.8	2.9	Cassava, Sugar Cane, Oil Palm Fruit	1.4	0.1	Small impact
Cote D'Ivoire	98,737	27.5	10.0	Yams, Cassava, Rice paddy	5.1	1.8	Small impact
DR Congo	1,212,281	51.8	#N/A	Cassava, Plantains, Sugar cane	34.9	1.2	Biomass burned before cassava planting
Djibouti	3,173	0.0	#N/A	Vegetables, Lemons, Beans	0.0	0.0	Small impact
Egypt	140,224	93.3	42.0	Sugar Cane, Sugar beet, Wheat	0.0	0.0	Use of synthetic fertilizers (Nitrogen)
Eritrea	4,240	0.5	2.1	Sorghum, Barley, Vegetables	0.0	0.0	Small impact
Gabon	23,703	1.4	#N/A	Cassava, Sugar cane, Plantains	0.3	0.0	Small impact
Gambia	27,260	0.4	0.3	Groundnuts, Millet, Rice Paddy	0.0	0.0	Small impact
Ghana	1,327,005	40.6	6.5	Cassava, Yams, Plantains	17.2	2.4	Biomass burned before cassava planting
Guinea	1,239,293	10.5	1.9	Rice Paddy, Cassava, Rice millet	1.4	0.8	Biomass burned before cassava planting
Kenya	106,020	23.1	14.8	Sugarcane, Maize, Potatoes	0.7	0.0	Use of synthetic fertilizers (Nitrogen)
Lesotho	7,462	0.3	#N/A	Potatoes, Maize, Vegetables	0.0	0.0	Small impact
Liberia	29,942	2.0	#N/A	Cassava, Rice Paddy, Sugar Cane	0.6	0.2	Small impact
Libya	5,770	2.2	#N/A	Potatoes, Watermelons, Tomatoes	0.0	0.0	Small impact
Madagascar	11,830	15.9	5.0	Rice Paddy, Sugar cane, Cassava	2.7	0.0	Small impact
Malawi	30,427	22.4	9.4	Cassava, Sweet potatoes, Sugar	5.0	0.0	Small impact
Mali	285,781	14.9	8.4	Rice paddy, Maize, Millet	0.0	0.0	Burning savanna
Mauritania	7,235	0.6	#N/A	Sugar cne, Rice paddy, Rice millet	0.0	0.0	Small impact
Morocco	27,721	29.6	16.2	Wheat, Sugar beet, Barley	0.0	0.0	Small impact
Mozambique	7,783	16.2	5.8	Cassava, Sugar cane, Maize	8.1	0.0	Small impact
Namibia	6,813	0.6	0.3	Roots & tubers, Maize, Millet	0.0	0.0	Small impact
Niger	23,282	12.0	6.0	Millet, Sorghum, Cow peas	0.2	0.0	Small impact
Nigeria	3,854,674	187.8	54.4	Cassava, Yams, Maize	57.6	7.9	Biomass burned before cassava planting
Rwanda	13,540	7.8	4.4	Bananas, Sweet Potatoes, Cassava	0.9	0.0	Small impact
Senegal	216,961	6.7	1.3	Grouundnuts, Rice Paddy, Sugar Cane	0.4	0.1	Biomass burned before cassava planting
Sierra Leone	231,641	6.6	3.6	Cassava, Rice Paddy, Vegetables	3.7	0.2	Biomass burned before cassava planting
Somalia	9,328	0.9	0.0	Sugar Canem Fruit, Sorghum	0.1	0.0	
South Africa	280,341	41.4	25.4	Sugarcane, Maize, Potatoes	0.0	0.0	Use of synthetic fertilizers (Nitrogen)
Swaziland	7,888	5.8	#N/A	Sugar Cane, Maize, Roots and tubers	0.0	0.0	Small impact
Tanzania	31,507	43.4	9.5	Maize, Cassava, Bananas	5.9	0.1	Small impact
Togo	194,596	4.0	2.4	Cassava, Maize, Yams	1.0	0.1	Biomass burned before cassava planting
Tunisia	9,174	9.0	6.5	Olives, Tomatoes, Wheat	0.0	0.0	
Uganda	1,275,924	21.1	#N/A	Plantains, Sugar Cane, Cassava	2.9	0.0	Biomass burned before cassava planting

It can be seen that the countries producing cassava usually encounter the highest impact. One reason is the volume of production; the other is the cultivation practice to plant cassava. Burning is often the option to prepare the land. It was discussed in Kintche et al. (2015) [14] for RD Congo: in more than 90% of the field across the country, biomass was burned before cassava planting. This culture is called "slash and burn" [15,16] in Sub-Sahara Africa. This consists of cutting and burning of plants in a forest or woodland to create a field. The impact of "slash and burn" was highlighted by the Satellite imagery from NASA, as shown in Figure 4.9.

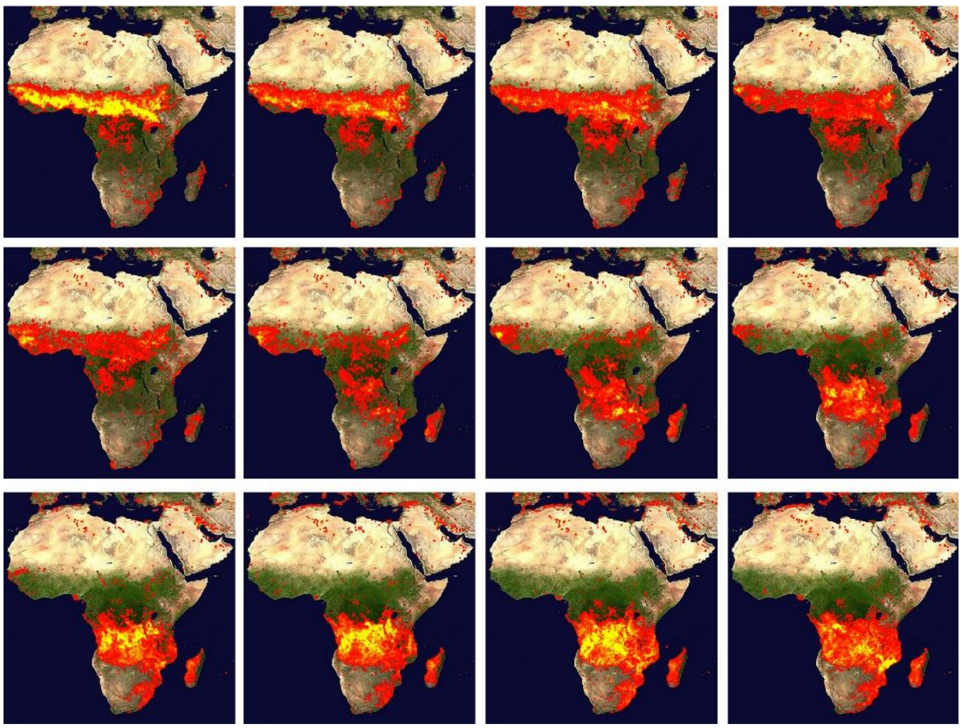


Figure 4. 11 Fire patterns across Africa from January to August

It can be confirmed from the previous figure that the countries showing the highest impact of agriculture are the countries also practicing this "slash and burn" culture. West Africa from January to April, RD Congo during the summer.

This highlights the need for life-cycle database containing the emissions of agricultural practices for each crop to provide advice to farmers. 7% of the world's population uses slash and burn agriculture, mainly in Africa. It is necessary to shift the practice to reduce air pollution and improve soil fertility.

Several policies can be taken to reduce the impact of agricultural Biomass burning [17]. Even though Agriculture sector employs 20% of the population in Sub-Sahara Africa, the average annual income is still low compared to non-farm workers (2.989$ vs. 4,991$) [18]. Fiscal incentives could be used to support farmers to change their environmental practices. Several countries are using the Common Agricultural Policy (CAP) to adopt environmental-friendly practices in the EU. For example, Ireland is spending 10% of its annual budget on promoting straw chopping following harvest in order to improve soil fertility [19]. EU standards have been adopted under the good agricultural and environmental condition (GAEC) to ban agricultural burning [20]. The Food and Agriculture Organization of the United Nations (FAO) has reported [21] that in recent years, some Sub-Saharan countries have even put disincentives by putting additional taxes (e.g., 26% in Nigeria) on the sector as shown in Figure 4.10. It then difficult for farmers to implement some changes.

Awareness campaigns can also play an essential role for both producers and consumers. For producers, Through the raise of awareness, the formation of farmers' community can be encouraged where farmer to farmer learning can facilitate new technologies/practices development (referred to as social capital). In Malawi, Mozambique & Zambia (Southern Africa), in the "Chinyanja Triangle" such operations have been already launched with positive results [22]. Our results show that hotel and restaurants have an important role in the burden from the agriculture sector for consumers. The awareness for the consumers of the tourism industry can be raised through eco-label. "La clef verte" (translated as the green key) [23] has been developed in Morocco (13 million visitors in 2019) based on the example of Denmark to raise awareness on eco-tourism.

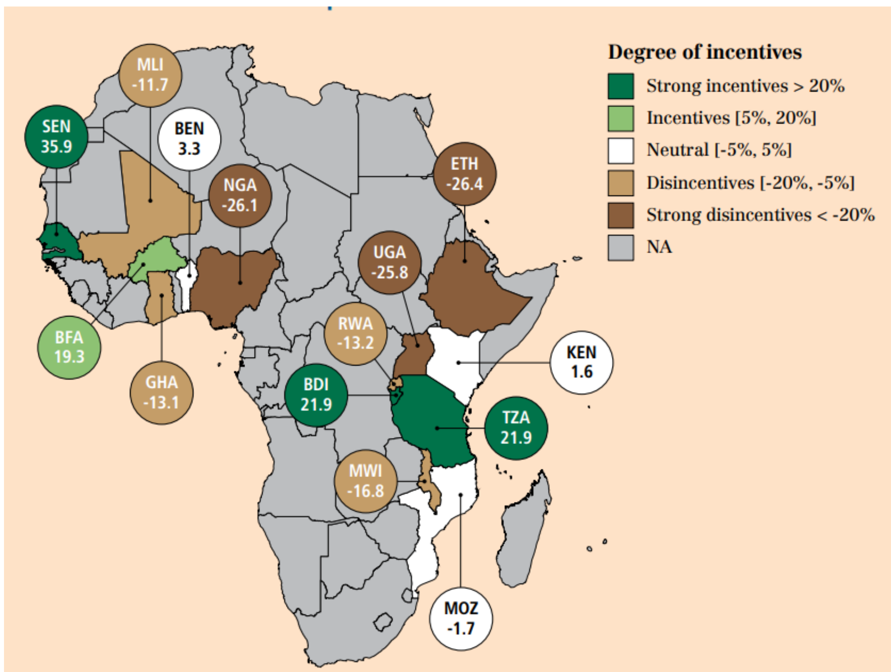


Figure 4. 12 Degree of incentive/ disincentives for the Agriculture sector

Finally, generally speaking, tax can be applied to limit wrong practices. Environmentally related tax revenue (ERTR) is an option to tackle the damages caused by air pollution [24]. Except in South Africa & Uganda, this type of tax still does not provide an important source of revenue as shown in Table 4.9.

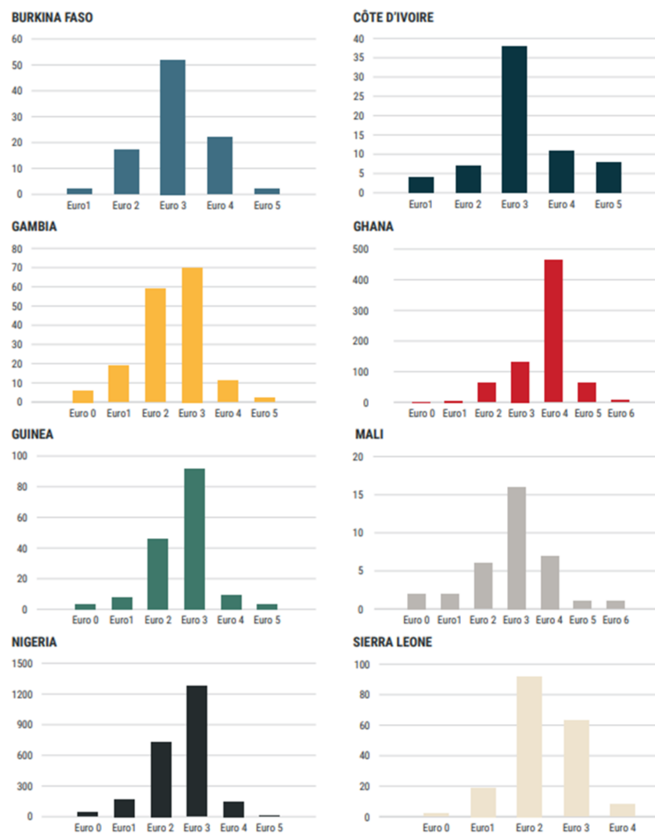
Table 4. 9 ERTR in Africa (2017)

Country	ERTR as % total GDP
Mauritania	17.064
South Africa	2.685
Kenya	2.243
Uganda	2.008
Ghana	1.846
Swaziland	1.779
Mali	1.408
Rwanda	1.296
Madagascar	1.101
Egypt	1.025
Senegal	0.996
Cameroon	0.786
Morocco	0.693
Cape Verde	0.396
Botswana	0.281
Cote D'Ivoire	0.154
Nigeria (2015)	0.019

4.3.2 Transport

Another burden is caused by the use of second-hand vehicles in Africa, this explains the burden of the transport sector. Recent statistics have been collected by the United Nations Environment Programme (UNEP) [25]. About 70% of these vehicles are imported from Europe. As shown in Figure 4.11. many of these vehicles are under the EURO4 standards (legislation adopted 15 years in European countries). Therefore, the emissions are higher than the current global emissions standards. The mileage of these vehicles is usually high, over 200,000km, with poor catalytic converters. As a result, the pollutant emissions are particularly high. Another issue is the diesel Sulphur level in the range of 50-5000ppm while it is below 15ppm in most countries in the world. This has an influence of sulfur dioxide emissions but also on diesel particulate filters. Two types of policies can be achieved to reduce the impact of second-hand vehicles: a limit on the age of imported cars, at the moment, only a few countries apply such a policy: Morocco (4-5 years), Algeria (3years), Chad (4-5 years), Mauritania (4-5 years), Cote d'Ivoire (4-5 years) & Gabon (4-5 years). Another possibility is to apply stricter vehicle standards, fifteen countries in West Africa (ECOWAS, Economic Commission of West African States) have jointly decided on new standards for clean fuels and vehicles. From 1 January 2021, all imported and newly registered vehicles will have to meet EURO4 standards in these countries.

The efforts could be also supported by G20 countries (especially the EU) to ban the exports of used cars that are not meeting the standards existing at exporting place, to developing countries.



Source: Used Vehicles Exported to Africa, Netherlands Human Environment and Transport Inspectorate, Ministry of Infrastructure and Water Management, Dutch Government, 2020

Figure 4. 13 Used cars imported from Netherlands in Weet Africa

4.3.3 Electricity

As stated previously, the generation of electricity in Africa is still small, with only 853 TWh generated for the whole continent in 2019 [26]. The top producer in 2017 [27] are: South Africa (250TWh), Egypt (188TWh), Algeria (76TWh), Libya (37TWh), Morocco (33TWh) & Nigeria (32TWh). The mix is: Coal (30%, with 86% produced in South Africa), Oil (8%), Natural Gas (39%), Nuclear (1%), Hydro (17%), Other Renewables (4%). The average carbon dioxide intensity is 556gCO_2/kWh.
That explains why in the production based-approach, electricity has an impact only in a few countries (mainly the ones cited above).

The International Energy Agency (IEA) in its last report, World Energy Outlook 2020 [26], schedules that the total production for the continent will be between 1700 and 2000 TWh by 2040 (about 4-5% of the global production vs. 3% currently). Therefore, African countries will have the choice to promote fossil fuels or renewables in the future, this could have an important impact on carbon dioxide emissions (0.25gCO_2/kWh or 0.08kgCO_2/kWh) but also on air pollution. Most of the African countries have already settled target for renewable energy [28]. It is necessary for African countries to adopt as soon as possible emissions standards following the example of South Africa's National Environmental Management Air Quality Act of 2004 [29]. These standards could either target the daily average concentration of air pollutants (PM2.5 concentration) or target the emission from power plants directly (g/kWh). Another option is to support households with incentives to switch to more efficient electronic appliances (air conditioner, TV). This option would also help to cut the electricity bill down.

The COVID-19 has also severely impacted electricity access for several African countries. While the population without electricity access was decreasing in recent years, more than 10 million people are predicted to lose access to electricity in 2020.

4.3.4 How can G20 countries reduce their environmental burden in Africa?

For this discussion we decided to consider all the G20 countries with an environmental burden superior than 100,000 DALYs in Africa: China (267,614 DALYs), France (286,100 DALYs), Germany (371,811 DALYs), India (168,565 DALYs), Italy (290,704 DALYs), Japan (162,605 DALYs), Korea (147,995 DALYs), the UK (199,544 DALYs) and the USA (559,216 DALYs). EORA results are combined with products exports information from OEC [10] and WITS [11] to establish some hypothesis.

4.3.4.1 China

The impact of Chinese sectors in Africa is shown in Figure 4.12. Overall "Construction" has the highest burden (111,503 DALYs) with especially a burden on Agriculture sector in Cameroon (25,908 DALYs) and Nigeria (21,014 DALYs). The highest impacts from China (total all sectors) occur in Cameroon (50,564 DALYs), Nigeria (49,958 DALYs) & South Africa (27,353 DALYs).

Therefore, about half of the total burden from China on Agriculture sector in Cameroon and Nigeria is due to Chinese construction sector. For South Africa, about half of the total burden from China (total all sectors) is on Electricity (8,517 DALYs) & Other mining (4,986 DALYs).

The top 10 exports related to agriculture in terms of weight from Cameroon to China are:

Item name	Netweight (kton)	Trade Value (Million USD)
Wood; in the rough, whether or not stripped of bark or sapwood, or roughly squared, untreated, n.e.s. in heading no. 4403	325.9	126.1
Wood, tropical; (as specified in subheading note 1, chapter 44, customs tariff), n.e.s. in item no. 4403.41, in the rough, whether or not stripped of bark or sapwood, or roughly squared, untreated	171.8	58.4
Wood, tropical; sapelli, sawn or chipped lengthwise, sliced or peeled, whether or not planed, sanded or end-jointed, thicker than 6mm	46.2	32.8
Cotton; not carded or combed	45.4	71.3
Wood; sawn or chipped lengthwise, sliced or peeled, whether or not planed, sanded or finger-jointed, thicker than 6mm, n.e.s. in heading no. 4407	44.3	32.5

Wood, tropical; (as specified in subheading note 1, chapter 44, customs tariff), n.e.s. in item no. 4407.2, sawn or chipped lengthwise, sliced or peeled, whether or not planed, sanded or finger-jointed, thicker than 6mm	19.5	19.0
Wood, tropical; (as in subheading note 1, chapter 44, customs tariff), n.e.s. in item no. 4408.31, sheets for veneer or plywood, other wood sawn length wise, sliced or peeled, whether or not planed, sanded or finger-jointed, not thicker than 6mm	2.7	2.9
Cocoa beans; whole or broken, raw or roasted	1.8	5.5
Vegetable products; n.e.s. in chapter 14	1.2	0.9
Rubber; natural rubber latex, whether or not pre-vulcanised, in primary forms or in plates, sheets or strip	1.0	1.4

The top 6 exports related to agriculture in terms of weight from Nigeria to China are:

Item name	Netweight (kton)	Trade Value (Million USD)
Wood; in the rough, whether or not stripped of bark or sapwood, or roughly squared, untreated, n.e.s. in heading no. 4403	749.6	348.9
Oil seeds; sesamum seeds, whether or not broken	5.1	6.3
Wood; sawn or chipped lengthwise, sliced or peeled, whether or not planed, sanded or finger-jointed, thicker than 6mm, n.e.s. in heading no. 4407	2.2	1.2
Vegetable products; n.e.s. in chapter 14	1.3	0.7
Rubber; technically specified natural rubber (TSNR), in primary forms or in plates, sheets or strip (excluding latex and smoked sheets)	1.3	1.9
Cocoa beans; whole or broken, raw or roasted	1.0	3.2

The top 10 exports related in terms of weight from South Africa to China are:

Item name	Netweight (kton)	Trade Value (Million USD)
Iron ores and concentrates; non-agglomerated	44924.2	3017.5
Chromium ores and concentrates	7573.4	1203.7
Manganese ores and concentrates, including manganiferous iron ores and concentrates with a manganese content of 20% or more, calculated on the dry weight	6425.5	732.0
Ferro-alloys; ferro-chromium, containing by weight more than 4% of carbon	1966.4	1667.7
Iron ores and concentrates; agglomerated (excluding roasted iron pyrites)	429.1	31.2

Wood pulp; chemical wood pulp, dissolving grades	358.7	297.2
Oils; petroleum oils and oils obtained from bituminous minerals, crude	269.8	116.9
Zirconium ores and concentrates	232.0	214.4
Granite; crude or roughly trimmed	87.8	15.4
Wood; in chips or particles, non-coniferous	87.8	16.6

Gathering all the previous information, impacts in Cameroon and Nigeria are probably due to the wood sector. For South Africa, this due to the mining production (consumed in "Construction" & "Wearing apparel" for example) exported to China especially Iron, Chromium or Manganese ores and ferro-alloys.

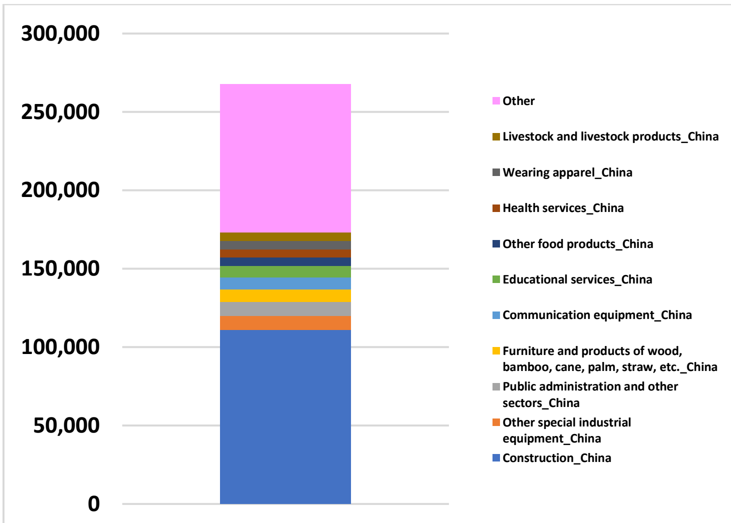


Figure 4. 14 Consumption-based impacts in Africa of Chinese sectors of activity (DALYs)

4.3.4.2 France

The impact of French sectors in Africa is shown in Figure 4.13. Overall "Food products and beverages" has the highest burden (71,486 DALYs) followed by "Construction work" (28,513 DALYs) & "Hotel and restaurant services" (19,337 DALYs). The highest impacts from France (total all sectors) occur in Chad (41,486 DALYs), Ghana (31,569 DALYs) & Cameroon (27,489 DALYs) with especially a burden on Agriculture sector in Chad (41,070 DALYs), Ghana (30,232 DALYs) and Cameroon (24,077 DALYs).

The impact due to French "Food products and beverages" occur mainly in the Agriculture sector of Ghana (10,679 DALYs), Guinea (9,599 DALYs) and Cameroon (8,712 DALYs).

The two main exports related to agriculture in terms of weight from Chad to France are Gum Arabic (6.7 kton, 12.8 Milllion USD) and Cotton (0.2 kton, 0.34 Million USD).

The top 10 exports related to agriculture in terms of weight from Ghana to France are:

Item name	Netweight (kton)	Trade Value (Million USD)
Cocoa beans; whole or broken, raw or roasted	45.0	155.2
Fruit, edible; bananas, other than plantains, fresh or dried	14.9	10.8
Fish preparations; tunas, skipjack and Atlantic bonito (sarda spp.), prepared or preserved, whole or in pieces (but not minced)	11.8	77.1
Fruit, edible; pineapples, fresh or dried	8.1	8.7
Wood, tropical; (as specified in subheading note 1, chapter 44, customs tariff), n.e.s. in item no. 4407.2, sawn or chipped lengthwise, sliced or peeled, whether or not planed, sanded or finger-jointed, thicker than 6mm	2.0	1.6
Rubber; technically specified natural rubber (TSNR), in primary forms or in plates, sheets or strip (excluding latex and smoked sheets)	1.4	2.0
Vegetable roots and tubers; yams (Dioscorea spp.) with high starch or inulin content, fresh, chilled, frozen or dried, whether or not sliced or in the form of pellets	1.2	1.4
Cocoa; paste, not defatted	1.1	4.4
Vegetable roots and tubers; arrowroot, salep, Jerusalem artichokes and similar roots and tubers, high starch or inulin content, whether or not sliced or in the form of pellets, fresh or dried; sago pith	0.7	0.7
Rubber; natural (excluding latex, technically specified natural rubber and smoked sheets), in primary forms or in plates, sheets or strip	0.7	1.0

The top 10 exports related to agriculture in terms of weight from Cameroon to France are:

Item name	Netweight (kton)	Trade Value (Million USD)
Fruit, edible; bananas, other than plantains, fresh or dried	154.9	108.5
Wood, tropical; (as specified in subheading note 1, chapter 44, customs tariff), n.e.s. in item no. 4407.2, sawn or chipped lengthwise, sliced or peeled, whether or not planed, sanded or finger-jointed, thicker than 6mm	20.2	18.3
Cocoa; butter, fat and oil	9.2	33.7
Coffee; not roasted or decaffeinated	7.1	14.0
Wood, tropical; sapelli, sawn or chipped lengthwise, sliced or peeled, whether or not planed, sanded or end-jointed, thicker than 6mm	5.5	4.8
Wood; sawn or chipped lengthwise, sliced or peeled, whether or not planed, sanded or finger-jointed, thicker than 6mm, n.e.s. in heading no. 4407	5.0	3.7
Rubber; technically specified natural rubber (TSNR), in primary forms or in plates, sheets or strip (excluding latex and smoked sheets)	4.3	6.6
Cocoa beans; whole or broken, raw or roasted	4.1	13.1
Wood, tropical; (as specified in subheading note 1, chapter 44, customs tariff), n.e.s. in item no. 4403.41, in the rough, whether or not stripped of bark or sapwood, or roughly squared, untreated	3.9	2.0
Cocoa; paste, not defatted	3.8	13.0

Gathering all the previous information, impact in Chad is probably due to natural gums (acacia gums). For Ghana, mainly due to cocoa beans. For Cameroon, fruits wood and cocoa related products (butter, paste, beans).

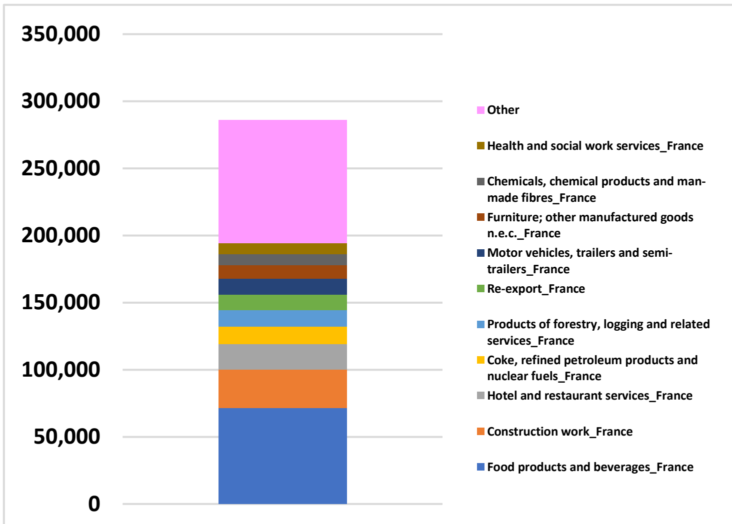


Figure 4. 15 Consumption-based impacts in Africa of French sectors of activity **(DALYs)**

4.3.4.3 Germany

The impact of German sectors in Africa is shown in Figure 4.14. Overall "Food products" (127,956 DALYs) & "Accommodation and restaurants" (47,091 DALYs) have the highest burden. The highest impacts from Germany (total all sectors) occur in Ghana (82,945 DALYs), Nigeria (78,937 DALYs) & Chad (62,001 DALYs) with especially a burden on Agriculture sector in Ghana (80,173 DALYs), Nigeria (74,334 DALYs) and Cameroon (61,051 DALYs).

The impact due to German "Food products" occur mainly in the Agriculture sector of Nigeria (37,124 DALYs), Ghana (35,411 DALYs) and Chad (26,539 DALYs). The impact due to German "Accommodation and restaurants" occur mainly in the Agriculture sector of Ghana (6,462 DALYs), Nigeria (5,506 DALYs) and Chad (3,877 DALYs). Therefore, nearly half of the impacts in the Agriculture sector of Nigeria and Ghana are due to these two previous German sectors.

The top 10 exports related to agriculture in terms of weight from Ghana to Germany are:

Item name	Netweight (kton)	Trade Value (Million USD)
Cocoa beans; whole or broken, raw or roasted	28.5	89.0
Cocoa; paste, not defatted	10.0	37.3
Wood, tropical; (as specified in subheading note 1, chapter 44, customs tariff), n.e.s. in item no. 4407.2, sawn or chipped lengthwise, sliced or peeled, whether or not planed, sanded or finger-jointed, thicker than 6mm	7.0	7.8
Fruit, edible; pineapples, fresh or dried	3.9	4.8

Rubber; technically specified natural rubber (TSNR), in primary forms or in plates, sheets or strip (excluding latex and smoked sheets)	1.0	1.5
Cocoa; powder, not containing added sugar or other sweetening matter	0.9	1.9
Fruit, edible; papaws (papayas), fresh	0.9	1.1
Fish preparations; tunas, skipjack and Atlantic bonito (sarda spp.), prepared or preserved, whole or in pieces (but not minced)	0.5	2.6
Vegetable fats and oils and their fractions; fixed, n.e.s. in heading no. 1515, whether or not refined, but not chemically modified	0.5	1.5
Wood, tropical; (as in subheading note 1, chapter 44, customs tariff), n.e.s. in item no. 4408.31, sheets for veneer or plywood, other wood sawn length wise, sliced or peeled, whether or not planed, sanded or finger-jointed, not thicker than 6mm	0.5	1.2

The top 10 exports related to agriculture in terms of weight from Nigeria to Germany are:

:

Item name	Netweight (kton)	Trade Value (Million USD)
Wood; charcoal of wood other than bamboo (including shell or nut charcoal), whether or not agglomerated	31.8	8.7
Cocoa beans; whole or broken, raw or roasted	24.5	75.3
Oil seeds; sesamum seeds, whether or not broken	8.5	16.3
Rubber; technically specified natural rubber (TSNR), in primary forms or in plates, sheets or strip (excluding latex and smoked sheets)	7.7	11.7
Vegetable products (including unroasted chicory roots, chicorium intybus sativum variety); n.e.s. in chapter 12, fresh or dried, ground or unground, primarily for human consumption	6.7	9.2
Cocoa; butter, fat and oil	4.8	32.5
Cocoa; paste, wholly or partly defatted	1.4	2.2
Animal products; tortoise-shell, whalebone and whalebone hair, horns, antlers, hooves, nails, claws and beaks, unworked or simply prepared but not cut to shape, waste and powder of these products	1.0	0.5
Spices; ginger, crushed or ground	1.0	3.1
Spices; ginger, neither crushed nor ground	0.6	1.4
Gum Arabic	0.4	1.1

The two main exports related to agriculture in terms of weight from Chad to Germany are Gum Arabic (1.0 kton, 2 Million USD) and Cotton (0.9 kton, 1.3Million USD).

For Ghana &Nigeria, this is due probably to Cocoa related products. For Chad, natural gums.

Gathering all the previous information, impacts in Ghana and Nigeria are probably due to Cocoa related products. For Chad, Arabic gum.

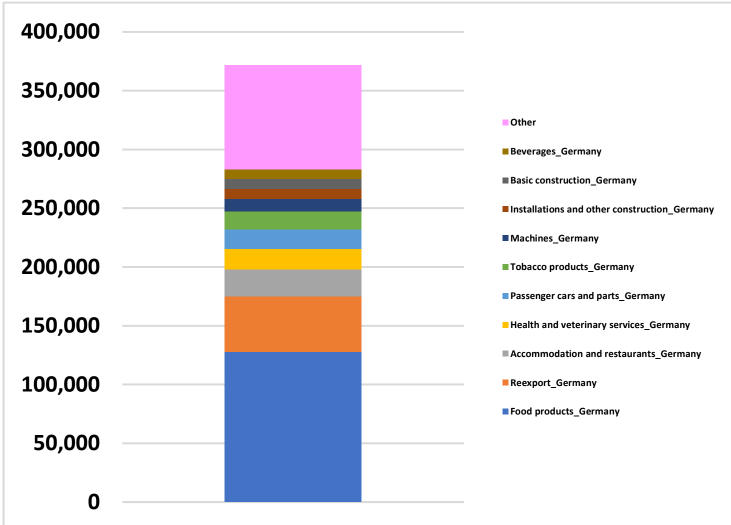


Figure 4. 16 Consumption-based impacts in Africa of German sectors of activity

4.3.4.4 India

The impact of Indian sectors in Africa is shown in Figure 4.15. Overall Construction has the highest burden (41,327 DALYs). The highest impacts from India (total all sectors) occur in Nigeria (72,208) & Ghana (24,573) with especially a burden on Agriculture sector in Nigeria (72,101 DALYs) and Ghana (23,899 DALYs).

The impact due to Indian "Construction" occur mainly in the Agriculture sector of Nigeria (17,598 DALYs). The impact from India on Agriculture sector in Ghana is mainly related to Indian Food sectors ("Miscellaneous food products", "Milk and milk products", "Hotels and restaurants").

The top 10 exports related to agriculture in terms of weight from Nigeria to India are:

Item name	Netweight (kton)	Trade Value (Million USD)
Nuts, edible; cashew nuts, in shell, fresh or dried	46.2	53.9
Wood, tropical; (as specified in subheading note 1, chapter 44, customs tariff), n.e.s. in item no. 4403.41, in the rough, whether or not stripped of bark or sapwood, or roughly squared, untreated	5.9	4.2
Gum Arabic	4.7	3.0
Spices; ginger, neither crushed nor ground	4.1	8.8
Oil seeds and oleaginous fruits; n.e.s. in heading no. 1207, whether or not broken	3.3	1.5
Oil seeds; sesamum seeds, whether or not broken	2.3	3.0
Cotton; not carded or combed	2.2	2.7
Cocoa beans; whole or broken, raw or roasted	1.0	3.5
Tanned or crust skins of sheep and lambs, without wool on, whether or not split, but not further prepared, in the wet state (including wet blue)	0.5	3.7

Spices; turmeric (curcuma)	0.5	0.8

The top 8 exports related to agriculture in terms of weight from Ghana to India are:

Item name	Netweight (kton)	Trade Value (Million USD)
Wood, tropical; (as specified in subheading note 1, chapter 44, customs tariff), n.e.s. in item no. 4403.41, in the rough, whether or not stripped of bark or sapwood, or roughly squared, untreated	76.2	54.3
Nuts, edible; cashew nuts, in shell, fresh or dried	69.4	88.6
Oil seeds and oleaginous fruits; n.e.s. in heading no. 1207, whether or not broken	25.1	14.5
Cocoa; paste, not defatted	2.2	9.2
Vegetable fats and oils and their fractions; fixed, n.e.s. in heading no. 1515, whether or not refined, but not chemically modified	1.9	2.1
Plants and parts (including seeds and fruits) n.e.s. in heading no. 1211, used primarily in perfumery, pharmacy or for insecticidal, fungicidal purposes; fresh or dried, whether or not cut, crushed or powdered	0.1	0.4
Wood; n.e.s. in heading no. 4408, sheets for veneer or plywood, other wood sawn lengthwise, sliced or peeled, whether or not planed, sanded or finger-jointed, not thicker than 6mm	0.1	0.2

Gathering all the previous information, impacts in Ghana and Nigeria are probably due to nuts and wood products.

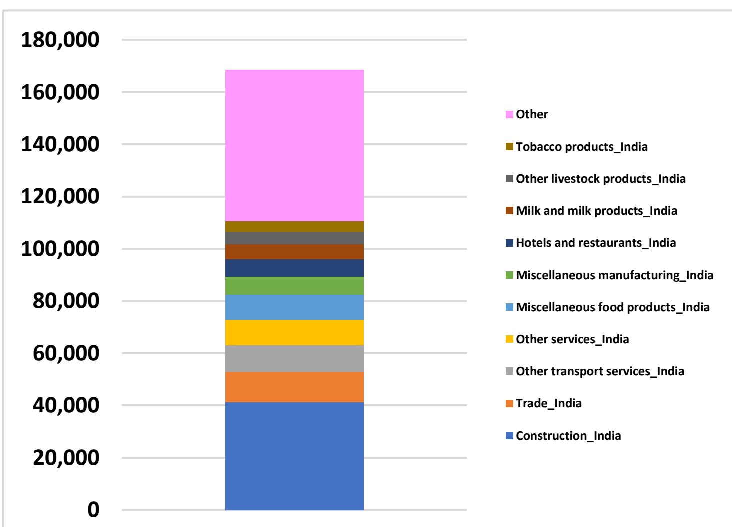


Figure 4. 17 Consumption-based impacts in Africa of Indian sectors of activity (DALYs)

4.3.4.5 Italy

The impact of Italian sectors in Africa is shown in Figure 4.16. Overall "Food products and beverages" (53,415 DALYs) has the highest burden. The highest impacts from Italy (total all sectors) occur in Cameroon (47,027) and Ghana (43,114) with especially an impact on Agriculture sector in Ghana (41,065 DALYs) & Cameroon (35,936 DALYs)

The impact of Italy on Agriculture sector in Ghana is mainly due to Italian "Food products and beverages" (11,621 DALYs) and "Hotel and restaurant services" (4,316 DALYs) sectors. The impact of Italy on Agriculture sector in Cameroon is mainly due to Italian "Furniture; other manufactured goods n.e.c." (8,198 DALYs), "Food products and beverages" (4,237 DALYs) &"Construction work" (3,444 DALYs) sectors.

The top 10 exports related to agriculture in terms of weight from Ghana to Italy are:

Item name	Netweight (kton)	Trade Value (Million USD)
Cocoa beans; whole or broken, raw or roasted	18.8	60.0
Vegetable products; n.e.s. in chapter 14	13.2	1.4
Wood; n.e.s. in heading no. 4408, sheets for veneer or plywood, other wood sawn lengthwise, sliced or peeled, whether or not planed, sanded or finger-jointed, not thicker than 6mm	2.0	4.5
Fish; yellowfin tunas (thunnus albacares), frozen (excluding fillets, livers, roes and other fish meat of heading no. 0304)	1.7	3.3
Fish preparations; tunas, skipjack and Atlantic bonito (sarda spp.), prepared or preserved, whole or in pieces (but not minced)	1.6	11.5
Rubber; technically specified natural rubber (TSNR), in primary forms or in plates, sheets or strip (excluding latex and smoked sheets)	1.3	1.9
Wood, tropical; (as specified in subheading note 1, chapter 44, customs tariff), n.e.s. in item no. 4407.2, sawn or chipped lengthwise, sliced or peeled, whether or not planed, sanded or finger-jointed, thicker than 6mm	0.9	1.1
Wood, tropical; (as in subheading note 1, chapter 44, customs tariff), n.e.s. in item no. 4408.31, sheets for veneer or plywood, other wood sawn length wise, sliced or peeled, whether or not planed, sanded or finger-jointed, not thicker than 6mm	0.7	1.7
Wood; sawn or chipped lengthwise, sliced or peeled, whether or not planed, sanded or finger-jointed, thicker than 6mm, n.e.s. in heading no. 4407	0.5	0.5
Wood; for fuel, sawdust and wood waste and scrap, whether or not agglomerated in logs, briquettes, pellets or similar forms; wood pellets	0.5	0.1

The top 10 exports related to agriculture in terms of weight from Cameroon to Italy are:

Item name	Netweight (kton)	Trade Value (Million USD)
Wood; sawn or chipped lengthwise, sliced or peeled, whether or not planed, sanded or finger-jointed, thicker than 6mm, n.e.s. in heading no. 4407	18.6	18.8
Wood, tropical; (as specified in subheading note 1, chapter 44, customs tariff), n.e.s. in item no. 4407.2, sawn or chipped lengthwise, sliced or peeled, whether or not planed, sanded or finger-jointed, thicker than 6mm	14.9	15.0

Wood, tropical; (as in subheading note 1, chapter 44, customs tariff), n.e.s. in item no. 4408.31, sheets for veneer or plywood, other wood sawn length wise, sliced or peeled, whether or not planed, sanded or finger-jointed, not thicker than 6mm	11.8	18.9
Fruit, edible; bananas, other than plantains, fresh or dried	10.2	6.7
Wood, tropical; (as specified in subheading note 1, chapter 44, customs tariff), n.e.s. in item no. 4403.41, in the rough, whether or not stripped of bark or sapwood, or roughly squared, untreated	8.8	3.6
Coffee; not roasted or decaffeinated	4.2	8.8
Rubber; technically specified natural rubber (TSNR), in primary forms or in plates, sheets or strip (excluding latex and smoked sheets)	3.8	5.9
Wood, tropical; iroko, sawn or chipped lengthwise, sliced or peeled, whether or not planed, sanded or end-jointed, thicker than 6mm	3.0	2.4
Wood, tropical; sapelli, sawn or chipped lengthwise, sliced or peeled, whether or not planed, sanded or end-jointed, thicker than 6mm	2.7	2.6
Rubber; natural (excluding latex), in smoked sheets	1.1	1.8

For Cameroon, this is probably due to wood & coffee beans. For Ghana, cocoa related products. For Egypt, crude oil.

Gathering all the previous information, impacts in Cameroon are probably mainly due to wood products and partly coffee. For Ghana, cocoa related products

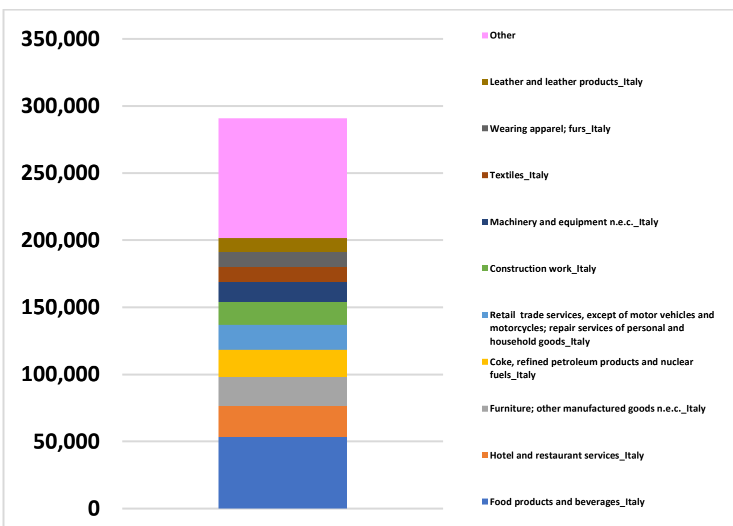


Figure 4. 18 Consumption-based impacts in Africa of Italian sectors of activity

4.3.4.6 Japan

The impact of Japanese sectors in Africa is shown in Figure 4.17. Overall Japanese sectors related to food products have the highest impacts: "General eating and drinking place" (14,344 DALYs), Slaughtering and meat processing (7,136 DALYs), Dishes, sushi and lunch boxes (6,099 DALYs) & Eating and drinking places for pleasures (3,310). The highest impacts from Japan (total all sectors) occur in Nigeria (37,766), Ghana (19,794) & Uganda (14,647 DALYs) with especially an impact on Agriculture sector in Nigeria (33,547 DALYs), Ghana (18,870 DALYs) and Uganda (14,198 DALYs). Therefore, the agriculture sector impacts represent more than 90% of the impacts in each of the three previous countries.

The top 4 exports related to agriculture in terms of weight from Nigeria to Japan are:

Item name	Netweight (kton)	Trade Value (Million USD)
Oil seeds; sesamum seeds, whether or not broken	55.8	97.1
Spices; ginger, crushed or ground	0.0	0.1
Wood, tropical; (as specified in subheading note 1, chapter 44, customs tariff), n.e.s. in item no. 4403.41, in the rough, whether or not stripped of bark or sapwood, or roughly squared, untreated	0.0	0.0
Crustaceans; frozen, shrimps and prawns, excluding cold-water varieties, in shell or not, smoked, cooked or not before or during smoking; in shell, cooked by steaming or by boiling in water	0.0	0.2

The top 5 exports related to agriculture in terms of weight from Ghana to Japan are:

Item name	Netweight (kton)	Trade Value (Million USD)
Cocoa beans; whole or broken, raw or roasted	28.4	94.1
Cocoa; paste, not defatted	4.3	18.5
Cocoa; powder, not containing added sugar or other sweetening matter	0.7	1.5
Fish fillets; frozen, tunas (of the genus Thunnus), skipjack or stripe-bellied bonito (Euthynnus (Katsuwonus) pelamis)	0.5	2.9
Wood, tropical; (as specified in subheading note 1, chapter 44, customs tariff), n.e.s. in item no. 4407.2, sawn or chipped lengthwise, sliced or peeled, whether or not planed, sanded or finger-jointed, thicker than 6mm	0.1	0.2

The top 5 exports related to agriculture in terms of weight from Uganda to Japan are:

Item name	Netweight (kton)	Trade Value (Million USD)
Coffee; not roasted or decaffeinated	2.7	6.5
Oil seeds; sesamum seeds, whether or not broken	2.2	3.4
Fish fillets; frozen, Nile Perch (Lates niloticus)	0.3	1.8
Vermiculite, perlite and chlorites; unexpanded	0.2	0.1
Dairy produce; milk and cream, concentrated or containing added sugar or other sweetening matter, in powder, granules or	0.1	0.4

other solid forms, of a fat content not exceeding 1.5% (by weight)		

Gathering all the previous information, impacts in Nigeria are probably mainly due to oil seeds (sesamum), impact in Ghana due to Cocoa related products and impact in Uganda due to coffee and oil seeds.

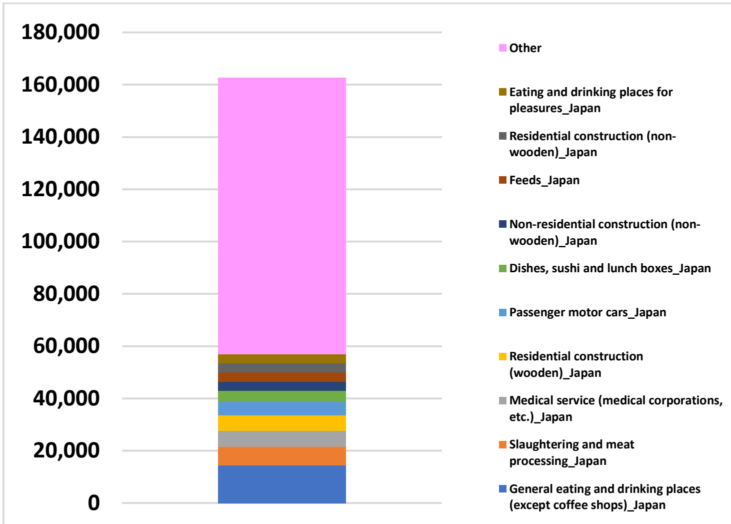


Figure 4. 19 Consumption-based impacts in Africa of Japanese sectors of activity

4.3.4.7 Korea

The impact of Korean sectors in Africa is shown in Figure 4.18 Overall sectors related to food products such as "Prepared livestock feeds", "Meat and dairy products", "Eating and drinking places, hotels and other lodging places", "Canned or cured fruits and vegetables and misc. food preparations" & "Bakery and confectionery products, noodles" have the highest burden (together 46,443 DALYs). The highest impacts from Korea (total all sectors) occur in Ghana (77,822 DALYs), Congo (13,028 DALYs) & Uganda (10,426 DALYs) with especially an impact on Agriculture sector in Ghana (77,129 DALYs) and Guinea (8,385 DALYs).

The top 6 exports related to agriculture in terms of weight from Ghana to Korea are:

Item name	Netweight (kton)	Trade Value (Million USD)
Cocoa beans; whole or broken, raw or roasted	4.2	14.0
Cocoa; shells, husks, skins and other cocoa waste	3.2	0.4
Cocoa; paste, not defatted	0.6	2.6
Dog or cat food; (not put up for retail sale), used in animal feeding	0.2	0.2
Wood; sawn or chipped lengthwise, sliced or peeled, whether or not planed, sanded or finger-jointed, thicker than 6mm, n.e.s. in heading no. 4407	0.1	0.2

Vegetable fats and oils and their fractions; fixed, n.e.s. in heading no. 1515, whether or not refined, but not chemically modified	0.1	0.2

Gathering all the previous information, impacts in Ghana are probably mainly due to cocoa related products.

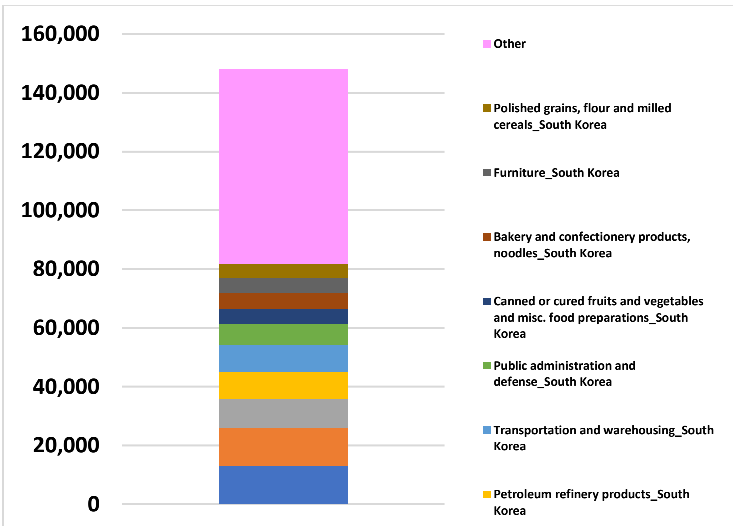


Figure 4. 20 Consumption-based impacts in Africa of Korean sectors of activity

4.3.4.8 UK

The impact of British sectors in Africa is shown in Figure 4.19. Overall, "Operation of dairies and cheese making", "Bars" & Restaurants" have the highest impacts (together 21,746 DALYs). The highest impacts from the UK (total all sectors) occur in Nigeria (70,566 DALYs) and Ghana (40,612 DALYs) with especially an impact on agriculture sector in Nigeria (68,384 DALYs) and Ghana (39,097 DALYs).

The top 10 exports related to agriculture in terms of weight from Nigeria to the UK are:

Item name	Netweight (kton)	Trade Value (Million USD)
Wood; charcoal of wood other than bamboo (including shell or nut charcoal), whether or not agglomerated	5.2	1.9
Beer; made from malt	2.1	3.5
Cocoa; butter, fat and oil	1.3	7.2
Waters; including mineral and aerated, containing added sugar or other sweetening matter or flavoured	1.0	1.2
Flour, meal and powder; of the products of chapter 8	0.9	0.1
Sauces and preparations therefor; mixed condiments and mixed seasonings	0.8	0.8

Rubber; technically specified natural rubber (TSNR), in primary forms or in plates, sheets or strip (excluding latex and smoked sheets)	0.7	1.1
Rubber; natural rubber latex, whether or not pre-vulcanised, in primary forms or in plates, sheets or strip	0.7	1.0
Wood; charcoal of bamboo (including shell or nut charcoal), whether or not agglomerated	0.5	0.2
Vegetable roots and tubers; arrowroot, salep, Jerusalem artichokes and similar roots and tubers, high starch or inulin content, whether or not sliced or in the form of pellets, fresh or dried; sago pith	0.4	0.1

The top 10 exports related to agriculture in terms of weight from Ghana to the UK are:

Item name	Netweight (kton)	Trade Value (Million USD)
Fruit, edible; bananas, other than plantains, fresh or dried	28.5	23.0
Fish preparations; tunas, skipjack and Atlantic bonito (sarda spp.), prepared or preserved, whole or in pieces (but not minced)	18.5	88.9
Cocoa beans; whole or broken, raw or roasted	18.0	44.1
Vegetable roots and tubers; yams (Dioscorea spp.) with high starch or inulin content, fresh, chilled, frozen or dried, whether or not sliced or in the form of pellets	9.7	9.2
Cocoa; butter, fat and oil	5.1	26.1
Fruit, edible; pineapples, fresh or dried	2.9	7.8
Rubber; natural rubber latex, whether or not pre-vulcanised, in primary forms or in plates, sheets or strip	2.6	3.7
Cocoa; paste, not defatted	2.0	8.7
Fruit, edible; guavas, mangoes and mangosteens, fresh or dried	1.9	16.0
Vegetable roots and tubers; arrowroot, salep, Jerusalem artichokes and similar roots and tubers, high starch or inulin content, whether or not sliced or in the form of pellets, fresh or dried; sago pith	1.2	1.3

Gathering all the previous information, impacts in Nigeria and Ghana are probably due to cocoa related products.

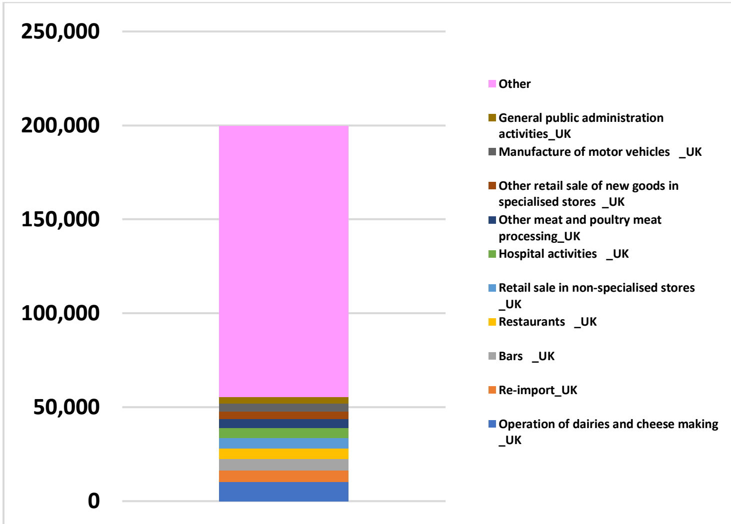


Figure 4. 21 Consumption-based impacts in Africa of British sectors of activity

4.3.4.9 USA

The impact of British sectors in Africa is shown in Figure 4.20. Overall Petroleum refineries (32,038 DALYs), Tire manufacturing (31,977 DALYs), & General state and local government services (31,712 DALYs). The highest impacts from the USA (total all sectors) occur in Chad (131,853 DALYs), Nigeria (99,031 DALYs) & Ghana (64,214 DALYs) with especially impacts on agriculture sector in Chad (130,473 DALYs), Ghana (59,384 DALYs) and Nigeria (38,567 DALYs).

The main export from Chad to the USA is Arabic gum (5,7 kton, 11.1 million USD).

The top 8 exports related to agriculture in terms of weight from Ghana to the USA are:

Item name	Netweight (kton)	Trade Value (Million USD)
Cocoa beans; whole or broken, raw or roasted	63.1	204.8
Wood, tropical; (as specified in subheading note 1, chapter 44, customs tariff), n.e.s. in item no. 4407.2, sawn or chipped lengthwise, sliced or peeled, whether or not planed, sanded or finger-jointed, thicker than 6mm	9.0	12.4
Vegetable roots and tubers; yams (Dioscorea spp.) with high starch or inulin content, fresh, chilled, frozen or dried, whether or not sliced or in the form of pellets	7.0	12.2
Cocoa; powder, not containing added sugar or other sweetening matter	5.8	13.0
Wood, tropical; (as in subheading note 1, chapter 44, customs tariff), n.e.s. in item no. 4408.31, sheets for veneer or plywood, other wood sawn length wise, sliced or peeled, whether or not planed, sanded or finger-jointed, not thicker than 6mm	1.3	3.5
Wood; n.e.s. in heading no. 4408, sheets for veneer or plywood, other wood sawn lengthwise, sliced or peeled, whether or not planed, sanded or finger-jointed, not thicker than 6mm	1.3	4.5
Cocoa; paste, not defatted	0.9	3.6

Nuts, edible; cashew nuts, shelled, fresh or dried	0.7	4.8

The top 10 exports related to agriculture in terms of weight from Nigeria to the USA are:

Item name	Netweight (kton)	Trade Value (Million USD)
Dog or cat food; (not put up for retail sale), used in animal feeding	39.5	6.4
Cocoa beans; whole or broken, raw or roasted	2.0	6.3
Spices; ginger, neither crushed nor ground	1.5	4.1
Plants and parts (including seeds and fruits) n.e.s. in heading no. 1211, used primarily in perfumery, pharmacy or for insecticidal, fungicidal purposes; fresh or dried, whether or not cut, crushed or powdered	1.2	3.6
Oil seeds; sesamum seeds, whether or not broken	1.1	2.0
Cocoa; butter, fat and oil	0.6	3.8

Gathering all the previous information, impact in Chad is probably due to Arabic gum. In Ghana & Nigeria, due to Cocoa related products.

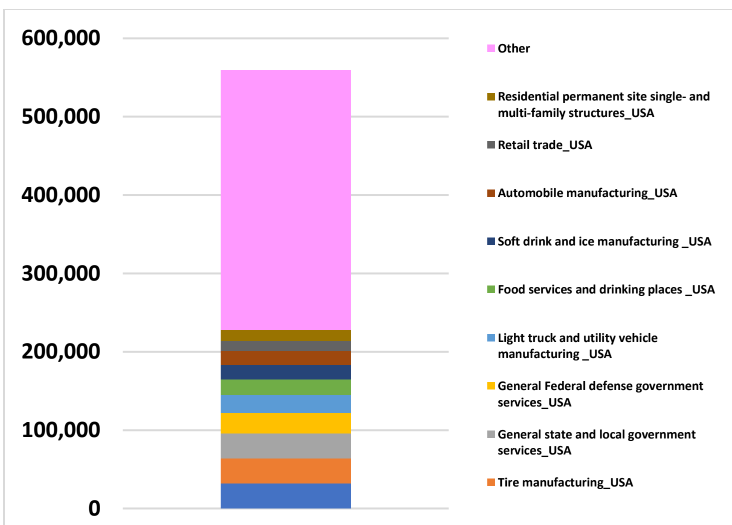


Figure 4. 22 Consumption-based impacts in Africa of American sectors of activity

4.4 Comment: the impact of African countries on G20 countries

As the impacts of G20 countries on African countries was measures. As a comment it was decided to estimate the impact of African countries on the 9 countries studied in the previous section. The results are shown in Figure 4.21:

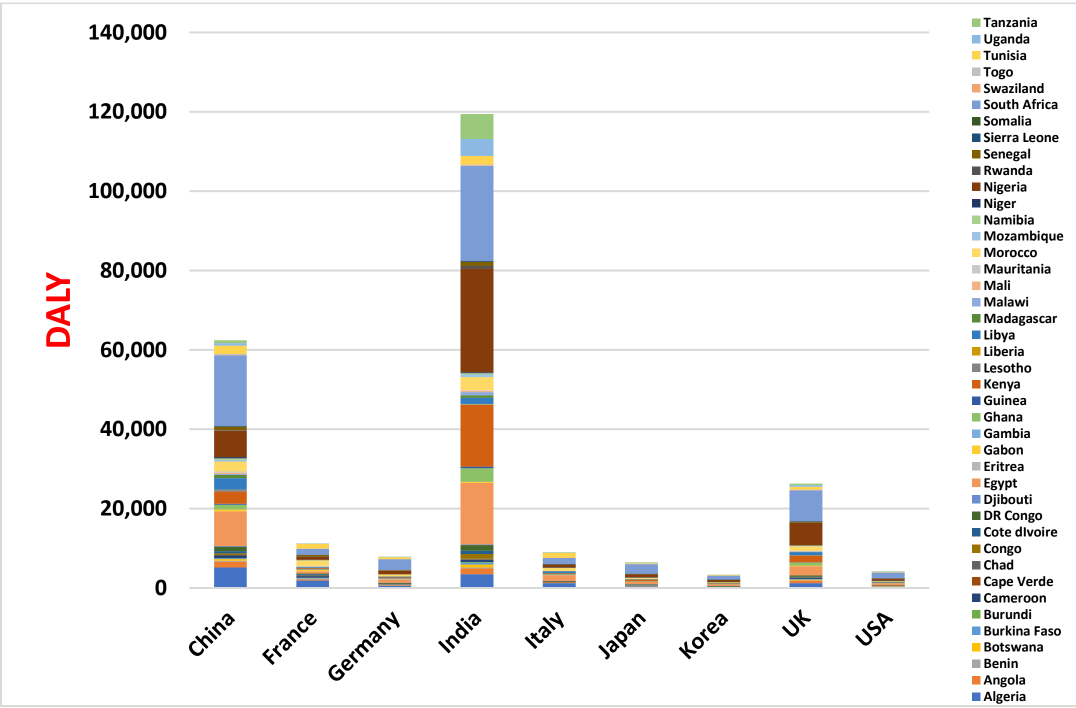


Figure 4. 23 Impacts of African countries on the 9 countries studied in section 4.4

It can be observed that except for India (119,427 DALYs) , China (62,460) and the UK (26,284), the damages caused by African imports on the 6 other countries (France, Germany, Italy, Japan, Korea and the USA) is under 20,000 DALYs.

- The value of exports **to Africa from China** is around **103 billion USD** (vs. 1 trillion to Asia, 596 billion to Asia or 489 to Europe). More than 50% of these exports are targeted to South Africa (15%), Nigeria (13%), Egypt (10%) and Algeria (8%) with mostly machineries and textile products that explain why the impact is shown higher for these 4 countries.
- The value of exports **to Africa from France** is around **30 billion USD** (vs. 316 billion to Europe, 93 to Asia or 49 to North America). More than 50% of these exports are targeted to North Africa with mostly electronic and medicines products with a low potential for air pollution formation at production stage
- The value of exports **to Africa from Germany** is around **24 billion USD** (vs. 792 billion to Europe, 242 to Asia or 152 to North America). More than 50% of these exports are targeted to South Africa (30%), Egypt (17%) and Algeria (13%) with mostly machineries products with a low potential for air pollution formation at production stage.
- The value of exports to **Africa from India** is around **26 billion USD** (vs. 116 to Asia, 55

billion to Asia or 53 to Europe). More than 50% of these exports are targeted to South Africa (16%),Kenya (12%), Egypt (9%) and Nigeria (9%) with several types of products such as Oil, electronic products, textile that explain why the impact is shown higher for these 4 countries.

- The value of exports **to Africa from Italy** is around **21 billion USD** (vs. 270 to Europe, 84 billion to Asia or 56 to North America). More than 50% of these exports are targeted to Algeria (22%), Egypt (15.6%), South Africa (10%) and Libya (8%) with mostly machineries products with a low potential for air pollution formation at production stage.
- The value of exports **to Africa from Japan** is around **10 billion USD** (vs. 379 to Asia, 163 billion to North America or 91 to Europe). Most of these exports are targeted to South Africa (21.5%) with mostly electronic products (printers, computers). The low intensity of exchange between African countries and Japan explain partly the low impacts caused by African imports
- The value of exports **to Africa from Korea** is around **14 billion USD** (vs. 324 to Asia, 100 to North America or 68 to Europe). Most of these exports are targeted to Angola (20%) and Egypt (18%). The low intensity of exchange between African countries and Korea explain partly the low impacts caused by African imports
- The value of exports **to Africa from the UK** is around **12 billion USD** (vs. 230 to Europe, 92 to Asia or 65 to North America). Most of these exports are targeted to South Africa (21%), Nigeria (13%) and Egypt (13%) with mostly machineries products with several types of products electronic products that explain why the impact is shown higher for these 3 countries.
- The value of exports **to Africa from the USA** is around **27 billion USD** (vs. 467 to Asia, 455 to North America or 332 to Europe). Most of these exports are targeted to South Africa (20%) and Egypt (20%) with mostly machineries and cereals products with a low potential for air pollution formation at production stage.

4.5 Limitations

In order to conduct a global analysis an inventory based on an input-output analysis was chosen. Economic sectors were 26 for most of the African countries. The emissions per sectors (g Pollutant/USD) are the average values for each sector. Several products (Tomato, Banana, Cassava) are grouped for example inside the agriculture sector. Therefore, the method can not be used to estimate the impact of each crop. Moreover, the analysis is based on the data publicly available, it is sometimes difficult to collect these data for each country, for example monetary spending from the personal users to the transport sector are difficult to be reported. Therefore, it was not considered in the calculation. A summary of the advantages and disadvantages of process-LCA vs IO LCA is proposed in Table 4.10.

Table 4.10 Comparison between Processed-LCA and Input-Output LCA Advantages/Disadvantages

	Processed-LCA	Input-Output LCA
Advantages	1-Higher reliability 2-Data specific to the product analyzed	1-Estimations can be done a larger scale (sector,country) 2- Can be used to make comparison between countries. 3-Useful to assess developing countries as precised LCI database are not established yet
Disadvantages	1- Difficult to collect detailed information (primary data) for each stage 2-Require often a LCI database (secondary data) in addition to the primary data	1-Can not be used to assess a specific product 2-Exclude some stages (Personal vehicle used for example)

4.6 Summary

In this chapter, it was shown that the impact related to African sectors of activity mainly occur in Africa:

- Nigeria, with more than 4 million DALYs, is the country with the highest impact, mainly due to agricultural practices
- Agriculture is having a high burden in Africa with more than 13 million DALYs related to the “slash and burn” culture in Sub-Sahara Africa
- Transport impacts are also significant with the use of second-hand vehicles and low oil quality
- The impact from electricity generation is limited however, production is predicted to grow and double by 2040 compared to 2019 levels. It is necessary to support standards and incentives as soon as possible.
- The effect of African consumption on other countries is limited
- G20 countries (Especially the USA) also have a responsibility for the air pollution damages in Africa due to their imports of oil products.

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Chapter 5: Air pollution in 2020: the impact of COVID-19 pandemic

5.1 Review of the link between air pollution & COVID-19 pandemic

The COVID-19 pandemic triggered an unprecedented change in people's daily lives worldwide, significantly impacting both the economy and human health [1-5]. The pandemic has officially caused more than 1,000,000 deaths (11 November, 2020 [6]), and the global economy is expected to shrink by 3.2% in 2020 [7]. This economic loss is partly due to the shortage of activity following the national lockdowns imposed by different governments, as shown in Figure 5.1. Specifically, from March to June, several countries installed a full lockdown. The total number reached 100 countries at that time. In some countries such as France, people were not allowed to go outside without specific permission. As of November, partial lockdowns were still applied in some countries (e.g., EU).

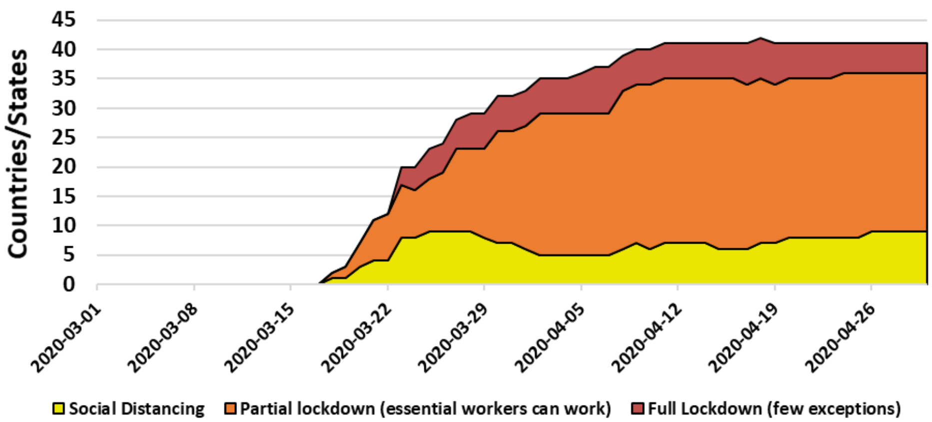

Figure 5. 2 Evolution of stay-at-home orders per country in Africa

Meanwhile, in several fields [8], the number of research articles submissions increased a lot compared to the previous year's same period. As shown in Figure 5.2, from the start of the pandemic, the research articles focusing on air pollution & COVID-19 also increased a lot. As a first step, researchers focused on the effect of lockdowns on outdoor air pollution (Section 5.1.1). Then as a second trend, the focus was put on the possible link between air pollution and COVID-19 case/fatality (Section 5.1.2). Finally, a focus was also done on indoor pollution (Section 5.1.3) and the benefits on human health of air pollution reduction (Section 5.1.3). A total of 200 research articles were collected, 140 articles focused on the effect of lockdown on air pollution, 47 on the link between air pollution and COVID-19, 7 on the link between COVID-19 & indoor environment. 6 on the reduction of outdoor air pollution & its benefits on human health. China is the country that received the highest attention (49 case studies), followed by India (23) & the USA (13). Several studies also proposed a global assessment (30).

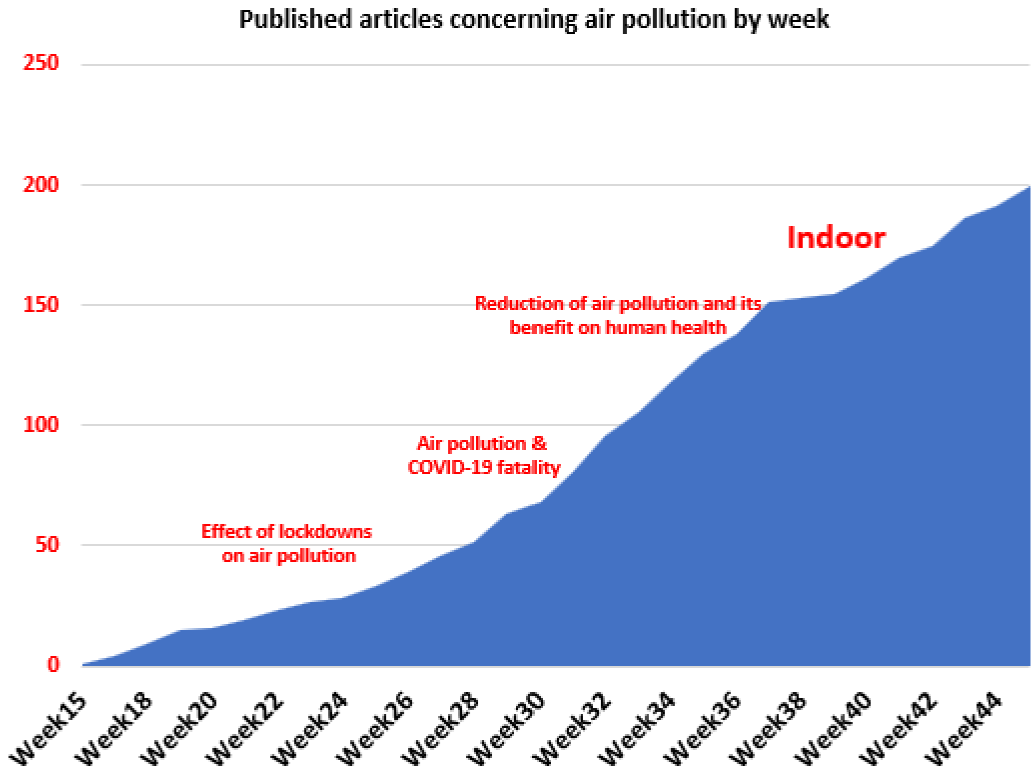

Figure 5. 3 Research articles focusing on air pollution and COVID-19

5.1.1 Reduction of Outdoor Air Pollution due to COVID-19 countermeasures

The countermeasures against the progress of the COVID-19 pandemic had a severe impact on the amount of activity. For example, the number of flights passenger decreased by nearly 90% in April-June [9]. The mobility was reduced by more than 80% in several cities worldwide (Paris, New York, Tokyo…) [10]. In April, industrial production in the EU decreased by 20% [11]. The energy demand was also reduced by up to 25% in the period, sometimes in April [12]. Especially the demand for fossil fuels was reduced: Coal demand was decreased by 8% compared with the first quarter of 2019, oil also, about 5% following the reduction of road & air transport.

This reduction of activity impacted the emissions and concentration of pollutants worldwide: In Europe, Sicard et al. [13] found that the PM2.5 concentration was reduced by 8% in average during the lockdown. In Malaysian urban areas, Kanniah et al. [14] found out that NO2 & PM2.5 concentrations were reduced by around 60% and 25%, respectively. In Egypt, the NO2 concentration was reduced by up to 33% in Alexandria city in the same period [15]. Finally, in the city of Sao Paulo, the PM2.5 concentration was reduced by 46% [16]. A summary of the findings is shown in Figure 5.3. It was found that seven indicators have been mainly studied recently. PM2.5, PM10, NO2, SO2, CO, NOx & O3. The information was extracted from each article and as shown in the figure the reduction for most of the indicators was around 30%. The only indicator that increased is Ozone (O3). This is due to the decrease of nitrogen oxide: in normal situation, O3 reacts with nitrogen oxide to form Nitrogen Dioxide (NO2) and Oxygen (O2) however, as the nitrogen oxide emissions decreased, there is much more Ozone left up.

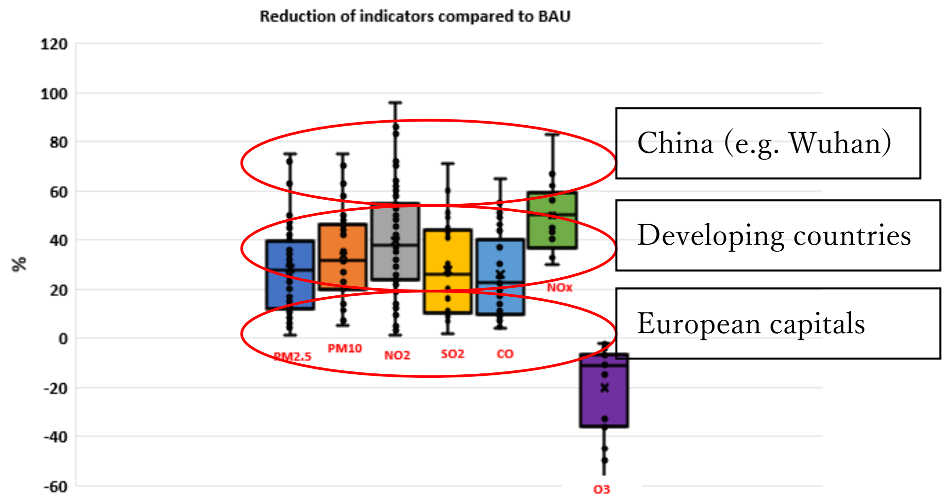

Figure 5. 4 Change of indicators compared with baseline scenario

A trend can be highlighted: for the Chinese cities, the most affected by the pandemic, the indicators' reduction was the highest (60-80%). For other developing countries or newly industrialized countries, the reduction was around 40%. For European cities, the reduction was around 10-20%

Several observations can be made for each indicator:

- For PM: the reduction is attributed to the decrease in transport, industrial activity, and construction
- For NOx, NO2: the decline is attributed to the reduction of transportation and industrial activity
- For SO2: the reduction is attributed to the decrease in electricity generation and the reduction of transport

Another type of assessment confirms this. To identify which sectors had the greatest reduction in the first half of 2020, it was decided to re-analyze the data published by one of the authors of our review: "Global socio-economic losses and environmental gains from the Coronavirus pandemic" [17]. The data were initially calculated n the article based on the consumption-based approach using an assessment based on a Multi-Regional Input-Output table (MRIO): EORA. The study focused on the reduction of PM2.5, SO2, NOx. The authors collected the information until the end of May 2020, and projection was only made for the air transport sector. The data were obtained from the authors, and a calculation was redone to obtain the results in the production-based approach. The calculation was made for 38 countries in the world. The results are shown in Table 5.1-5.3**.**

The hypothesis collected in the 140 articles agreed with the calculation. Electricity, transport (both air & road), and mining sectors were the sectors with the highest reduction.

Table 5.1 TOP5 sectors with the highest reduction of PM2.5 emissions in the production-based approach

Country	TOP1	TOP2	TOP3	TOP4	TOP5
Australia	Chemicals & plastics'	Other transport & storage'	Equipment'	Metal products'	Solid fuels'
Brazil	Other transport & storage'	Private services'	Mining'	Air transport'	Chemicals & plastics'
Canada	Other transport & storage'	Air transport'	Electricity'	Solid fuels'	Forestry, wood, paper'
China	Mining'	Chemicals & plastics'	Equipment'	Electricity'	Textiles & leather'
France	Other transport & storage'	Private services'	Chemicals & plastics'	Mining'	Air transport'
Germany	Chemicals & plastics'	Other transport & storage'	Electricity'	Equipment'	Business services'
HK	Electricity'	Other transport & storage'	Mining'	Chemicals & plastics'	Metal products'
India	Other transport & storage'	Mining'	Metal products'	Chemicals & plastics'	Ceramic & other manufacturing'
Indonesia	Electricity'	Private services'	Other transport & storage'	Mining'	Metal products'
Iran	Other transport & storage'	Mining'	Agriculture'	Electricity'	Chemicals & plastics'
Italy	Other transport & storage'	Private services'	Mining'	Agriculture'	Chemicals & plastics'
Japan	Mining'	Other transport & storage'	Metal products'	Chemicals & plastics'	Electricity'
Malaysia	Mining'	Other transport & storage'	Private services'	Construction'	Metal products'
Mexico	Other transport & storage'	Mining'	Electricity'	Chemicals & plastics'	Metal products'
Middle East	Mining'	Other transport & storage'	Retail & wholsesale'	Electricity'	Private services'
Nigeria	Mining'	Other transport & storage'	Liquid fuels'	Chemicals & plastics'	Food'
Rest of Africa	Other transport & storage'	Mining'	Electricity'	Retail & wholsesale'	Agriculture'
Rest of Central America	Other transport & storage'	Electricity'	Mining'	Private services'	Air transport'
Rest of East Asia	Electricity'	Equipment'	Forestry, wood, paper'	Textiles & leather'	Metal products'
Rest of EU	Other transport & storage'	Private services'	Mining'	Chemicals & plastics'	Air transport'
Rest of Europe	Other transport & storage'	Electricity'	Mining'	Agriculture'	Retail & wholsesale'
Rest of FSU	Chemicals & plastics'	Mining'	Retail & wholsesale'	Other transport & storage'	Air transport'
Rest of Oceania	Chemicals & plastics'	Other transport & storage'	Metal products'	Construction'	Ceramic & other manufacturing'
Rest of OPEC	Other transport & storage'	Mining'	Electricity'	Chemicals & plastics'	Ceramic & other manufacturing'
Rest of South America	Other transport & storage'	Mining'	Electricity'	Chemicals & plastics'	Agriculture'
Rest of South Asia	Other transport & storage'	Mining'	Agriculture'	Chemicals & plastics'	Electricity'
Rest of South East Asia	Mining'	Electricity'	Other transport & storage'	Metal products'	Ceramic & other manufacturing'
Russia	Electricity'	Public services'	Air transport'	Private services'	Retail & wholsesale'
Scandinavia	Other transport & storage'	Forestry, wood, paper'	Chemicals & plastics'	Equipment'	Construction'
Singapore	Private services'	Other transport & storage'	Solid fuels'	Equipment'	Chemicals & plastics'
South Africa	Private services'	Electricity'	Other transport & storage'	Retail & wholsesale'	Mining'
South Korea	Electricity'	Mining'	Metal products'	Chemicals & plastics'	Ceramic & other manufacturing'
Spain	Other transport & storage'	Private services'	Textiles & leather'	Electricity'	Mining'
Taiwan	Electricity'	Mining'	Ceramic & other manufacturing'	Chemicals & plastics'	Other transport & storage'
Thailand	Metal products'	Mining'	Ceramic & other manufacturing'	Private services'	Construction'
UAE	Mining'	Forestry, wood, paper'	Chemicals & plastics'	Other transport & storage'	Air transport'
UK	Other transport & storage'	Private services'	Chemicals & plastics'	Air transport'	Retail & wholsesale'
USA	Other transport & storage'	Air transport'	Electricity'	Chemicals & plastics'	Private services'

Table 5.2 TOP5 sectors with the highest reduction of SO2 emissions in the production-based approach

Country	TOP1	TOP2	TOP3	TOP4	TOP5
'Australia	Chemicals & plastics'	Electricity'	Other transport & storage'	Solid fuels'	Equipment'
'Brazil	Other transport & storage'	Private services'	Electricity'	Chemicals & plastics'	Air transport'
'Canada	Electricity'	Other transport & storage'	Private services'	Chemicals & plastics'	Air transport'
'China	Electricity'	Chemicals & plastics'	Equipment'	Textiles & leather'	Metal products'
'France	Private services'	Other transport & storage'	Retail & wholesale'	Chemicals & plastics'	Air transport'
'Germany	Electricity'	Chemicals & plastics'	Equipment'	Business services'	Metal products'
'Hong Kong	Electricity'	Retail & wholesale'	Chemicals & plastics'	Metal products'	Construction'
'India	Metal products'	Chemicals & plastics'	Electricity'	Ceramic & other manufacturing'	Retail & wholesale'
'Indonesia	Electricity'	Metal products'	Other transport & storage'	Ceramic & other manufacturing'	Solid fuels'
'Iran	Electricity'	Other transport & storage'	Construction'	Air transport'	Chemicals & plastics'
'Italy	Other transport & storage'	Electricity'	Private services'	Chemicals & plastics'	Construction'
'Japan	Metal products'	Electricity'	Other transport & storage'	Chemicals & plastics'	Air transport'
'Malaysia	Electricity'	Construction'	Metal products'	Ceramic & other manufacturing'	Other transport & storage'
'Mexico	Electricity'	Retail & wholesale'	Solid fuels'	Private services'	Other transport & storage'
'Middle East	Electricity'	Chemicals & plastics'	Retail & wholesale'	Other transport & storage'	Private services'
'Nigeria	Retail & wholesale'	Chemicals & plastics'	Mining'	Liquid fuels'	Electricity'
'Rest of Africa	Electricity'	Retail & wholesale'	Chemicals & plastics'	Other transport & storage'	Air transport'
'Rest of Central America	Electricity'	Retail & wholesale'	Chemicals & plastics'	Air transport'	Liquid fuels'
'Rest of East Asia	Electricity'	Equipment'	Textiles & leather'	Forestry, wood, paper'	Metal products'
'Rest of EU	Electricity'	Private services'	Other transport & storage'	Chemicals & plastics'	Forestry, wood, paper'
'Rest of Europe	Electricity'	Other transport & storage'	Retail & wholesale'	Private services'	Mining'
'Rest of FSU	Electricity'	Chemicals & plastics'	Metal products'	Equipment'	Retail & wholesale'
'Rest of Oceania	Electricity'	Chemicals & plastics'	Metal products'	Construction'	Ceramic & other manufacturing'
'Rest of OPEC	Electricity'	Other transport & storage'	Solid fuels'	Retail & wholesale'	Ceramic & other manufacturing'
'Rest of South America	Electricity'	Chemicals & plastics'	Other transport & storage'	Retail & wholesale'	Private services'
'Rest of South Asia	Electricity'	Retail & wholesale'	Liquid fuels'	Other transport & storage'	Metal products'
'Rest of South East Asia	Electricity'	Chemicals & plastics'	Metal products'	Ceramic & other manufacturing'	Construction'
'Russia	Electricity'	Chemicals & plastics'	Air transport'	Public services'	Private services'
'Scandinavia	Other transport & storage'	Forestry, wood, paper'	Electricity'	Equipment'	Chemicals & plastics'
'Singapore	Solid fuels'	Liquid fuels'	Other transport & storage'	Electricity'	Private services'
'South Africa	Electricity'	Private services'	Ceramic & other manufacturing'	Retail & wholesale'	Chemicals & plastics'
'South Korea	Electricity'	Solid fuels'	Metal products'	Chemicals & plastics'	Construction'
'Spain	Electricity'	Textiles & leather'	Other transport & storage'	Air transport'	Construction'
'Taiwan	Electricity'	Ceramic & other manufacturing'	Metal products'	Chemicals & plastics'	Equipment'
'Thailand	Electricity'	Metal products'	Ceramic & other manufacturing'	Construction'	Chemicals & plastics'
'UAE	Forestry, wood, paper'	Electricity'	Chemicals & plastics'	Air transport'	Other transport & storage'
'UK	Other transport & storage'	Electricity'	Solid fuels'	Retail & wholesale'	Private services'
'USA	Other transport & storage'	Electricity'	Air transport'	Chemicals & plastics'	Private services'

Table 5.3 TOP5 sectors with the highest reduction of NOx emissions in the production-based approach

Country	TOP1	TOP2	TOP3	TOP4	TOP5
Australia	Air transport'	Other transport & storage'	Electricity'	Chemicals & plastics'	Equipment'
Brazil	Other transport & storage'	Air transport'	Food'	Private services'	Electricity'
Canada	Air transport'	Private services'	Electricity'	Other transport & storage'	Chemicals & plastics'
China	Electricity'	Other transport & storage'	Equipment'	Air transport'	Chemicals & plastics'
France	Other transport & storage'	Private services'	Air transport'	Retail & wholesale'	Food'
Germany	Electricity'	Equipment'	Chemicals & plastics'	Air transport'	Metal products'
HK	Electricity'	Other transport & storage'	Chemicals & plastics'	Metal products'	Construction'
India	Other transport & storage'	Air transport'	Metal products'	Electricity'	Retail & wholesale'
Indonesia	Electricity'	Air transport'	Metal products'	Ceramic & other manufacturing'	Other transport & storage'
Iran	Other transport & storage'	Electricity'	Construction'	Air transport'	Private services'
Italy	Private services'	Other transport & storage'	Air transport'	Retail & wholesale'	Electricity'
Japan	Electricity'	Air transport'	Metal products'	Other transport & storage'	Chemicals & plastics'
Malaysia	Electricity'	Construction'	Other transport & storage'	Metal products'	Ceramic & other manufacturing'
Mexico	Electricity'	Other transport & storage'	Retail & wholesale'	Solid fuels'	Private services'
Middle East	Electricity'	Other transport & storage'	Air transport'	Chemicals & plastics'	Retail & wholesale'
Nigeria	Retail & wholesale'	Chemicals & plastics'	Liquid fuels'	Mining'	Other transport & storage'
Rest of Africa	Retail & wholesale'	Other transport & storage'	Electricity'	Air transport'	Food'
Rest of Central America	Electricity'	Air transport'	Other transport & storage'	Retail & wholesale'	Food'
Rest of East Asia	Electricity'	Agriculture'	Textiles & leather'	Equipment'	Forestry, wood, paper'
Rest of EU	Electricity'	Private services'	Other transport & storage'	Air transport'	Chemicals & plastics'
Rest of Europe	Other transport & storage'	Electricity'	Agriculture'	Retail & wholesale'	Private services'
Rest of FSU	Electricity'	Air transport'	Other transport & storage'	Chemicals & plastics'	Metal products'
Rest of Oceania	Electricity'	Air transport'	Chemicals & plastics'	Metal products'	Ceramic & other manufacturing'
Rest of OPEC	Other transport & storage'	Electricity'	Liquid fuels'	Air transport'	Ceramic & other manufacturing'
Rest of South America	Other transport & storage'	Electricity'	Air transport'	Food'	Retail & wholesale'
Rest of South Asia	Electricity'	Other transport & storage'	Air transport'	Retail & wholesale'	Food'
Rest of South East Asia	Electricity'	Metal products'	Ceramic & other manufacturing'	Chemicals & plastics'	Construction'
Russia	Electricity'	Air transport'	Other transport & storage'	Public services'	Private services'
Scandinavia	Air transport'	Electricity'	Other transport & storage'	Forestry, wood, paper'	Equipment'
Singapore	Solid fuels'	Other transport & storage'	Electricity'	Private services'	Equipment'
South Africa	Electricity'	Air transport'	Other transport & storage'	Private services'	Ceramic & other manufacturing'
South Korea	Electricity'	Other transport & storage'	Metal products'	Air transport'	Solid fuels'
Spain	Air transport'	Electricity'	Textiles & leather'	Other transport & storage'	Construction'
Taiwan	Electricity'	Other transport & storage'	Ceramic & other manufacturing'	Metal products'	Chemicals & plastics'
Thailand	Metal products'	Electricity'	Ceramic & other manufacturing'	Construction'	Food'
UAE	Electricity'	Forestry, wood, paper'	Air transport'	Other transport & storage'	Ceramic & other manufacturing'
UK	Other transport & storage'	Air transport'	Electricity'	Retail & wholesale'	Private services'
USA	Other transport & storage'	Air transport'	Electricity'	Private services'	Retail & wholesale'

5.1.2 Air pollution, a link with COVID-19 incidence/mortality?

The second topic of research was the link between air pollution and the COVID-19 incidence of mortality. As several conclusions have been developed, it was decided to focus on 31 research articles. The summary is given Table 5.4. 17 research articles found that air pollution is linked to a higher number of deaths from COVID-19 (Air pollution as comorbidity): for example, Pozzer et al. [18] found that COVID-19 contributed to 15% of mortality worldwide, Coker et al. [19] declared that a one-unit increase in PM2.5 concentration (µg/m3) is associated with a 9% increase in COVID-19 related mortality.. 19 articles found a possible correlation between air pollution and the number of incidence case: Huang et al. [20] found that nitrogen dioxide (NO2) is significantly associated with COVID-19 incidence, with a 1 µg/m3 increase in long-term exposure to NO2 increasing the COVID-19 incidence rate by 5.58%. Travaglio et al. [21] revealed that an increase of 1 µg/m3 in the long-term average of PM2.5 was associated with a 12% increase in COVID-19 cases.

There are mainly two conclusions as shown in Figure 5.4:

- As comorbidity: Chronic exposure to PM2.5 causes alveolar ACE-2 receptor overexpression (higher number of the receptor), which is actually the entry receptor of COVID-19 (COVID-19 binds to the receptor). Continuous exposure to fine particles causes severe inflammation of lung tissue. The angiotensin II converting enzyme (ACE- 2) is involved in this inflammation process [22, 23].
- As a mean of transport: Correlation was shown between air pollution and incidence case. However, the only study that collected air samples in Germany [24] found that neither air samples nor purified pollen were infectious or could act as a carrier for virus particles. Barakat et al. [25] highlighted the importance of experimental and in vitro results that could confirm or disprove if PM are indeed vectors of SARS-CoV-2 in particular, and viruses in general

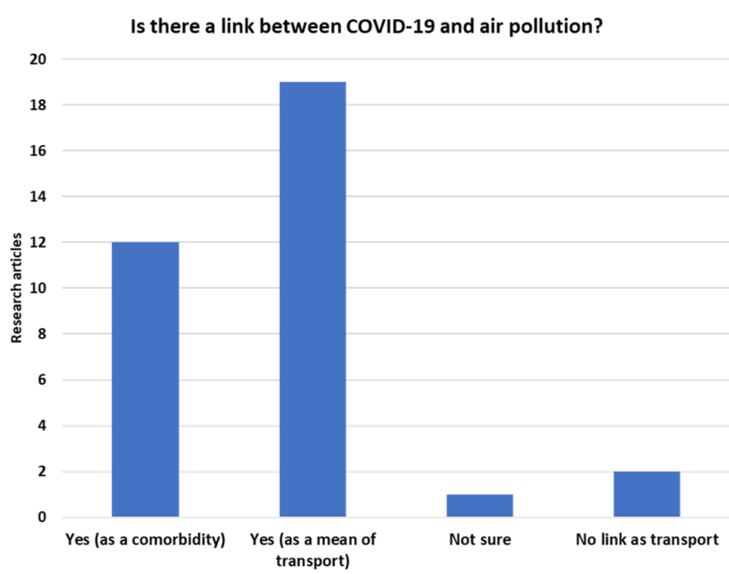

Figure 5. 5 Is there a link between COVID-19 and air pollution?

Table 5.4 Summary of the link between air pollution and COVID-19 incidence/mortality

Title	Country	Summary	Yes (as a comorbidity)	Yes (as a mean of transport)	Not sure	No link as transport
Association of particulate matter pollution and case fatality rate of COVID-19 in 49 Chinese cities	China	For **every 10 μg/m3 increase in PM2.5 and PM10 concentrations**, **the COVID-19 Case Fatality Rate (CFR) increased by 0.24% and 0.26%** , respectively.	x			
Temporal association between particulate matter pollution and case fatality rate of COVID-19 in Wuhan	China	A **positive relationship was found between PM2.5 and PM10 concentrations and the CFR of COVID-19 in Wuhan (R>0.65)**	x			
Possible environmental effects on the spread of COVID-19 in China	China	Results may suggest an **enhanced impact of Air Quality Index on the COVID-19 spread under low humidity (RR=1.007)**		x		
Environmental pollution and COVID-19 outbreak: insights from Germany	Germany	**PM10**, humidity, and environmental quality index **have a significant relationship with the active cases from COVID-19 pandemic.**		x		
Air Pollution Exposure and Covid-19 in Dutch Municipalities	Netherlands	Our results indicate that, other things being equal, a municipality with **1 μg/m3 more PM2.5 concentrations** will have **9.4 more Covid-19 cases, 3.0 more hospital admissions, and 2.3 more deaths**	x	x		
Particulate matter and SARS-CoV-2: A possible model of COVID-19 transmission	Review	Indirectly, **exposure to PM increases ACE2 expression in the lungs which facilitates SARS-CoV-2 viral adhesion**. **PM could be both a direct and indirect transmission model for SARS-CoV-2 infection.**	x	x		

Region-specific air pollutants and meteorological parameters influence COVID-19: A study from mainland China	China	Findings suggest that higher ambient **CO concentration is a risk factor for increased transmissibility of the novel coronavirus**, while higher temperature and air pressure, and efficient ventilation reduce its transmissibility (**Pearson correlation coefficient=0.145**)		x		
The Effects of Air Pollution on COVID-19 Related Mortality in Northern Italy	Italy	A **one-unit increase in PM2.5 concentration (μg/m3)** is associated with a **9% increase in COVID-19 related mortality.**	x			
The association between COVID-19 deaths and short-term ambient air pollution/meteorological condition exposure: a retrospective study from Wuhan, China	China	**PM2.5 was the only pollutant exhibiting a positive association (relative risk (RR) = 1.079) with COVID-19 deaths.**	x			
Potential link between compromised air quality and transmission of the novel corona virus (SARS-CoV-2) in affected areas	India	Through **a critical review of the current literature and a preliminary analysis of the link between SARS-CoV-2 transmission and air pollution in the affected regions**, we offer a perspective that **polluted environment could enhance the transmission rate of such deadly viruses under moderate-to-high humidity conditions (Pearson's r= 0.54)**		x		
COVID-19 and Environmental - Weather Markers: Unfolding Baseline Levels and Veracity of Linkages in Tropical India	India	A strong association of COVID-19 mortality was found with baseline **PM2.5 levels (80% correlation)** to which the population is chronically exposed and may be considered as one of the critical factors	x			
Impact of climate and ambient air pollution on the epidemic growth during COVID-19 outbreak in Japan	Japan	Results suggested that **short-term exposure to suspended particles might influence respiratory infections caused by the severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) (R=1.01 per μg/m3)**		x		

An ecological analysis of long-term exposure to PM2.5 and incidence of COVID-19 in Canadian Health Regions	Canada	Long-term PM2.5 exposure exhibited a positive association with COVID-19 incidence (**incidence rate ratio 1.07 per µg/m3**).		x		
Aerosol transmission of SARS-CoV-2? Evidence, prevention and control	x	Several studies support that aerosol transmission of **SARS-CoV-2 is plausible, and the plausibility score (weight of combined evidence) is 8 out of 9.**		x		
Hazardous air pollutant exposure as a contributing factor to COVID-19 mortality in the United States	USA	**An increase in the respiratory hazard index is associated with a 9% increase in COVID-19 mortality**	x			
COVID-19 and Air Pollution and Meteorology-an intricate relationship: a review	Global	Review found that **an increase in particulate matter concentration causes more COVID-19 cases and mortality**. Gaseous pollutant and COVID-19 cases are positively 19 correlated	x	x		
Asymmetric link between environmental pollution and COVID-19 in the top ten affected states of US: A novel estimations from quantile-on-quantile approach	USA	On the other side, **air pollution predominantly caused to increase in the intensity of COVID- 19 cases across all states** except lower quantiles of Massachusetts, and extreme higher quantiles of Arizona and New Jersey, where this effect becomes less pronounced or negative.		x		
Effects of long-term exposure to air pollutants on the spatial spread of COVID-19 in Catalonia, Spain	Spain	**Long-term exposure to nitrogen dioxide (NO2) and, to a lesser extent, to coarse particles (PM10) have been independent predictors of the spatial spread of COVID-19**. For every 1 µm/m3 above the mean the risk of a positive test case increased by 2.7% for NO2 and 3.0% for PM10.				x
Ambient nitrogen dioxide pollution and spread ability of COVID-19 in Chinese cities	China	R0 **was positively associated with NO2 concentration** at city level with correlation between **NO2 concentration and R0 (r>0.51)**		x		

Impact of meteorological conditions and air pollution on COVID-19 pandemic transmission in Italy	Italy	Our main findings highlight that temperature and humidity related variables are negatively correlated to the virus transmission, **whereas air pollution (PM2.5) shows a positive correlation (at lesser degree)**. In other words, **COVID- 19 pandemic transmission prefers dry and cool environmental conditions, as well as polluted air.**		x			
COVID-19 and its relationship to particulate matter pollution – case study from part of greater chennai, india	India	If Covid is a visible, brutally virulent, incredibly contagious pandemic that kills rapidly and mercilessly, air pollution is its unseen evil twin. **Under the radar, but even ruthlessly, if Covid and PM paired together lead to murder without delay. The observations of the materials (+ve cases, PM 10, PM 2.5) collected proved that during precovid regime less polluted areas are indicated now with less than 5 infection cases reflecting the healthy people with less pollution and they are less vulnerable to covid**		x			
Is Particulate Matter of Air Pollution a Vector of Covid-19 Pandemic	Global	**Even though studies showed that genetic material of SARS-CoV-2 might be associated with PM obtained from highly infected areas**, none of them investigated whether the virus was infectious or not. In addition, no study of virus-PMsurface interactions have been conducted to date.			x		
How do low wind speeds and high levels of air pollution support the spread of COVID-19	Italy	cities located in hinterland zones (mostly those bordering large urban conurbations) with little wind speed and **frequently high levels of air pollution had higher numbers of COVID-19 related infected individuals**					

Assessing correlations between short-term exposure to atmospheric pollutants and COVID-19 spread in all Italian territorial areas	Italian	The results of the statistical analysis suggest **the hypothesis of a moderate-to-strong 40 correlation between the number of days exceeding the annual regulatory limits of PM10, PM2.5 and NO2 atmospheric pollutants and COVID-19 incidence, mortality and lethality rates for all the 107 territorial areas in Italy (Incidence rate: Spearman coefficient 0.61 for PM2.5, Lethality rate: Spearman coeffcient 0.45)**	x	x		
No SARS-CoV-2 detected in air samples (pollen and particulate matter) in Leipzig during the first spread	Germany	**Air samples collected at measuring station** in Leipzig and purified pollen were analyzed for SARS-CoV-2 typical signals or for virus induced cytopathic effects, to test if the virus could bind to bioaerosols and if so, whether these complexes are infectious. The results **show that neither air samples nor purified pollen were infectious or could act as carrier for virus particles**.				x
How air quality and COVID-19 transmission change under different lockdown scenarios? A case from Dhaka city, Bangladesh	Bangladesh	O3 was the dominant factors that could be associated with COVID-19 cases during the study period (**Relative importance around 80**)		x		
Associations between Air Pollution and COVID-19 epidemic during quarantine period in China	China	**Significant positive associations of short-term exposure to air pollutants, including particulate matter with diameters ≤2.5µm (PM2.5), par**ticulate matter with diameters ≤10µm (PM10), and nitrogen dioxide (NO2) with daily new confirmed cases were observed during the epidemic. Per interquartile range (IQR) **increase in PM2.5 (lag0-15), PM10 (lag0-15), and NO2 (lag0-20) were associated with a 7%, 6% and 19% increase in the counts of daily onset cases, respectively.**		x		

Links between air pollution and COVID-19 in England	UK	An increase of **1 µg/m3 in the long-term average of PM2.5 was associated with a 12% increase** in COVID-19 cases		x		
Regional and global contributions of air pollution to risk of death from COVID-19	Global	Estimatins showed that particulate **air pollution contributed 15% to COVID-19 mortality worldwide**, 27% in East Asia, 19% in Europe, and 17% in North America. Globally, 50–60% of the attributable, anthropogenic fraction is related to fossil fuel use, up to 70–80% in Europe, West Asia, and North America.	x			
Associations between mortality from COVID-19 in two Italian regions and outdoor air pollution as assessed through tropospheric nitrogen dioxide	Italian	Using a multivariable negative binomial regression model, **we found an association between nitrogen dioxide and COVID-19 mortality**	x			
Population-weighted exposure to air pollution and COVID-19 incidence in Germany	Germany	**The results show that nitrogen dioxide (NO2) is significantly associated with COVID-19 incidence**, with a 1 µg/m3 increase in long-term exposure to NO2 increasing the **COVID-19 incidence rate by 5.58%**		x		

5.1.3 Indoor environment & COVID-19

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COVID-19 had an impact on the indoor environment through the use of disinfectants used to keep a safe environment. Domínguez-Amarillo et al. [26] showed that the increased time at home had an impact (cooking and cleaning activities) on indoor air pollution emissions with an increase of VOC concentration by 37-559%. It was further confirmed by Zheng et al. [27], who focused on Quaternary ammonium compounds (QACs) found in Disinfecting products. By collecting dust samples, they showed that the average concentration changed by 62%. Finally, Steinemann et al. [28] showed that 26 commonly used pandemic products such as hand sanitizers, air disinfectants, multipurpose cleaners, and handwashing soap (both regular but last the ones labeled as green), totally emitted 399VOCs with 127VOCs classified as potentially hazardous. Furthermore, only 4% of all VOCs and 11% of potentially hazardous VOCs were indicated on the label or datasheet.

A second aspect was developed: the ventilation of the indoor area was pointed as critical. It is said that improved ventilation can reduce the COVID-19 impacts [29]; however, air conditioning can also increase the risk of infection: Background air velocity is an environmental factor that impacts the transmission of contagious diseases by influencing the spreading distance of droplets. The standard indoor air velocity is around 0.3m/s; however, if it is increased, droplets' spreading distance can be increased from 2 to 20 meters [30]. Therefore Melikov et al. [31] recommend designing personalized ventilation as this option is unlikely to increase the reproductive number (R0) of the virus.

5.2 Calculation: reduction of air pollution burden in the first quarter of 2020

Our study aimed at evaluating the global mortality reduction in the first quarter of 2020 due to the reduction in PM2.5 concentration. Compared to existing studies on the topic, we highlighted the change in global PM2.5 concentration but also tried to estimate the reduction in burden due to the change in concentration [32].

Compared with the traditional approach (national or continental) used, for example, in LCA, this study was based on a grid-scale approach to improve the accuracy of the assessment.
PM2.5 concentration (μg/m3) was collected from the European Centre for Medium-RangeWeather Forecasts (ECMWF) satellite [33] at grid scale (0.125°,, which is about 15 km or 4,150,080 grids globally);
data were collected for the periods from 1 January to 30 April, 2019, and from 1 January to 30 April, 2020. Data post-treatment was performed using MATLAB software [35]. For each month, the average concentration as a common indicator for air quality measurement was calculated for both 2019 and 2020. Several studies demonstrated the reliability of satellite data in comparison with ground measurements [36–38]. As ground measurement stations are still limited in Africa and Southern America [39], the satellite data helped to overcome this limitation.

The gridded population data were collected for 2020 from the Center for International Earth Science Information Network (CIESIN) [40]; the data are represented in Figure 5.5. The different age groups foreach grid were obtained from the same source for 2010, which was the year with the latest data available. We further confirmed from different sources [41,42] that the share in the age groups in the cities did not change significantly in the last 10 years. Finally, the data provided by the CIESIN at a resolution of 0.042 were converted to the same scale as the PM2.5 concentration data (0.125°).

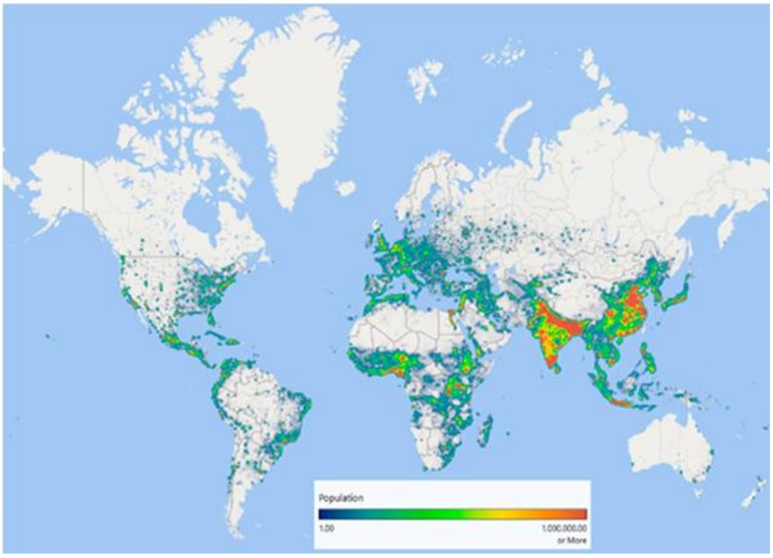
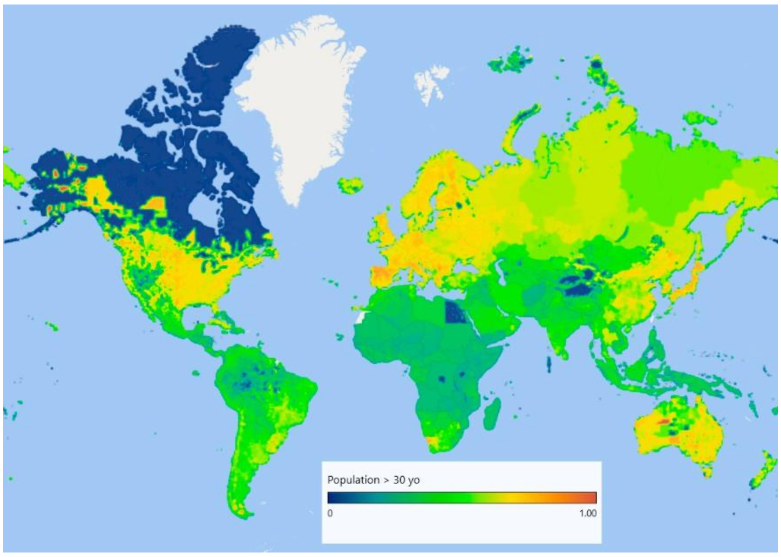
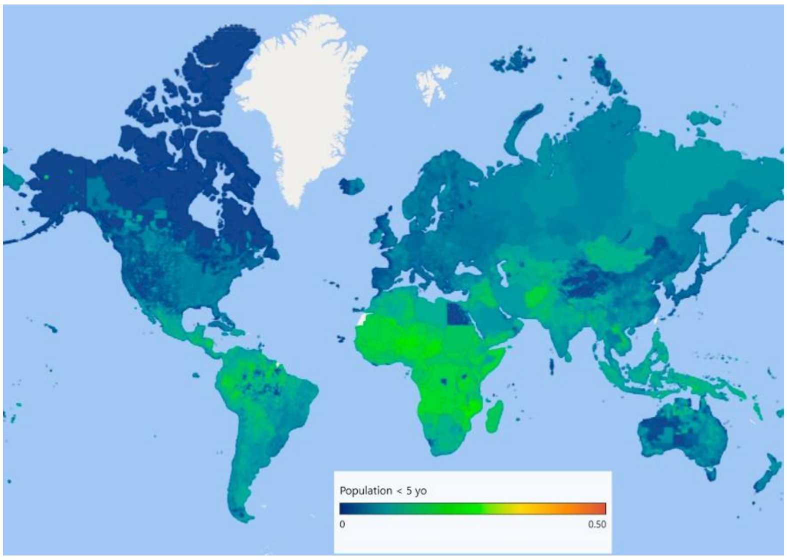


Figure 5. 6 World population in 2020 [23].

Data from the WHO [43] were collected for each country, representing the annual mortality rate per health effect (in 2016). In accordance with previous studies [44-46], the population under 5 years old and over 30 years were considered. The information collected corresponds to the mortality rate for health diseases related to air pollution: for people aged above 30 years old, ischemic heart disease (IHD), stroke, lung cancer (LC), and chronic obstructive pulmonary disease (COPD) and for people aged under five years old, acute lower respiratory infections (ALRI). The maps of the populations under 5 years old and over 30 years old are shown in Figure 5.6.



(a)



(b)

Figure 5. 7 Ratio of population (a) > 30 years old and (b) < 5 years old

Based on previous cohort studies [44,45,47], it was decided to pick a relative risk of 1.01 per µg/m3 per health effect. The equation for the CRF applied in each grid is

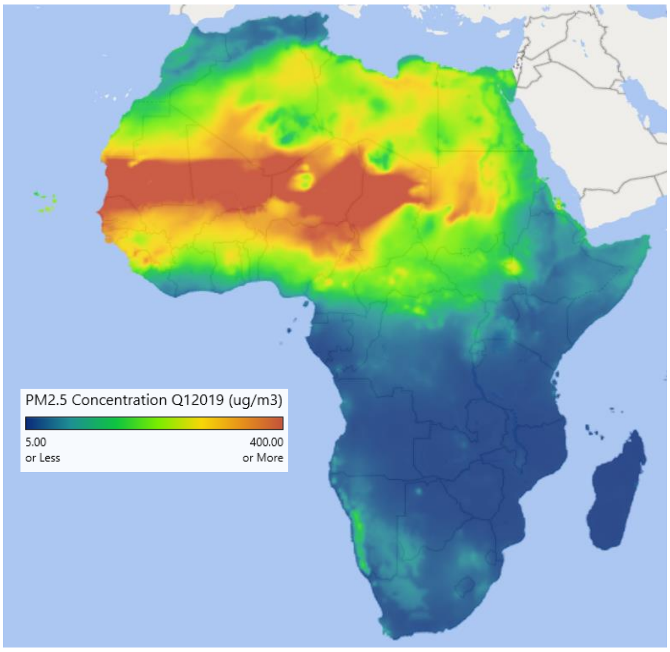
$$CRF = RR * MR * \Delta C * Pop$$

where:

- RR is the relative risk of a health effect due to exposure to PM2.5 (µg/m3 of air).
- MR (death/person/month) is the mortality rate specific to each country for the health effects related to air pollution.
- ΔC is the difference in PM2.5 concentration (µg/m3 of air) between each monthly average in the first quarter of years 2019 and 2020.
- Pop is the population under 5 years old and over 30 years old in the grid.

To express the overall burden, the number of deaths was converted to disability-adjusted life years (DALYs) using the WHO data .

A decrease of PM2.5 concencentration was observed in Africa compared with 2019 for example in Western Africa as shown in Figure 5.7



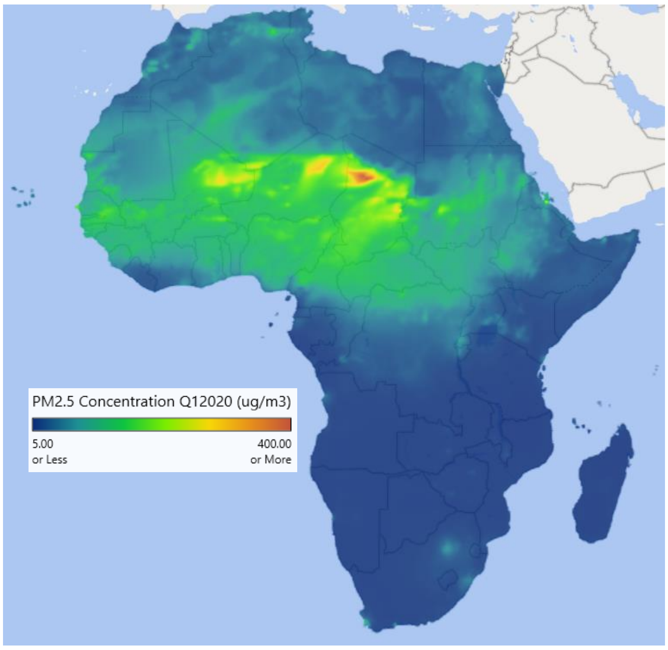


Figure 5. 8 PM2.5 concentration in Africa Q1 2019 (left); PM2.5 concentration in Africa Q2 2020 (right)

The highest reductions in burden occurred for China (−13.9 million DALY), India (−6.3 million), and Nigeria (−2.3 million). Italy (26,943 DALY), Germany (23,150), and Switzerland (4,744) showed increases in mortality compared to the same period last year. The results are shown in Table 5.5 and Figure 5.7. The results for each grid can be found online on: https://zenodo.org/record/3932692#.X8A9CWj7SUl.

Table 5.5 Comparison of the burden of air pollution at the country level between Q1 2019 and Q1 2020.

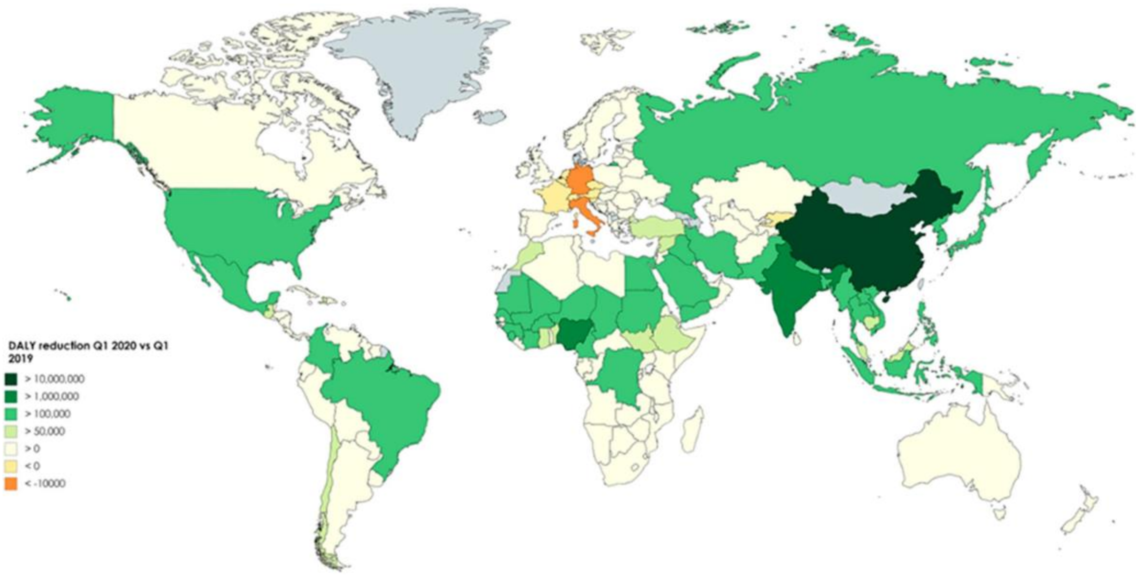
Rank (By DALY Reduction)	Country	Average Concentration Q1 2019 (μg/m^3)	Average Concentration Q1 2020 (μg/m^3) [Di*ff*erence in %]	∆Burden (DALY) (Year)	∆Burden (Death) (Person)
1	China	44.28	18.88 [−57%]	**−13,904,672**	**−646,164**
2	India	49.90	30.99 [−38%]	**−6,300,012**	**−206,727**
3	Nigeria	75.30	34.31 [−54%]	**−2,296,551**	**−40,790**
4	Indonesia	12.44	5.33 [−57%]	**−938,082**	**−32,650**
5	Pakistan	43.96	27.76 [−37%]	**−822,236**	**−24,560**
6	Bangladesh	70.44	45.26 [−36%]	**−728,264**	**−24,836**
7	Egypt	65.13	12.28 [−81%]	**−567,987**	**−21,409**
8	Niger	121.56	43.91 [−64%]	**−531,374**	**−9221**
9	Mexico	21.55	17.52 [−19%]	**−391,795**	**−18,050**
10	Mali	108.49	38.52 [−64%]	**−371,698**	**−7666**
11	USA	6.24	4.56 [−27%]	**−345,296**	**−16,826**
12	Chad	108.44	44.61 [−59%]	**−335,997**	**−5266**
13	Sudan	67.60	24.43 [−64%]	**−326,182**	**−8689**
14	Philippines	16.97	5.99 [−65%]	**−286,481**	**−9135**
15	Myanmar	51.17	24.21 [−−53%]	**−265,381**	**−8674**
16	Korea	45.67	19.82 [−57%]	**−248,186**	**−11,682**
17	Viet Nam	37.58	16.62 [−56%]	**−231,642**	**−9426**
18	Saudi Arabia	91.00	15.95 [−82%]	**−216,057**	**−8157**
19	DR Korea	41.00	21.09 [−49%]	**−209,621**	**−9.047**
20	Burkina Faso	79.81	34.64 [−57%]	**−206,691**	**−4301**
21	Senegal	103.73	33.31 [−68%]	**−194,609**	**−5111**
22	Iraq	65.42	27,33 [−58%]	**−194,020**	**−6251**
23	Japan	12.53	7.05 [−44%]	**−190,996**	**−11,610**
24	Yemen	64.34	12.00 [−81%]	**−187,702**	**−5047**
25	Guinea	78.47	29.07 [−63%]	**−176,165**	**−3771**
26	Russia	3.29	2.09 [−37%]	**−175,918**	**−8925**
27	Cameroon	49.28	26.35 [−47%]	**−174,854**	**−3622**
28	Laos	134.95	34.20 [−75%]	**−154,851**	**−4166**
29	Brazil	6.03	3.74 [−38%]	**−151,322**	**−6336**
30	Thailand	34.40	16.89 [−51%]	**−141,147**	**−5685**
31	Iran	33.12	14.26 [−57%]	**−138,746**	**−6358**
32	Côte d’Ivoire	38.58	16.56 [−57%]	**−123,258**	**−2752**
33	Nepal	37.21	28.85 [−22%]	**−119,319**	**−4289**
34	Colombia	18.35	10.00 [−46%]	**−119,130**	**−5243**
35	Congo DR	14.84	10.80 [−27%]	**−109,275**	**−2054**
36	Mauritania	113.31	21.76 [−81%]	**−106,973**	**−2303**
37	Sierra Leone	75.40	23.66 [−69%]	**−103,114**	**−2266**
38	Ghana	49.27	22.89 [−54%]	**−94,944**	**−2775**
39	Chile	8.60	3.33 [−61%]	**−91,702**	**−4455**
40	Syrian Arab Republic	44.39	22.60 [−49%]	**−82,341**	**−3311**
41	Turkey	13.48	7.81 [−42%]	**−79,542**	**−3461**
42	Benin	61.28	27.52 [−55%]	**−69,186**	**−1345**
43	Malaysia	13.59	5.90 [−57%]	**−68,465**	**−2724**
44	Guatemala	40.11	11.38 [−72%]	**−63,437**	**−1980**
45	Haiti	24.80	9.20 [−63%]	**−63,354**	**−1766**
46	Morocco	27.56	5.90 [−50%]	**−57,008**	**−2691**
47	Ethiopia	20.27	13.30 [−34%]	**−56,294**	**−1280**
48	South Sudan	39.58	23.27 [−41%]	**−55,947**	**−998**
49	Cambodia	47.79	17.67 [−63%]	**−55,843**	**−1724**
50	Venezuela	16.17	7.24 [−55%]	**−45,261**	**−1907**
51	Uzbekistan	25.09	12.16 [−52%]	**−44,100**	**−1805**
52	Peru	5.94	4.49 [−24%]	**−43,536**	**−1794**
53	Libya	79.65	12.65 [−84%]	**−40,488**	**−1586**
54	Somalia	15.74	6.12 [−61%]	**−40,184**	**−623**
55	Sri Lanka	21.55	13.49 [−37%]	**−40,079**	**−1654**
56	Turkmenistan	28.43	15.06 [−47%]	**−36,702**	**−1305**
57	Argentina	6.12	3.64 [−41%]	**−35,376**	**−1779**
58	Dominican Republic	25.58	8.95 [−65%]	**−35,302**	**−1380**
59	Togo	54.84	25.98 [−53%]	**−34,637**	**−805**
60	UAE	79.41	15.44 [−81%]	**−32,864**	**−869**
61	Uganda	16.39	10.79 [−34%]	**−32,578**	**−642**
62	CAF	49.91	29.97 [−40%]	**−32,128**	**−674**

63	El Salvador	48.74	10.57 [−78%]	**−31,487**	**−1426**
64	Ukraine	6.94	5.70 [−18%]	**−30,239**	**−1611**
65	Algeria	67.05	20.12 [−70%]	**−28,523**	**−1098**
66	Gambia	96.73	36.07 [−63%]	**−28,479**	**−655**
67	Lebanon	36.85	20.14 [−45%]	**−28,453**	**−1367**
68	Canada	1.00	0.77 [−23%]	**−28,230**	**−1497**
69	Romania	8.42	6.36 [−24%]	**−26,036**	**−1418**
70	Jordan	54.94	12.88 [−77%]	**−25,171**	**−937**
71	Tanzania	5.67	2.83 [−50%]	**−25,075**	**−574**
72	South Africa	11.24	4.61 [−59%]	**−23,956**	**−760**
73	Guinea−Bissau	88.07	32.12 [−64%]	**−23,582**	**−468**
74	Afghanistan	22.92	14.04 [−39%]	**−23,285**	**−540**
75	Israel	52.89	17.89 [−66%]	**−22,654**	**−1227**
76	Angola	6.42	2.91 [−55%]	**−21,834**	**−382**
77	Kuwait	102.18	32.21 [−68%]	**−21,474**	**−664**
78	Qatar	84.64	20.91 [−75%]	**−21,457**	**−622**
79	Greece	12.79	4.85 [−62%]	**−19,301**	**−1147**
80	Bulgaria	9.77	5.06 [−48%]	**−18,738**	**−1015**
81	Australia	19.56	3.38 [−83%]	**−18,118**	**−1057**
82	Honduras	26.58	13.70 [−48%]	**−18,097**	**−703**
83	Ecuador	13.35	7.80 [−42%]	**−17,392**	**−736**
84	Cuba	12.52	7.67 [−39%]	**−17,241**	**−877**
85	Tunisia	45.76	14.42 [−68%]	**−17,028**	**−788**
86	Liberia	30.90	8.96 [−71%]	**−16,825**	**−383**
87	Kazakhstan	10.05	6.48 [−36%]	**−15,329**	**−679**
88	Singapore	64.49	25.35 [−61%]	**−11,832**	**−537**
89	Oman	66.80	11.83 [−82%]	**−9612**	**−324**
90	Spain	6.47	4.77 [−26%]	**−8932**	**−543**
91	Kenya	9.20	5.59 [−39%]	**−8222**	**−140**
92	Mozambique	3.80	2.25 [−41%]	**−8209**	**−158**
93	UK	5.06	4.14 [−18%]	**−7558**	**−416**
94	Azerbaijan	11.55	8.92 [−23%]	**−6922**	**−298**
95	Mongolia	20.92	5.92 [−71%]	**−6510**	**−231**
96	Poland	6.87	6.16 [−10%]	**−6493**	**−345**
97	Tajikistan	7.09	7.62 [7%]	**−6073**	**−217**
98	Portugal	7.28	4.09 [−44%]	**−5830**	**−349**
99	Belarus	5.35	4.20 [−21%]	**−5725**	**−296**
100	Georgia	7.82	5.14 [−34%]	**−5573**	**−303**
101	Papua New Guinea	5.39	2.79 [−48%]	**−5246**	**−142**
102	Bahrain	97.49	37.87 [−61%]	**−5007**	**−172**
103	Panama	13.30	18.93 [−26%]	**−4970**	**−228**
104	Serbia	8.62	5.28 [−60%]	**−4859**	**−243**
105	Bhutan	25.49	6.44 [−25%]	−4708	−143
106	Nicaragua	14.32	6.42 [−55%]	−4607	−162
107	Costa Rica	14.69	4.73 [−68%]	−4600	**−230**
108	Jamaica	25.67	10.54 [−59%]	**−4592**	**−243**
109	Burundi	11.96	9.87 [−17%]	**−4479**	**−88**
110	Zambia	4.16	2.21 [−47%]	**−4445**	**−87**
111	Hungary	8.06	6.67 [−17%]	**−4366**	**−229**
112	Albania	10.32	4.60 [−55%]	**−4251**	**−226**
113	Paraguay	9.00	7.48 [−17%]	**−4020**	**−161**
114	Eritrea	30.16	20.08 [−33%]	**−3933**	**−94**
115	Malawi	4.63	2.91 [−37%]	**−3544**	**−77**
116	Bosnia and Herzegovina	7.67	4.78 [−38%]	**−3381**	**−176**
117	Rwanda	18.19	15.53 [−15%]	**−3270**	**−81**
118	Namibia	14.40	2.32 [−84%]	**−3232**	**−100**
119	Republic of Moldova	7.71	5.53 [−28%]	**−3203**	**−164**
120	New Zealand	5.74	1.95	**−3074**	**−172**
121	Sweden	2.87	1.56 [−45%]	**−3013**	**−181**
122	Djibouti	25.86	11.00 [−57%]	**−2926**	**−79**
123	Madagascar	2.60	2.01 [−23%]	**−2644**	**−65**
124	Croatia	8.44	6.37 [−25%]	**−2556**	**−145**
125	Armenia	10.59	7.68 [−27%]	**−2307**	**−120**
126	Cyprus	21.41	7.83 [−63%]	**−2225**	**−126**
127	Uruguay	6.09	3.64 [−40%]	**−2020**	**−106**
128	Lesotho	9.57	4.30 [−55%]	**−1933**	**−58**
129	Cape Verde	52.28	12.22 [−77%]	**−1841**	**−97**
130	Denmark	5.69	3.96 [−30%]	**−1747**	**−95**
131	Zimbabwe	3.96	2.75 [−30%]	**−1743**	**−41**
132	Macedonia	8.76	5.52 [−37%]	**−1729**	**−81**
133	Latvia	6.33	4.97 [−21%]	**−1524**	**−87**
134	Finland	2.40	1.57 [−35%]	**−1408**	**−81**
135	Trinidad and Tobago	12.04	6.71 [−44%]	**−1231**	**−54**
136	Norway	2.21	1.55 [−30%]	**−1201**	**−69**
137	Slovakia	7.57	6.62 [−13%]	**−1198**	**−61**

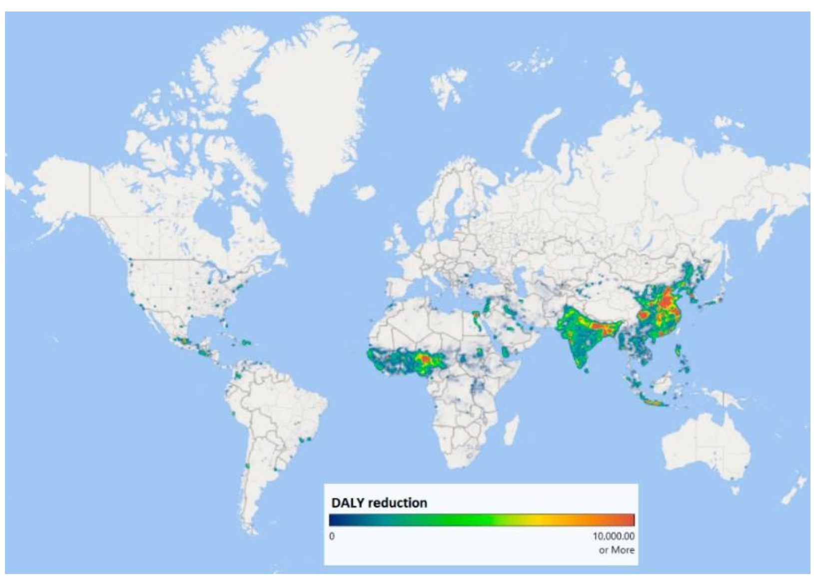
138	Equatorial Guinea	10.64	6.95 [−35%]	**−1120**	**−24**
139	Montenegro	8.65	3.99 [−54%]	**−1080**	**−59**
140	Ireland	5.61	4.16 [−26%]	**−1079**	**−59**
141	Botswana	7.99	2.51 [−69%]	**−1017**	**−35**
142	Gabon	8.03	5.02 [−38%]	**−1004**	**−30**
143	Lithuania	6.19	5.29 [−15%]	**−983**	**−59**
144	Suriname	10.67	3.65 [−66%]	**−968**	**−39**
145	Estonia	5.82	3.94 [−32%]	**−754**	**−44**
146	Congo	13.22	9.49 [−28%]	**−753**	**−18**
147	Swaziland	9.97	6.18 [−21%]	**−728**	**−19**
148	Guyana	9.94	4.52 [−55%]	**−709**	**−27**
149	Malta	20.97	6.87 [−67%]	**−709**	**−41**
150	Brunei Darussalam	25.30	10.55 [−58%]	**−707**	**−26**
151	Timor−Leste	4.47	2.18 [−51%]	**−575**	**−14**
152	Fiji	4.17	2.20 [−47%]	**−377**	**−13**
153	Bolivia	4.03	3.63 [−10%]	**−372**	**−14**
154	Belize	12.95	6.43 [−50%]	**−270**	**−11**
155	Solomon Islands	3.13	0.98 [−69%]	**−162**	**−5**
156	Barbados	11.53	7.41 [−36%]	**−115**	**−6**
157	Mauritius	7.09	6.05 [−15%]	**−99**	**−4**
158	Maldives	14.25	7.67 [−46%]	**−78**	**−3**
159	Vanuatu	4.55	2.54 [−44%]	**−71**	**−2**
160	Saint Vincent	10.52	6.81 [−35%]	**−61**	**−3**
161	Saint Lucia	9.61	6.78 [−29%]	**−57**	**−3**
162	Grenada	11.32	7.20 [−36%]	**−47**	**−2**
163	Sao Tome and Principe	4.99	3.27 [−34%]	**−32**	**−1**
164	Iceland	1.40	1.31 [−6%]	**−23**	**−1**
165	Tonga	5.36	3.21 [−32%]	**−18**	**−1**
166	Micronesia (Federated States of)	7.39	4.28 [−42%]	−17	-1
167	Samoa	2.47	1.36 [−42%]	**−17**	**−1**
168	Antigua and Barbuda	6.84	5.32 [−22%]	**−10**	**0**
169	Seychelles	3.62	2.28 [−37%]	**−9**	**0**
170	Kiribati	4.22	3.50 [−17%]	**−4**	**0**
171	Comoros	5.63	5.30 [−6%]	**−2**	**0**
172	Bahamas	5.60	7.12 [+27%]	**83**	**3**
173	Luxembourg	5.20	6.62 [+27%]	**112**	**6**
174	Slovenia	7.13	7.44 [+4%]	**186**	**11**
175	Czechia	7.28	7.44 [+2%]	**357**	**20**
176	Netherlands	6.36	6.43 [+1%]	**811**	**44**
177	Kyrgyzstan	7.26	6.92 [−5%]	**845**	**37**
178	Austria	5.19	6.29 [+21%]	**1148**	**70**
179	Belgium	6.43	7.18 [+12%]	**1327**	**75**
180	France	6.48	6.19 [−4%]	**1616**	**92**
181	Switzerland	2.92	6.32 [+117%]	**4744**	**283**
182	Germany	5.25	6.12 [+17%]	**23,150**	**1373**
183	Italy	7.52	8.19 [+9%]	**26,943**	**1826**

The $PM_{2.5}$ concentration was generally low in Western Europe in the first quarter of the year; events related to lockdowns, such as the reduction in transportation or the temporary reduction in industrial activity, did not affect the level of pollution.

The total reduction in the burden globally was 34.4 million DALY (or 1.3 million deaths), confirming that the actions taken against the COVID-19 pandemic indirectly helped to improve air quality.



(a)



(b)

Figure 5. 9 ***DALY reduction Q1 2020 vs. Q1 2019: (a) by country; (b) by grid.***

The results for each city were also observed: the top 10 is occupied by Chinese cities (eight) and Indian cities (two). With these cities having a high population density and being among the most polluted cities in the world, these results were expected (Table 5.6).

Table 5.6 Comparison of the burden of air pollution at the city(area) level between Q1 2019 and Q2 2020 (top10 DALY reduction).

Rank	**City/Area [Country]**	**Average Concentration Q1 2020 (μg/m3) [Difference in %]**	**∆Burden (DALY) (Year)**	**∆Burden (Death) (Person)**
1	Beijing [CHN]	51.24 [−40%]	−405,447	−18,922
2	Chongqing [CHN]	36.33 [−53%]	−389,247	−18,110
3	Shanghai [CHN]	26.28 [−57%]	−323,425	−15,104
4	Chengdu [CHN]	48.61 [−49%]	−297,614	−13,889
5	Xian [CHN]	53.02 [−52%]	−274,686	−12,788
6	Tianjin [CHN]	48.76 [−47%]	−236,113	−11,014
7	Wuhan [CHN]	48.58 [−53%]	−235,140	−10,691
8	Hangzhou [CHN]	27.37 [−54%]	−210,310	−9,808
9	New Delhi [IND]	54.95 [−37%]	−190,616	−6,325
10	Kolkata [IND]	59.75 [−39%]	−189,12	−6,502

To confirm the validity of the results, we compared the results obtained in this study with the level of confinement in the different countries. The duration of these confinements was considered, as shown in Table 5.7 and Figure 5.8.

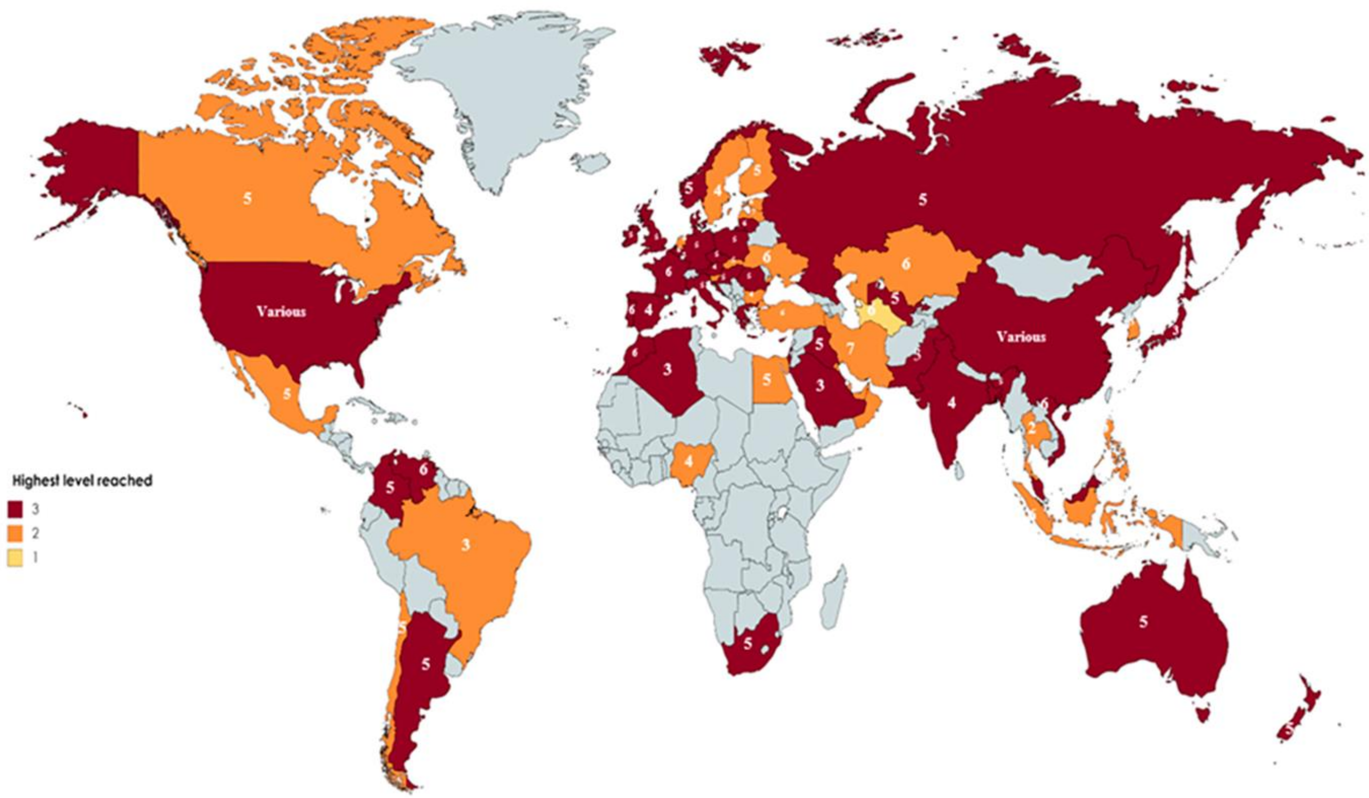


Figure 5. 10 Highest confinement level by country between 1 January and 30 April 2020 (numbers represent the number of weeks under the highest level).

Table 5.7. Definition of the confinement level [48].

Level	Description
0	No restrictions
1	Low restrictions (e.g., public gatherings >5000 people forbidden)
2	Medium restrictions (e.g., borders closed, public gatherings >100 people forbidden, schools and restaurants closed)
3	High restrictions (e.g., household confinement as much as possible, public gatherings banned)

From the previous information, it was confirmed that the countries with the highest burden reduction adopted strict measures to stop the progress of the COVID-19 pandemic. It can also be supposed that the reduction of pollutant emissions in each country probably improved the air quality in the surrounding countries (even though these surrounding countries adopted less strict measures). Several studies highlighted the importance of the air pollution transboundary effect [49-51].

The results were also compared with the annual estimation of the WHO [52]. A comparison for the countries experiencing a reduction in burden above 500,000 DALY according to our results is shown in Table 4.

Table 5.8. Comparison between this study and the annual burden of air pollution.

Rank	Country	Reduction (DALYs)	Annual Impact (DALYs)	Reduction (%)
1	China	−13,904,672	25,824,548	−54%
2	India	−6,300,012	33,727,823	−19%
3	Nigeria	−2,296,551	7,523,259	−31%
4	Indonesia	−938,082	2,953,382	−32%
5	Pakistan	−822,236	4,705,933	−17%
6	Bangladesh	−728,264	2,580,528	−28%
7	Egypt	−567,987	2,068,658	−27%
8	Niger	−531,374	841,844	−63%

Except for China (54%) and Niger (63%), all of the results were below 50%. Even though direct comparison of the results is difficult (2020 vs. 2016), several studies, such as in China [53,54], showed that the monthly concentration at the end and the beginning of each year are much more important than during the rest of year. This would explain why the reduction in each country was within the range of 20–50%. To confirm this observation, the monthly average for 2019 of each country listed above was collected (Figure 5.9). In these countries, the level of air pollution in the first quarter of the year (as well as the last quarter of the year) was the highest.

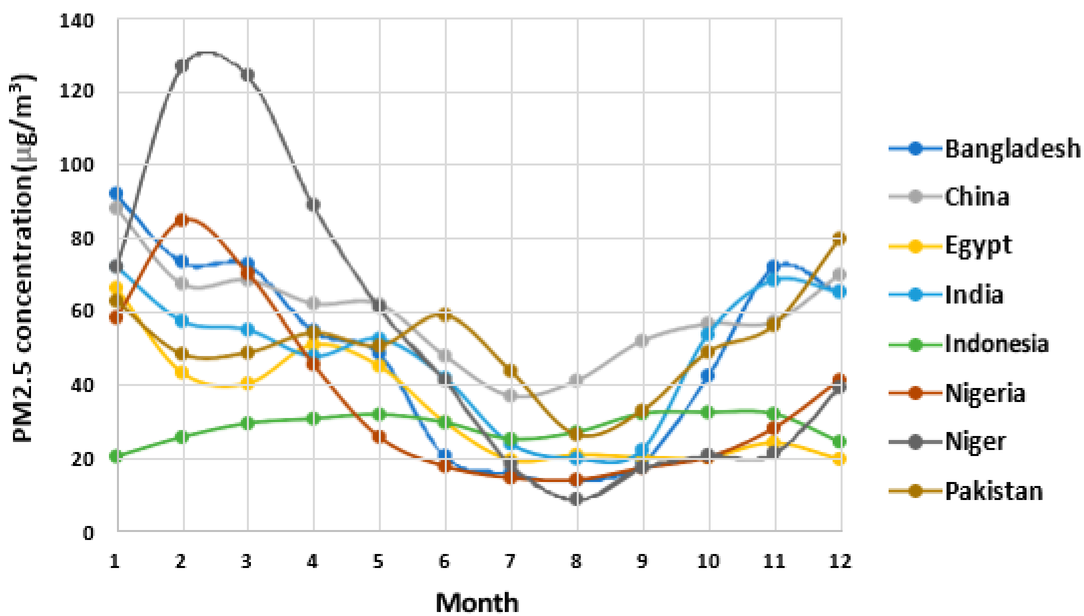


Figure 5. 11 Monthly population-weighted PM2.5 (μg/m3) concentration in 2019

5.3 Discussion

5.3.1 Comparison with the number of DALYs caused by the COVID-19 pandemic

The discussion in this section has to be interpreted with a lot of caution, it is only provided as an indication. The aim is not to minimize the COVID-19 (which is a very serious disease) but rather to highlight that air pollution is a very important issue to tackle. The results found in the section 5.2 were compared with the burden caused by the COVID-19 pandemic. To calculate the burden of the COVID-19 (in DALYs), even if the information is relatively scarce, the average death from the COVID-19 was calculated using information collected for several Africa countries ([55-58]). Based on World Bank regional division, it was found that for North Africa the average death was around 66.5 years old, for the rest of Africa (except South Africa): 55 years old, and for South Africa: 64 years old. The number of deaths for each African country was collected from official source [X]. By combining these two information, it is possible to calculate the burden from COVID-19 as follows (it is assumed that YLL=DALY as the information it is still scarce). The following equation were used to calculate the burden from COVID-19:

$$DALY/Death_{Country,COVID-19} = Life\ Expectancy_{Country} - Age\ of\ Death_{Country,COVID-19}$$

$$Burden\ from\ COVID19_{Country}\ (DALY) = Number\ of\ Death\ COVID19_{Country} * DALY/Death_{Country,COVID-19}$$

The highest burden was calculated for Tunisia (49,098 DALYs), South Africa (48,397) and Morocco (48,022). The comparison between the COVID-19 burden and results obtained in section 5.2 is provided in Table 5.9 and Figure 5.11

Table 5.9 Comparison of the COVID-19 burden with results obtained in section 5.2

	Death COVID-19	DALY COVID-19	DALY reduction air pollution
Algeria	2,756	29,214	28,523
Angola	405	3,281	21,834
Benin	44	370	69,186
Botswana	42	302	1,017
Burkina Faso	85	655	206,691
Burundi	2	18	4,479
Cameroon	448	3,315	174,854
Cape Verde	113	2,147	1,841
Chad	104	478	335,997
Democratic Republic of the Congo	591	4,373	109,275
Djibouti	61	659	2,926
Egypt	7,631	40,444	567,987
Equatorial Guinea	86	619	1,120
Eritrea	3	27	3,933
Eswatini	205	554	728
Ethiopia	1,923	26,345	56,294
Gabon	64	736	1,004
Gambia	124	1,302	28,479
Ghana	335	3,786	94,944
Guinea	81	486	176,165
Guinea-Bissau	45	234	23,582
Ivory Coast	137	1,082	123,258
Kenya	1,670	18,537	8,222
Liberia	83	755	16,825
Libya	1,478	13,745	40,488
Madagascar	261	2,688	2,644
Malawi	189	2,003	3,544
Mali	269	2,098	371,698
Mauritania	347	4,650	106,973
Mauritius	10	191	99
Morocco	7,388	48,022	57,008
Mozambique	166	515	8,209
Namibia	205	1,968	3,232
Niger	104	863	531,374
Nigeria	1,289	9,796	2,296,551
Republic of the Congo	108	1,048	753
Rwanda	92	1,297	3,270
São Tomé and Príncipe	17	262	32
Senegal	410	5,576	194,609
Sierra Leone	76	441	103,114
Somalia	130	195	40,184
South Africa	28,469	48,397	23,956
South Sudan	63	491	55,947
Sudan	1,468	20,699	326,182
Tanzania	21	258	25,075
Togo	68	632	34,637
Tunisia	4,676	49,098	17,028
Uganda	251	2,937	32,578
Zambia	388	2,910	4,445
Zimbabwe	363	2,069	1,743

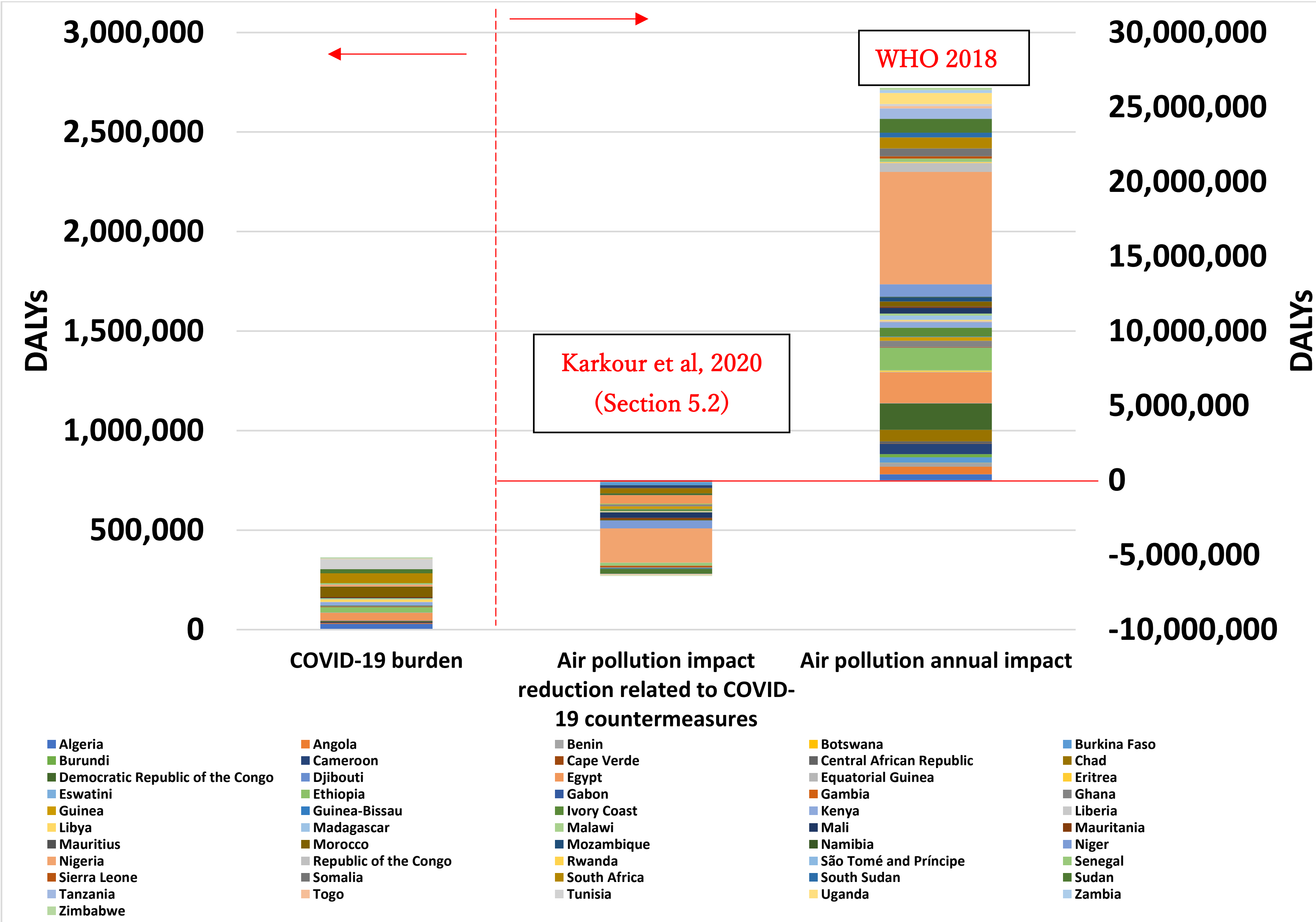


Figure 5. 12 Comparison of the COVID-19 burden with results obtained in section 5.2 and annual impact caused by air pollution (WHO)

As it can be observed in Figure 5.11 the impact caused by COVID-19 is lower than the estimated reduction of air pollution due to the countermeasures. The comparison especially with the annual damage estimated by the WHO shows the importance to tackle air pollution impact as soon as possible. The impacts caused by air pollution (26,000,000 DALYs) occur on annual basis and the COVID-19 pandemic provides a nice occasion to rethink about the magnitude of environmental impacts.

5.3.2 Why have air pollution levels not dropped to zero during lockdowns?

One of the first questions that one may ask could be: “why have air pollution levels not dropped to zero and even increased in some areas where a lockdown was active?”.
It should be clarified that PM2.5 emissions as a primary source, followed by NOx, SO2 and, NH3 as secondary sources, contribute to the PM2.5 concentration.
There are several reasons that the PM2.5 concentration did not fall to zero: electricity generation from industry decreased [60], but electricity generation in the residential sector did not stop during the lockdown period [61]. Many countries (e.g., in Asia) still rely considerably on coal-fired power plants, which emit a large amount of PM2.5, NOx and SO2 (especially when technologies such as electrostatic precipitators (ESP), selective catalytic redactors (SCR) and flue-gas desulfurization (FGD) are not applied), thereby contributing to the PM2.5 concentration. According to the user data provided by Apple [62], in different cities all around the world, key workers were still active during lockdowns. Shipments by heavy trucks, one of the major contributors of NOx emissions, were popular during the different lockdowns. Finally, agriculture, a major source of NH3 emissions, also contributed to keeping the PM2.5 concentration at a certain level.

5.3.3 Post-COVID green recovery

The second question is how to maintain low air pollution emissions globally in the future in the post-COVID society?

There are several political actions that can support the post-COVID green recovery as listed in Table **5.10**

Table 5.10 Example of policies with field of application

Type of policy/Field of application	Example	Country of application (World)	Country of application (Africa)
Agriculture sector	Tax reduction to support green farms	France [63]	-
Transport sector	Incentives to buy zero-emission vehicle/modification of city architecture	France [64,65]	-
Energy sector	Invest into renewables/Cut subsidies for fossil fuels	New Zealand [66]	Ethiopia [67]
Environmental tax (All sectors)	Implement taxes on combustion emissions	Sweden [68]	South Africa [69]
Employment (All sectors)	Support the reskill/training of workers for green jobs	UK [70]	-

➔ Agriculture sector:

For the agriculture sector, in the EU, it has been shown that 60% of the total NH3 emissions could be reduced by better manure management and 25% by using better fertilizer [71]. Therefore, tax reduction could be provided to farmers wishing to reduce their farms' environmental impacts; such policy is undergoing discussion in France [63].

➔ Transport sector:

In several countries around the world (Europe, South America) architecture of cities has been modified [65] after the lockdowns as the number of people walking and using bicycles increased. Cycling tracks have been extended (Paris, for example, is currently opening 150km of pop-up cycle lanes), and incentives have been deployed, such as in France to encourage people to repair their bikes (50$/people) [72]. The French COVID-19 stimulus package also includes a bonus of 7.000$ to purchase a battery electric vehicle (BEV) [65]. To reach a zero-emission society, half of the 100 million passenger cars sold worldwide should be electric by 2030 [X103].

Moreover, even though the technology is still under development. Policies could support the research and development of green hydrogen as it could bring down emissions to zero (also for aircraft) by 2050. It also has the opportunity to create several jobs [74]

➔ Energy sector:

The shift to renewables energies is also a major solution to reducing pollutants' emissions, especially in developing countries or newly industrialized countries (as shown in Chapter 1). To keep a safe environment in the future, it would be needed for the global electricity mix to shift from 37% in 2020 to 15% in 2030 and 5% in 2040. The renewables mainly (Hydro, Solar and Wind) should reach 72% by 2040. About 30 trillion dollars would be needed to realize it. The global subsidies for fossil fuel fuels reached 4.5 US billion dollars in 2015 [75], with more than 2 billion in Asia. It is estimated that about 50% of air pollution deaths could be removed if these energy subsidies would be removed, as shown in Figure 5.10.

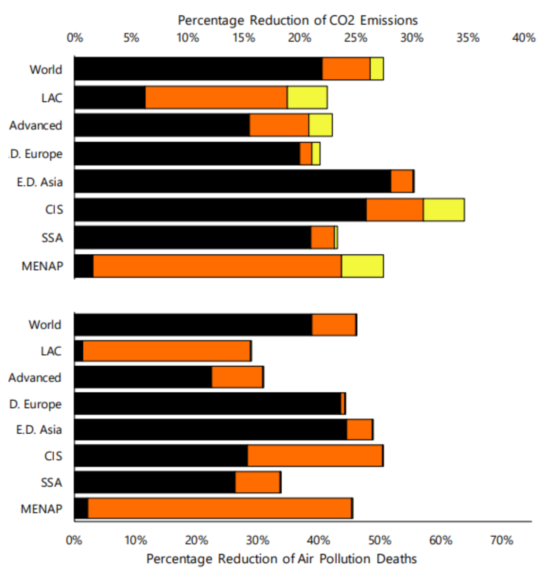


Figure 5. 13 Environmental Gains from Removing Energy Subsidies, 2015 [75]

➔ Environmental taxes:

On the opposite, in addition to emissions standards, environmentally related tax revenue (ERTR) is also an option to tackle the damages caused by air pollution. In the OECD [76], these taxes are mostly applied to energy, especially motor fuels. They are still not used enough, and the revenue from ERTR even decreased since 2000, representing only 5.3% of the total tax revenue in 2018. Table 5.11 shows their amount as % of the countries total GDP.

Table 5.11 ERTR as % of annual country GDP 2017-2018 [76].

Country	ERTR as % total GDP	ERTR directly related to pollution as % total GDP
Denmark	3.625	0.096
Netherlands	3.338	0.176
South Africa	2.685	0.019
Portugal	2.603	0.019
United Kingdom	2.295	0.04
France	2.344	0.423 (2013)
Germany	1.786	0
Japan	1.345	0.006
India	1.251	0.002 (2014)
Egypt	1.025	0
United States	0.713	0.008 (2015)
Morocco	0.693	0
Nigeria	0.019 (2015)	0

As it can be seen, pollution tax bases do not represent a significant revenue source in recent years. Taxes related to pollution could be an option to reduce labor taxes and prioritize the reduction of environmental impacts. In Sweden, for example, a tax on nitrogen oxide (NOx) emissions from energy generation (about 4,500$/ton) helped to reduce emissions from 0.4kg/GWh to 0.18kg/GWh [68].

➔ Employment:

Finally, any green recovery must promote a reskill of workers. According to research published in the UK [70], 2.1 million workers (10% of the active population in the UK) will need to reskill in the future to enter a net-zero (carbon) emissions society by 2050. Additionally, more than 4,000,000 jobs will be impacted in the country. It has been shown globally that spending on renewable energy and energy efficiency would create more jobs than spending on fossil fuel [77]. Per 10 million dollars spent in either renewables technologies, energy efficiency, or fossil fuel, 75, 77, and 27 jobs are created, respectively. It is especially necessary to support the communities that have been relying on revenues from fossil energies (e.g., coal miners) for long years.

5.4 Limitations

In order to calculate the reduction of human health burden at global scale it was chosen to consider input information from satellite data as the ground-stations are limited. Even satellite payloads have been improved a lot in recent years the average uncertainty remain globally around 20%. A second point to highlight is that the estimations are based on models they do reflect the clinical situation even though several studies reported a reduction of air pollution related disease during or post-lockdown. Finally similarly to chapter 3, the data from the WHO were collected based on country's average information, it does not reflect the specific characteristics (urban,rural) of population within a country. A comparison of the approach using satellite data vs. traditional LCA approach is provided in Table 5.12.

Table 5.12 Advantanges/Disadvantages of using satellite data vs. conventional LCA data

	Conventional LCA data	Satellite data
Advantages	1- Lower uncertainty	1- Can be used to assess a specific area within a specific period 2- Can analyzed data at a resolution that traditional LCA cannot evaluate
Disadvantages	1- Data limited in time and location 2- Difficult to collect information especially in developing countries at the moment	1-Precision is lower than conventional LCA 2- Top-down approach (similar to IO LCA), difficult to confirm the source

5.5 Summary

Several points have been raised in this chapter:

- The countermeasures against the COVID-19 helped to reduce the air pollution indicators by nearly 30%, especially when full lockdowns were implemented.
- Following the review made using the research articles published in 2020, it could be shown that global pandemics such as the COVID-19 pandemic are strongly related to other environmental impacts. COVID-19 is linked to air pollution, in the way that damages from air pollution through the body cell receptors ACE-2 can amplify the fatality of the COVID-19. Is not clear yet if the virus can be transported through aerosols but still, it highlights to importance to diminish all types of environmental impacts in the post-COVID recovery
- The improvement of air quality helped to reduce the environmental burden caused by air pollution, especially due to the reduction in transport and electricity generation. To keep a clean air in the post-COVID society, several can be achieved, such as modifying the architecture of cities to encourage low-emission means of transport. Invest more in renewable energies to produce electricity. Decrease the subsidies provided to fossil fuels. Implement taxes related to air pollution emissions. Support the reskill of communities which have been linked to revenues from fossil fuels for long years.

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Chapter 6: Conclusions

6.1 Results obtained in this thesis

In this thesis, the environmental impact of air pollution in Africa was quantified. This is a primordial step for LCA studies conducted in Africa. At first damage, factors were developed for African regions/countries based on a chemical transport model. Later, these damage factors were applied to African sectors of activity using a multi-regional input-output analysis. This thesis also analyzes the latest air pollution trends, detailing the link between air pollution and COVID-19.

Chapter 1 summarizes the current trend of environmental impact in Africa. Especially the impact of air pollution is highlighted with more than 1,000,000 deaths occurring annually in the continent. The importance of regionalization in LCA is also highlighted. Regionalization consists of developing specific tools to conduct LCA at a higher resolution. Specific tools for African LCA have not been developed yet, and the research networks are also limited. The results obtained so for air pollution model are still rough and diverse. Therefore the need to increase the accuracy was highlighted.

Chapter 2 describes this thesis's research plan: at first, the damage factors for air pollution are obtained using a chemical transport model. Then these factors are applied to African sectors of Activity using a multi-regional input-output table: EORA. Later the global reduction of air pollution burden is also quantified for 2020 due to COVID-19 countermeasures.

Chapter 3 describes the method for obtaining the air pollution damage factors in 20 African regions. A chemical transport model is used, and 80 simulations (4 pollutants x 20 regions) are conducted using supercomputers. The output of each analysis is provided. The highest damage factors are obtained for BCOC, the lowest for NH3. Overall, the impacts are the highest in Egypt and Nigeria due to the higher population number and density. The transboundary effect was also quantified for the regions.

Chapter 4 quantifies the impact of each African sector of activity using the damage factors for air pollution developed in Chapter 3. A multi-regional input-output is used to link all the global sectors of activity together (more than 14,000 sectors). Two approaches are considered, the production-based approach (what the country produces) and the consumption-based approach (what the country consumes). Overall, contrary to G20 countries, the African country's production-based impacts are mainly occurring inside Africa. It is explained by the fact that countries are not importing/exporting a lot. The production is mainly consumed inside Africa. Agriculture and transport sectors are identified as key polluters due to the burning of forest and second-hand vehicles, respectively.

Chapter 5 details the latest information in 2020 with the relationship between COVID-19 and air pollution. 3 links are highlighted:

- The reduction of air pollution due to lockdown countermeasures
- The link with air pollution and COVID-19 number of case/mortality
- The reduction of human health burden due to air pollution reduction

It was shown that important human health burden could be reduced. In the discussion, policy suggestions are provided for the COVID-19 post green recovery.

6.2 Policy recommendation

Based on the results obtained in Table 4.4, it was found that 3 sectors are mainly responsible for the human health damage from air pollution in Africa: Agriculture, Transport and Electricity. Therefore African countries can be classified in three groups following on which sector should be prioritized first. The grouping is provided in Table 6.1:

Table 6.1 Sectors to prioritize for policy makers

Agriculture	Algeria, Benin, Burkina Faso, Cameroon, Chad, Congo, Cote d'Ivoire, DR Congo, Gabon, Gambia, Ghana, Guinea, Lesotho, Liberia, Madagascar, Malawi, Mali, Niger, Nigeria, Senegal, Sierra Leone, Somalia, Swaziland, Tanzania, Togo, Uganda
Electricity	Cape Verde, Djibouti, Eritrea, Libya, Mauritania, Morocco, South Africa, Tunisia
Transport	Angola, Egypt, Kenya, Mozambique

It has to been noted that even the total impacts of Mining and Quarriying sector is shown lower that the 3 sectors detailed above, This sector is the leading source of impact in Angola (17,779 DALY), Kenya (36,288 DALYs) and Rwanda (15,005 DALYs). Also in country such as Nigeria, not only the agriculture sector should be reformed but also the transport sector. Examples of policies are provided in the following three subsections **6.2.1-6.2.3**.

6.2.1 Agriculture

In Chapter 3, we developed damage factors for air pollution that we applied to EORA IO database. We found that the impact of the agriculture sector was particularly high. This is especially due to "slash and burn" culture, which has lasted for many years in Africa, especially in Western Africa and RD Congo. Even though the Agriculture sector employs 20% of the population in Sub-Sahara Africa, the average annual income is still low compared to non-farm workers (2.989$ vs. 4,991$). Fiscal incentives could support farmers in changing their environmental practices based on the example of the EU. At the moment, there are actually disincentives in several African with a high burden put on farmers (26% in Nigeria). Standards could also be established to ban agricultural burning.

Awareness campaigns can also play an important role for both producers and consumers as shown in Figure 6.1. Through the raise of awareness, the formation of farmers' community can be encouraged where farmer-to-lander learning can facilitate the development of new technologies/practices (referred to as social capital). It was shown in a previous study conducted in Southern Africa [1] that awareness was more or less equal to adoption when it comes to environmental-friendly agriculture practices. The study showed that the chance that a farmer follow good practices increased (odds ratio 1.7 and 2.6, respectively, shown in Table **6.2**) when she/he is member of an organization or as access to advice. It encourages governments to push for farmer cooperatives to accelerate innovation. It is further confirmed in Cameroon where better practices were adopted in slash and burn regions for farmers members of a formal club [2].

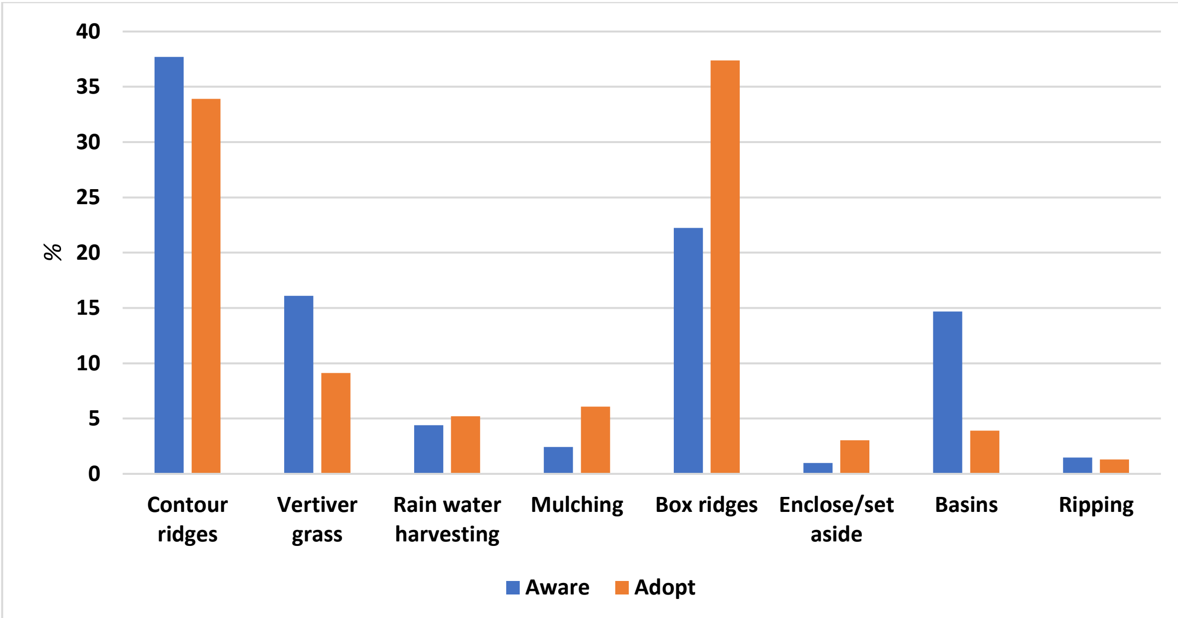

Figure 6. 1 Awareness vs Adoption for environmental-friendly practices in Southern Africa [1]

Table 6.2 Main parameters affecting the adoption of sustainable environmental practice (adapted from [1])

Variable	Adoption Odds ratio	Awareness Odds ratio
Age of household head in years	1.0	1.0
Gender of household head	1.0	0.8
Years of formal education	1.1	1.2
Access to agricultural advice	1.7	2.6
Membership to community group/organisation	2.6	2.1

Finally, generally speaking, tax can be applied to limit wrong practices. Environmentally related tax revenue (ERTR) is an option to tackle the damages caused by air pollution. Except in South Africa & Uganda, this type of tax still does not provide an important revenue source to African countries.

6.2.2 Transport

Another burden is caused by the use of second-hand vehicles in Africa. This explains the burden of the transport sector. About 70% of these vehicles are imported from Europe and many of these vehicles are under the EURO4 standards (legislation adopted 15 years in European countries). An overview of the Euro standards is provided in Table 6.3.

Table 6.3 Euro standards for vehicles (P:Petrol; D:Gasoline) [3]

Certification for vehicles	Year of application (EU)	NOx (g/km)	PM2.5 (g/km)
Euro 1	1994	0	0.14 (D)
Euro 2	1999	0	0.08 (D)
Euro 3	2002	0.15 (P)/0.5 (D)	0.05 (D)
Euro 4	2007	0.06 (P)/ 0.25 (D)	0.025 (D)
Euro 5	2012	0.180 (P)	0.045
Euro 6	2016	0.06 (P)/ 0.08 (D)	0.045

Therefore, the emissions are higher than the current global emissions standards. The mileage of these vehicles is usually high, over 200,000km, with poor catalytic converters. As a result, the pollutant emissions are particularly high. Two major policies exist to mitigate emissions from transport as shown in Figure 6.2.

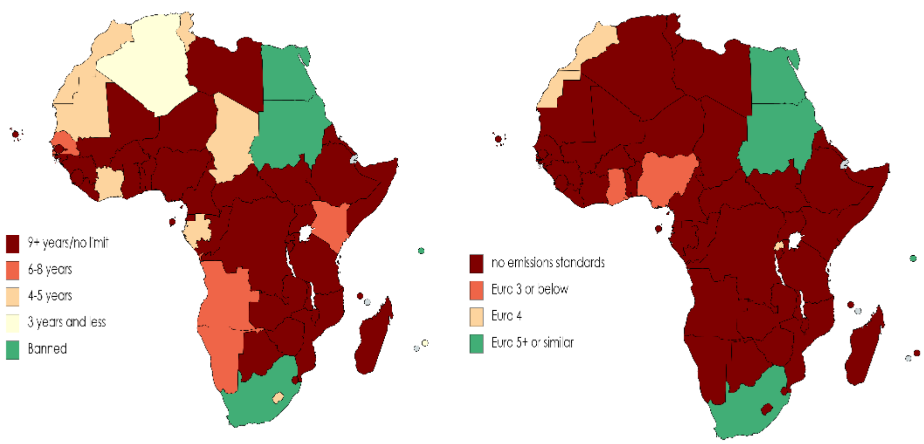

Figure 6. 2 Ban on vehicles imports in Africa (left); Emissions standards for vehicles in Africa (right)

1- Ban the import of second-hand vehicles (Egypt, South Africa, Sudan) or impose a limit of age on the vehicles (Algeria, Chad, Morocco)

. 2- Impose standards on vehicles emissions such as Euro 4 (Morocco, Rwanda). Most of the African countries still not impose any ban

The importance of vehicle standards can be viewed through an example for Nigeria. Officially 11,733,425 vehicles are registered in the country [X]. It can be estimated that about 90% of the vehicles imported every year by the country follows Euro 3 or below [X] and also that in average the age of vehicles in Nigeria cities is about 14 years. If the Euro4 standards are applied as projected and the fleet is replaced, using Ecoinvent database it could be estimated that at least the annual reduction of human health impact would be:

$$Reduction\ of\ emissions = \text{Number of vehicles} * \text{ Vehicles Euro3(\%)} * \text{Emissions vehicles } \left(\frac{g}{km}\right)_{(\text{Euro 3}-\text{ Euro 4})} * \text{Annual mileage (km)}$$

$$Reduction\ of\ emissions_{NOx} = 11733425 * 0.93 * 0.13 * 15000 = 21.3 kton$$

$$Reduction\ of\ emissions_{PM25} = 11733425 * 0.93 * 0.0025 * 15000 = 0.41\ kton$$

$$Reduction\ of\ emissions_{SO2} = 11733425 * 0.93 * 0.036 * 15000 = 5.8\ kton$$

$$Reduction\ of\ Human\ health\ impact\ (DALYs) = \sum DF_x * Reduction\ of\ emissions_x$$

$$Reduction\ of\ Human\ health\ impact\ (DALYs) = 353 * 21.3 + 2131 * 0.41 + 1182 * 5.8 = 15{,}248\ DALYs$$

Due to the limitation of information, it is difficult to confirm the exact reduction of impact, knowing that the performance of a vehicle decreases after using (A Euro3 vehicle after 15 years of use is different from a vehicle at mileage 0). As an additional information, according to the EDGAR V5.0 database, the emissions from road transport is about: 2.2 kton PM2.5 and 269 kton NOx that would lead to about 100,000 DALYs annualy.

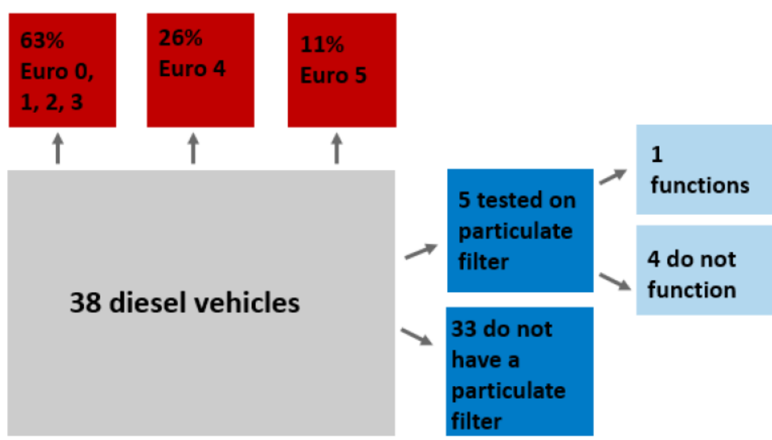

Figure 6. 3 Overview of vehicles imported from Netherlands to Africa and tested by the UNEP [4]

Another issue is the diesel Sulphur level in the range of 50-5000ppm while it is below 15ppm in most countries in the world. This has an influence on sulfur dioxide emissions but also on diesel particulate filters. Two types of policies can be achieved to reduce the impact of second-hand vehicles: a limit on the age of imported cars, at the moment, only a few countries apply such a policy.

G20 countries (especially the EU) could also support the efforts to ban the exports of used cars that are not meeting the exporting place standards to developing countries.

6.2.3 Electricity

The COVID-19 has also severely impacted access to electricity for several African countries. While the population without electricity access was decreasing in recent years, more than 10 million people are predicted to lose access to electricity in 2020. The continent only generates 3% of global electricity. Following the example of South Africa's National Environmental Management Air Quality Act of 2004, African countries must adopt emission standards as soon as possible. An example for these standards is shown in Figure 6.4

Table 6.4 Example of emissions standards for South African coal power plants [5]

Pollutant	Plant status	Emission limit, mg/m3
Particulate matter	New	50
	Existing	100
SO2	New	500
	Existing	3500
NOx	New	750
	Existing	1100

These standards could either target the daily average concentration of air pollutants (PM2.5 concentration) or target the emission from power plants directly (g/kWh). Another option is to support households with incentives to switch to more efficient electronic appliances (air conditioner, TV). This option would also help to cut the electricity bill down.

Cut subsidies for fossil fuels could also help to decrease the future impacts of electricity. The example of Ethiopia is a very good example to follow. The country removed all it fossil fuels subsidies in 2008 (about 600 million dollars) [6]. The money saved was used to invest into renewables, especially hydropower. Since then the country has been producing almost all its electricity from hydropower as shown in Figure **6.4**.

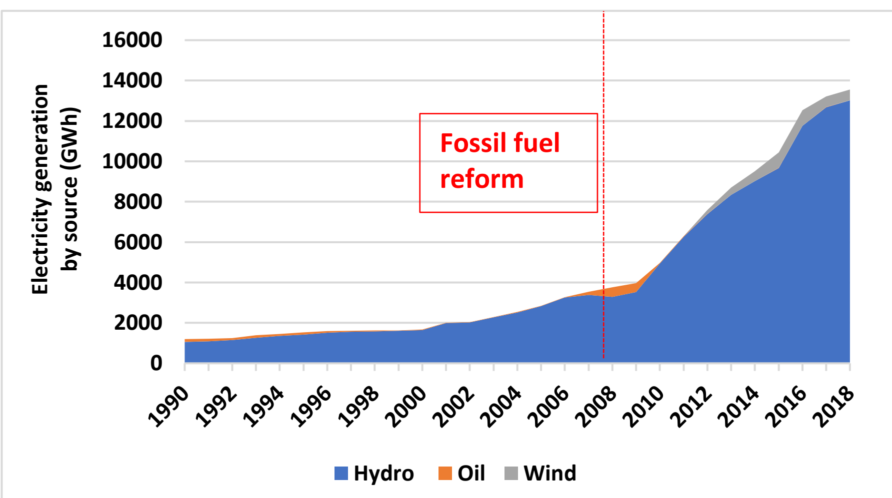

Figure 6. 4 Influence of the Ethiopian 2008 fossil fuel reform on the electricity mix (Data from IEA[7])

Finally, setting future targets for renewables energies is an important step to take further actions and anticipate further impacts/investments. 41 African countries have already set-up targets to provoke a shift in the energy mix or cooking fuels. The past and future targets of African countries are presented in Table 6.5

Table 6.5 Past/Future Target for renewables energies [8]

Country	Share of total energy	Share of electricity	Target year	Additional information
Algeria	40	0	2030	5% by 2017
Angola	0	0		50% of rural electricity
Benin	0	0	2025	
Botswana	0	0		No target
Burkina Faso	0	0		No target
Burundi	2	0	2010	
Cameroon	0	0		No target
Cape Verde	0	50	2020	
Central African Republic	0	0		No target
Chad	0	0		No target
Comoros	0	0		No target
Democratic Republic of the Congo	0	0		No target
Djibouti	30	0	2017	(solar PV off-grid)
Egypt	14	0	2020	
Equatorial Guinea	0	0		
Eritrea	0	50		From wind power
Eswatini	0	0	2014	20% of all public buildings installed with solar water heaters
Ethiopia	0	0	2013	No target
Gabon	80	0	2020	
Gambia	0	0		No target
Ghana	0	10	2020	
Guinea	0	8	2025	
Guinea-Bissau	2	0	2015	
Ivory Coast	5/15/20	0	2015/2020/2025	
Kenya	0	0	2030	Double installed renewable energy capacity by 2012 and 5 000 MW of geothermal capacity by 2030
Lesotho	0	35	20	Share of rural electricity
Liberia	0	0		No target
Libya	10	0	2020	
Madagascar	54	0	2020	
Malawi	7	0	2020	
Mali	15	0	2020	
Mauritania	20	0	2020	
Mauritius	0	35	2025	
Morocco	0	42	2020	
Mozambique	0	0		No target
Namibia	0	0		No target
Niger	10	0	2020	
Nigeria	0	20	2030	18% by 2025
Republic of the Congo	0	0		No target
Rwanda	0	90	2012	
São Tomé and Príncipe	0	0		No target
Senegal	15	0	2025	
Seychelles	0	15		
Sierra Leone	0	0		No target
Somalia	0	0		No target
South Africa	0	13	2020	
South Sudan	0	0		No target
Sudan	0	0		No target
Tanzania	0	0		No target
Togo	0	0		No target
Tunisia	0	25	2030	11% by 2016
Uganda	0	61	2017	
Zambia	0	0		No target
Zimbabwe	0	10	2015	10% share of biofuels in liquid fuels

6.3 Future works

① Development of air pollution damage factors at grid-scale level

As pointed previously, it would be necessary in the future to evaluate the damage of air pollution at a grid-scale level, not only in Africa but in the entire world. Indeed, it would be possible to estimate each power plant's damage depending on the location. We could imagine a better comparison for vehicles between emissions in urban area due to conventional vehicles and emissions in remote areas due to electricity generated for battery electric vehicles. Developing factors at a grid-scale level would also help to provide damage assessment at the same scale as the WHO.

② Development of a life cycle inventory database for African countries

There is no specific life-cycle inventory database for African countries. Therefore, it is still difficult to conduct accurate life cycle assessment case studies in Africa. National project could start similarly to Japan 20 years ago. It was a key step to develop further LCA, and African countries could take an example of it. The life-cycle initiative is pushing for it under the Global LCA Data network (GLAD).

③ Estimation of future environmental impact in Africa

As a starting point of this Ph.D. thesis, it was highlighted that both economy and population would grow at a high speed in the near future. It can be easily predicted in the business as usual scenario; impacts will grow at the same speed. It would be interesting to estimate air pollution's damage factors in the future, using future emissions scenarios of air pollutants. Policies could be planned in advance to avoid the growing number of deaths related to air pollution, especially to infants in Sub-Sahara Africa.

④ Improvement of resolution for the global MRIO for African countries

Currently, the level of detail for the African input-output table is still limited. In Eora, most African country's sectors are only divided into 26 sectors. It is then difficult to give advanced recommendations for products. Also, satellite accounting is mostly done based on secondary data. Information should be collected directly in the future.

⑤ Development of Life Cycle Impact Assessment method for African countries

The number of Life cycle impact assessment methods for developing countries is still limited. Some projects started in Asia (for example, in Thailand). There is a need for development tools for air pollution and other impact categories such as human toxicity, groundwater, etc. The development of weighting factors for developing countries also represents a nice challenge in the future.

⑥ Clinical cohort studies

Currently, the impact of air pollution in the world is mainly calculated using the observations made in Europe and North America. There is a need to conduct clinical studies in Africa to confirm that the African population's observations are similar. The calculation of air pollution relative risk specific to young African children is critical. Several types of research have also pointed out the impact of air pollution on mental health

⑦ Conduct case studies

As pointed out in the third chapter, the number of research articles is still limited for African products. It is needed to launch national projects to evaluate products emissions. The African manufacturing industry is developing, and it would be important to evaluate African-made products as future air pollution might come not only from agriculture but also industry, electricity production.

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APPENDIX

APPENDIX 1.1: Summary of selected LCA studies conducted in Africa

Algeria [20]	This articles assessed the environmental impacts of the drilling mud system in Algeria's arid region where Water-based mud (WBM) and oil-based mud (OBM) are used during well drilling in Hassi Messaoud petroleum field. =>The local environmental impact is the most important of the drilling mud lifecycle and is mainly linked to emissions from reserve pits, treated cuttings, and drilling phase due to aromatic hydrocarbons fraction and metals in particular barium, zinc, antimony, arsenic, and aluminum. The toxic substances fate modeling can be improved by taking into account their site-specific impact, the evaluation of the local impact categories such as human toxicity or terrestrial eco-toxicity with generic characterization factors can lead to miscalculation given that they were established in temperate zone (western Europe and North America).
Algeria [21]	The environmental performance of the various water recycling technologies was compared on the basis of the associated potential environmental impacts by using the life cycle analysis. =>The results of life cycle assessment, suggest that the biofiltration in slows and filter option is most respectful of the environment friendly out of the three technologies under all impact categories for the most impacts. In general, technologies based on natural treatment processes have relatively lower environmental impact than membrane-based technologies. The use phase had a larger contribution (mainly due to electricity consumption) to most environmental impacts.
Algeria [22]	LCA developed for the environmental evaluation of potable water production near Algiers, Algeria. => The main source shown that for the studied water treatment process, the highest environmental burdens are coagulant preparation (30% for all impacts), mineral resource and ozone layer depletion the repartition of the impacts among the different processes varies in comparison with the other impacts. Mineral resources are mainly consumed during alumine sulfate solution preparation; Ozone layer depletion originates mostly from tetrachloromethane emissions during alumine sulfate production. It should also be noted that, despite the small doses needed, ozone and active Carbone treatment generate significant impacts with a contribution of 10% for most of the impacts. Moreover impacts of energy are used in producing pumps (20-25 GHC) for plant operation and the unitary processes (coagulation, sand filtration decantation) and the most important impacts are localized in the same equipment (40-75 GHC)
Algeria [23]	The aim of this study is the use of Life Cycle Assessment, to evaluate the impact generated by cement manufactory situated in Sour EL Ghozlane town in Algeria country, which use the dry process to produce cement Portland.
Algeria [24]	In this paper, a Life Cycle Analysis (LCA) from “cradle to gate” of one anhydrous ton of ammonia with a purity of 99% was achieved. =>The results show that Cumulative Energy Requirement (CER) is of 51.945 × 103 MJ/t of ammonia, which is

	higher than the global average. Global Warming Potential (GWP) is of 1.44 t CO2 eq/t of ammonia; his request is 25.16% higher than the world average, which is of 41.5 × 103 MJ/t (IEA, 2007). Despite the fact that the Algerian process fuel is 100% natural gas and is more proper than coal and oil, the overconsumption in the Algerian process increases the cumulative energy requirement. Two factors contribute to explaining this overconsumption of energy: the first is related to the multiple restarts of the plant following the failures that usually occur. These failures are due to age of the plant (opened in 1982). The second factor is reformer operations, in which hydrogen content in the process gas (CH4) is separated from carbon as a result of fuel gas combustion. Reformer operations are the main causes of over consumption of energy and GHG emissions in the studied process. This is due to the low efficiency of the catalytic reaction in which the catalysts were used more than 10 years
Algeria [25]	The mud causes considerable pollution impacting several sectors, especially the groundwater system and the staff working on Drilling wells ,so as to mitigate the environmental effects of the sludge on the environment two treatment processes were analysed :Thermal desorption and Stabilization/Solidification off line. => The second best scenario is thermal desorption who gets the lowest score of the impact of carcinogenic effects as a result of the reduction of hydrocarbons (<1%) and avoided impacts of recovered oil. The modeling of toxic substances out will be improved by considering their particular impact site.
Algeria [26]	A Life Cycle Assessment (LCA) was applied for evaluating the environmental impact of suspended mussel culture in Algeria and suggest management practices which could reduce it. In order to estimate the current and perspective impact of this industry, LCA was applied to one of the few farms currently operating in Algeria and to farms to be established in the future in the same coastal area. The first scenario (Comp_S)represents the continuity with the current situation, in which each farm is competing with the other ones and is therefore managing the production cycle independently. In the second scenario (Coop_S), mussel farms are grouped in an aquaculture management area and shared the same facilities for postprocessing harvested mussels before sending them to the market => Reduction of 3150 MJ and 156 kg CO2eq per functional unit could be obtained if mussel farming activities would be operated in cooperation, thus reaching higher levels of efficiency. A database more adapted for the African aquaculture sector would be more convenient and could considerably reduce uncertainties.
Algeria [27]	A life cycle analysis approach was used to assess the environmental impacts for three types of hotel buildings having various envelope configurations and materials, built in different climates: Algeria and France. The study assesses through a comparative approach the impact of building components on its energy performance and their environmental cost over the building's entire life cycle. => The results show that it is possible to reduce the energy requirements of both traditional and standard building envelopes by assigning low-consumption building scenarios. However, although these scenarios could reduce some environmental impacts, they could also enhance others. In order to improve the results of life

	cycle analysis, another variant that generates less impacts than previously simulated variants was developed by retaining the following environmental scenarios: superfluous material at the site, 5%; lifetime of doors and windows should be 30 years; coating life-time should be 10 years; use of natural gas for heating; wood energy for domestic hot water; consumption of cold water should be 0.2 m3/person/day; selective collection of glass, 50%;selective collection of paper, 30%; incinerated waste, 30%; and the produced waste should not be more than 1 kg/person/day.
Algeria [29]	The aim of this paper was to present a one-year performance analysis of four grid-connected PV systems installed at Ghardaia city in Algeria's Sahara. The grid-connected PV systems are based on four different PV module technologies which are: monocrystalline silicon (m-Si), multi-crystalline silicon (mc-Si), cadmium telluride (Cd-Te) and amorphous (a-Si) PV module technologies. =>The PV systems based on the thin film technologies have their performance ratio better throughout the year when the performance ratio of the mc-Si technology is better in the winter season. The a-Si PV system has its performance ratio about 6.13 % more better than mc-Si and 8.90 % better than m-Si. The AC energy produced with the a-Si PV system is 13.32 % more than what the mc-Si system produces. It was found that the a-Si PV system performs better than the other technologies under the Saharan climate conditions of Ghardaia city. The energy payback time (EPBT) and greenhouse gases (GHG) emissions of the different PV systems were analyzed. The EPBT and GHG emissions per year, vary from a minimum value of 2.8 years to a maximum value of 5.73 years and from 13.24 tons to 32.03 tons of CO2/kWh for CdTe and m-Si respectively
Benin [30]	There is therefore a need for an integrated evaluation of urban agricultural practices. Here, we studied tomato production in Benin cities. =>.Our results show that yields were low and variable, averaging at 9,533 kg.ha−1 and ranging from 0 to21,163 kg.ha−1. The average TFI for pesticides was 8.9. The maximum TFI of 25 was observed for an insecticide applied weekly at 2.3 times the official rate. It was observed an excess of the average nutrient budget of 120 kg N and 84 kg P. ha−1. Inconclusion, this study of urban tomato production revealed poor practices and high risks for health and the environment.
Benin [31]	This study focused on producing references for tomatoes grown in urban gardens in Benin, and examining how their impacts were affected by the variability of field emissions of reactive nitrogen, responsible for a major share of non-toxic impacts. A stratified sample of 12 fields was surveyed and used to design a representative mean for urban tomato gardens in Benin => To analyze the sensitivity of environmental impacts to management practices and environmental conditions, yields and nitrogen emissions from extreme scenarios were simulated with the crop model STICS. Overall, the environmental impacts of urban garden tomatoes in Benin were 4-23-fold greater than the impacts of tomatoes grown in European cropping systems, due to low and variable crop yields, high fuel consumption for irrigation, large emissions of nutrients and excessive use of insecticides. For extreme scenarios, impacts were up to 3-fold greater than the impact of the representative mean as a result of complex biophysical mechanisms involved in nitrogen emissions. It was concluded that parameters relative to irrigation (total rate and application frequency)

	and soil properties (pH, water holding capacity)should be included in the estimation of nitrogen emissions for LCA of vegetables.
Burkina Faso [32]	This study's main objective is to find the most sustainable power supply option with regards to a specific zone of Burkina Faso. This article discusses the possibility of deploying a sustainable system providing water purification and electricity to a village of Burkina Faso. Three scenarios are considered to power up the water purification plant (A: electricity grid, B: diesel generator and C: solar panels supported by second life EV batteries) =>The third scenario is especially relevant because it reuses EV batteries, providing an affordable energy storage system and giving an additional value to this automotive waste, which still has an 80% of its initial capacity. Moreover, this system transforms solar energy to electricity with the photovoltaic panels. On the contrary, the other two scenarios need to obtain energy or raw materials from third parties. The "Energy Power plant" scenario demands monthly payments to the energy company to have access to the electricity grid, while the “Diesel generator” needs to buy fuel to distributors to run the generator.
Burkina Faso [33]	Jatropha curcas has been introduced as a low-cost energy crop in Burkina Faso for the production of straight vegetable oil (SVO) and biodiesel. => The study found that all J. curcas production pathways substantially reduced greenhouse gas emission (68–89%) and saved energy(65–90%) compared to diesel fuel, however, very lowland-use efficiency (6.5–9.5 GJ/ha production) characterized Jatropha intercropping and monoculture plantations, rendering the plant a competitor to food crops and increasing the risk of conversion of savanna land to Jatropha cultivation. Moreover, High labor requirements constrain integration of Jatropha plantation systems within small farm holdings
Burkina Faso [34]	This study presented how multi-criteria methods such as the weighted technical analysis are useful to select the best heat transfer fluid to be used in a relatively small Concentration Solar Power plant in the Burkina Faso. =>Results show that Dowtherm A is the best choice for Burkina Faso and Marlotherm is the worst, but these results change considerably if the comparison is done in the USA, where the environmental factor gains relevance in contrast to the economic factor.
Cameroon [35]	The use of palm oil as a biofuel has been heavily debated for its land-use conflict with nature and its competition with food production, being the number one cooking oil worldwide. In that context, a life cycle assessment study focused on a palm oil production process yielding both biodiesel and cooking oil, incorporating the land-use impact and evaluating the effect of treating the palm oil mill effluent (POME) prior to disposal. => This system shows less energy requirement, global warming and acidification reduction, and less eutrophication increase compared to the reference than the same system converting all palm oil into biodiesel (no cooking oil production).

Cameroon [36]	A methodological approach of Life Cycle Assessment was presented in order to compare the energy consumption of three variants of a road tracing in Cameroon. The three variants are stretches of 11.99 km (variant 1), 9.68 km (variant 2) and 11.11 km (variant 3) on the road from Ngaoundéré(departure point in the North of Cameroon) to Moundou (arrival point in South-West of Chad). => The results obtained show that in both cases, variant 1 consumes more energy than variant 3. Variant 2 consumes the least energy. The exploitation phase's contribution to the energy consumption is high, amounting 85.5% in scenario 1 and 78.1% in scenario 2. Energy consumption in construction mainly depends on the presence of architectural arts works on the section and its contribution to the overall energy consumption that remains weak lower than to 5.32% or 8.08% in scenario 1 and 2, respectively.
Cameroon [37]	In sub-Saharan Africa, fish constitutes the main source of animal protein for human consumption. This study analyzed four farms that integrated fish farming with other agricultural production, and in which fish ponds were fertilized either by pig manure and/or crop by-products, in two regions of the western highlands of Cameroon => Eutrophication impact was higher for Cameroon farms than for an intensive trout monoculture (France) or extensive carp polyculture (Brazil) due to poor water management (water loss >5%/day),which drained nutrients out of ponds, and poor manure management (application> 150 kg DM/ha/day),. The sources of inputs need to be adapted by looking for local and easily available feed ingredients that do not compete with human food supplies
Cameroon [38]	This work was about the life cycle assessment (LCA) of the effluents of a spontaneous housing neighborhood. Effluents refer to gray water (domestic), surface water(rainwater) and faeces =>The construction stage has impacts on energy, resources,water, waste and radioactive waste as well as odours. The maintenance and production stages generate impacts characterized by toxicity, eco-toxicity, acidification, GWP, eutrophication and smog. The EcoSan latrine is the most polluting system for the majority of indicators, except for the water and eco-toxicity indicators. However, considering the pollution-induced by the chemical fertilizers. For the energy, acidification and eutrophication indicators, this system yields an environmental benefit. For the devices actually used by the population in the Bonamoussadi neighborhood, scenario A is the most pollutant.
Cameroon [39]	A Jatropha-biofuel chain was organized in the north-west of Cameroon. The aim of the project was to implement an integrated biofuel chain, based on nontoxic Jatropha cultivation, which could provide vegetable oil for energy use instead of fossil fuel and, contemporary supply cake protein for the rural population => Conversely, the possibility of improving the efficiency of this Jatropha-biofuel chain by trying to increase the seed yield with the use of chemical fertilization and an increase in mechanization of the cultivation phase, should be carefully considered. In fact, against a possible but unsure efficiency improvement, an increase of greenhouse gas emissions should be considered. A positive aspect of this study is the utilization of a nontoxic. curcas accession, which avoids the implementation of the essential health and safety requirements to reduce the exposure risk for workers involved in a Jatropha-biofuel chain, allows higher protection of human health

	with respect to the toxic accessions. Moreover, adopting these nontoxic accessions, the seedcake obtained as main byproduct, could be utilized as a source of protein for animal feed and for humans, to improve food security.
Egypt [40]	Life cycle assessment (LCA) methodology was used. The urban water system was modelled. => The results of the research revealed that the WWTP are the most problematic part of the system because they represent about 68% of the total impact of the system. The impact of the WWTP was due to the very low removal efficiency of the nutrients. The impact of the water treatment plants and the transportation of the water and the wastewater were mainly due to the use of fossil fuel-generated energy. A significant impact of the untreated wastewater was reported, however, the treatment of the untreated wastewater using the current system will not reduce the environmental impact much, because of the lack of nutrient removal.
Egypt [41]	The treatment efficiency of a primary wastewater treatment plant (WWTP), in Alexandria, Egypt, was studied. The improvement scenarios are: scenario 1, use of engineered wetland instead of the current treatment system, scenario 2, use of the engineered wetland as a secondary treatment after the existing treatment system and scenario 3, replace the existing treatment system with a secondary WWTP => The results showed that the highest contribution to the total impact was the impact resulting from the low removal efficiency of the nutrients due to its negative impact on the open water bodies (causing eutrophication) where the treated wastewater is discharged to Lake Mariout. Therefore, the proposed improvement scenarios focused mainly on improving the removal efficiency of the nutrients. The three improvement scenarios' analysis revealed that the use of the combined system from natural and traditional systems (scenario 2) is the best scenario. It achieved a reduction in the total environmental impact by about 23.71%. However, scenario 3 achieved a very close result with a reduction of about 21.28%. The lowest improvement was from scenario 1 (12.77%). Moreover, better results in scenarios 2 and 3 could be achieved by better optimization of the wetland operation.
Egypt [42]	Life cycle assessment (LCA) program developments were intended for the construction of life cycle inventory (LCI) database for refrigerators, computers, and general consumer products. But buildings are different from general consumer products for their long life span, and possess different characteristics from consumer goods. => The review can summarize that to calculate the CO_2 emissions and energy consumption from building material in Egypt from LCA view is more difficult because Egypt does not has tool/program to estimate carbon emissions from building LCA, ECE-LCA must include a building's life cycle, and be devised to permit input and output of Egyptian LCI database for the respective stages of this life cycle.
Egypt [44]	This study suggested an organizational and managerial framework for the development of a national database and sheds light on the required LCI database categories and data quality for practical solutions reflecting who is equipped to do what in order to keep pace with the world. => The results from this review are useful to standardize the study of the life cycle assessment concept in Egypt;

	to form a foundation for development of an Egyptian database for facilitating a cleaner environment; to encourage stakeholders, such as the environmental agencies.
Egypt [45]	This study compared the environmental impacts related to the production of cotton yarn from cultivation to washing and drying when cotton is supplied by four companies located in four different countries (Egypt, China, India and the USA). => The highest greenhouse effect is produced by the Indian company, with 0.89 kg of CO_2 equivalent (per 1 kg of cotton).Fuel consumption and Ammonium nitrate are the first items of the greenhouse effect in all companies because of their extensive use and the lack of rotation with other unprofitable crops. In Chinese and Egyptian companies the irrigation sources are severely threatened, and it is necessary to switch from flood irrigation to a drip irrigation system. The production phase of cotton yarn provides an impact equal to 2.81 CO_2 kg-equivalent. The most critical impacts of cotton yarn production are due to Dyeing (1.24 CO_2 kg-eq.) and Spinning (0.64 CO_2 kgeq.) phases, and they are essentially connected to reactive reagents and pigments, electrical and thermal energy.
Egypt [46]	This paper aimed to use life cycle assessment (LCA) to assess groundwater pumping systems' environmental impacts, diesel fuel and solar power for lifting irrigation water for one feddan (1.037 acre) of rice. The study area lies in Tanta semi-arid central Nile Delta, Egypt => Results indicated that the diesel-powered pumping systems are more harmful to the environment than solar power pumps. The contribution to midpoint environmental impacts of the diesel fuel pump impacts reach 70 % for natural resources, 18 % for human health, 10% for climate change and 2% for ecosystem quality. On the other hand, solar pumping system contributes to 3 % to climate change, 2% to human health and natural resources impacts, and 0.5 % to ecosystem quality.
Egypt [49]	The aim of this paper was to contribute to the development of a comprehensive, practical and reliable tool for a systematic sustainability assessment, based on the Life Cycle Assessment (LCA) and the Analytic Hierarchy Process (AHP) to support decision-makers in complex decision problems in the field of environmental sustainability. => The results was a dynamic analysis and iterative integrated sustainability assessment of corporate performance. The strength of the proposed method is the simplicity and at the same time completeness of the analysis. Furthermore, the flexibility and the adaptability to different scenarios represent a strategic implication of the model, which gives a better insight into the complex world of sustainability assessment
Egypt [50]	Egyptian aquaculture is gaining importance as an affordable and nutritious source of animal protein among Egyptians. Nile tilapia dominates production (77% of total production), followed by carps (17%) and mullets (11%). Inventory data representing 137 farmers and four groups (control, BMP, G9 and BMP + G9) were evaluated. => The application of Best management practice (BMP) could reduce lifecycle environmental impacts by up to 22%, while G9 tilapia,(genetically improved tilapia) could reduce emissions by up to 36%.

Egypt [51]	Egypt do not have LCA tool to estimate emissions from construction of asphalt pavements, thus the paper highlighted on UK model to take advantage from it, moreover to be a guide in creating LCA tool. => The review can summarize that calculation of emissions and energy consumption from pavement construction in Egypt from LCA view is more difficult because Egypt does not have any LCA tool/program to estimate emissions from road construction. EGY-LCA Tool must include a road's lifecycle, and be devised to permit input and output of Egyptian LCI database for the relevant stages of this life cycle.
Egypt [52]	The scope was to study the life cycle of the yearly used tires by vehicles travelling on the Egyptian road network. => Results indicated that, Egyptian road tires contributes highly and mainly to GW on the midpoint effect and contribute mainly to the damage regarding terrestrial acidification and nitrification with about 1.02*108. Regarding the normalized effect, it was found that the highest contribution is in respiratory effects on human health with 3.52*104 (person-year/kg) followed by terrestrial acidification of 3.1*104 (person-year/kg).
Egypt [53]	Life cycle assessment (LCA) was employed to determine the environmental impacts of tilapia production and compare semi-intensive and intensive production systems. => Four impact categories were taken into consideration: Global Warming Potential (GWP), Acidification Potential (AP), Eutrophication Potential (EP), and Cumulative Energy Demand (CED). Results and discussion LCA revealed that production of tilapia in intensive farming has less impact on GWP, AP, and CED, while its impact on EP is higher than in semi-intensive farming. The identified impacts from 1-tonne live weight production of tilapia were the following: GWP 960.7 and6126.1 kg CO2 eq; AP 9.8 and 24.4 kg SO2 eq; EP 14.1 and 6.3 kg PO2 eq; and CED 52.8 GJ and 238.3 GJ eq in intensive and semi-intensive system.
Egypt [54]	The aim of the current study was to analyze the impacts of acrylic fiber manufacturing on the environment and to obtain information for assisting decision makers in improving relevant environmental protection measures for green field investments in developing countries especially in Africa and Middle East and North Africa (MENA) regions =>The highest impact was detected on fossil fuel depletion due to the high-energy consumption of raw materials used as inputs for the manufacturing of acrylic fiber. Impacts on the respiratory system of the human body, carcinogen, and climate change potentials were next due to the inorganic chemicals used during the manufacturing process of the product. The lowest impact was on ecosystem quality which could be attributed to the acidification impact on the environment upon the usage o facrylonitrile and chemical compounds as raw materials. LCA results of acrylic fiber manufacturing on the environment show that 82.0 % of the impact is on fossil fuel depletion due to the high-energy requirement for acrylonitrile production, 15.9%of the impact is on human health, and 2.1% on ecosystem quality.

Egypt [55]	This study investigated the LCA of the cement industry in Egypt compared to the Swiss industry, using two methodologies. The first one has been done on-site, surveying the most common types of cement used in the construction industry in Egypt. Two plants were compared: An Egyptian cement plant (ECP) which uses electricity, natural gas, and diesel as energy sources; a Swiss cement plant (SCP) which depends mainly on electricity, natural gas, and coal. => The respiratory inorganics, aquatic acidification, global warming and nonrenewable energy in ECI plants have higher impacts than the ordinary processes by percentages of 35, 60, 35 and 35 %,respectively. This is due to the SO2 emissions from the plant chimneys during the combustion stage of coal in accordance with the provisions of the environmental protection Agency (EPA). Based on the difference in the chemical compositions of the fuels used in the oven process, for the SCP,global warming and respiratory inorganics recorded 5 % higher adverse impacts than the EHP. Considering the endpoint method, the damage to human health of the Egyptian coal-based plants(EHP) have been recorded as having higher adverse impacts compared with the other two plants, Egyptian(ECP) and Swiss (SCP). The expected damage from the SCP (which uses mixed fuels) is 162 (46 %) Eco-points lower than the Egyptian coal-based plant, which is a reasonable proportion if it is applied in Egypt. A coal-based plant has higher adverse environmental impacts compared to others. The mitigation of the environmental impact of coal-burning using scrubbers must have an important role in the future design of ECP.
Egypt [56]	Life cycle assessment was employed in order to model the environmental impacts of each waste streaming approach separately then compare them together => Results revealed that incineration was the more eco-friendly approach. The highest impacts of both approaches were on ecotoxicity and carcinogenic potentials due to release of metals from pigment wastes. Landfill had an impact of 46.8 % on human health as compared to 28 % by incineration. Incineration impact on ecosystem quality was higher than landfill impact(68.4 and 51.3 %, respectively). As for resources category, incineration had a higher impact than landfill (3.5 and 2.0 %), respectively.
Egypt [57]	The article was aimed at investigating energy and environmental assessments to compare among six Egyptian (Cement, Clay and sandstone bricks) and Japanese products (3/each). All cases were investigated using MiLCA. Moreover, one kg of brick products sets as a functional unit and from cradle to gate phase are the study's boundary. =>As for the characterization (mid-point) results, the Cement brick (CEB), almost impact categories have exceeded more than 60%, however, the waste impact records around 15.83% and 0.69% of total waste produced due to the CEB and sandstone brick (SSB).
Egypt [58]	The study aimed to evaluate the environmental impacts of used lubricating oil (ULO) recovery in the largest oil consumer country in Africa, Egypt => Fossil fuel depletion was the highest category impacted as significant amounts of oil are saved as a result of the efficient waste management of used oil recovery. The potential emission of the respiratory inorganic particulate matter and GWP was highly affected due to particulate emissions from the industrial processes. In order to reduce the overall the environmental impacts of ULO recovery strategies.

Egypt [59]	This study aimed to investigate the environmental and economic benefits of improving current conventional WWTPs in developing countries by adding tertiary treatment and/or anaerobic digestion of sludge. For this purpose, life cycle assessment (LCA)for four different scenarios was studied for a wastewater plant located in Gamesa, Egypt. => The 1st scenario is the plant in its current state. The 2nd scenario is the addition of anaerobic digestion of sludge. The 3rd scenarios the addition of a tertiary treatment stage. The 4th scenario is the addition of anaerobic digestion of sludge and tertiary treatment stage. The 4th scenario attained maximum environmental benefits for all categories due to the energy saving and the prospect of water reuse
Egypt [61]	This study aimed to assess the environmental impacts of upgrading the wastewater treatment plants from primary to secondary treatment => It is worth noting that employing the secondary treatment units at Abu Rawash WWTP have both positive and negative impacts. The positive impacts include a reduction in the human toxicity, eco-toxicity, eutrophication potential, terrestrial eutrophication, freshwater eutrophication, and water depletion by 92%, 41%, 79%, 92%, 99%, and 47%, respectively, for each 1 m3 of treated wastewater. The negative consequences of employing the secondary treatment units for each 1 m3 of treated wastewater include an increase in GWP, ODP, AP, terrestrial acidification, metal depletion, fossil depletion, and ADP elements + fossil by about 17%, 99%,91%, 91%, 75%, 20%, and 87%, respectively.
Ethiopia [63]	A life cycle assessment (LCA) was conducted for Ethiopian rose cultivation. The LCA covered the cradle-to gate production of all inputs to Ethiopian rose cultivation and included transport to the Ethiopian airport.Primary data were collected about materials and resources used as inputs to, and about the product outputs from 21 farms in 4 geographical regions (i.e. Holleta, Sebeta, Debre Ziet, and Ziway). This study collected an extensive set of high quality primary data. Data collection covered 21 farms, which represent 50% of the reproduction area. => The largest contribution comes from the production of the used fertilizers, specifically nitrogen-based fertilizers. The use of calcium nitrate dominates Abiotic Depletion(AD), Global Warming (GW), Human Toxicity (HT) and Marine Aquatic Ecotoxicity (MAET). It also makes a large contribution to Ozone Depletion (OD), Acidification (AD) and Fresh water Aquatic Ecotoxicity(FAET). Acidification (AC) and Eutrophication (EU) are dominated by the emission of fertilizers. The emissions from the use of pesticides, especially insecticides dominate Terrestrial Ecotoxicity (TE) and make a considerable contribution to Freshwater Aquatic Ecotoxicity (FAET) and Photochemical Oxidation (PhO)
Ethiopia [64]	In developing countries dung cakes combustion as a household cooking fuel is a common practice; however this traditional fuel comes along with related environmental issues. The objective of this study was to assess the environmental impacts of the substitution of dung combustion by biogas systems in rural Ethiopia. => In terms of greenhouse gas emissions, the results demonstrate that mainly avoided methane and nitrous oxide emissions from dung drying and dung combustion lead to an environmental advantage of biogas systems in all scenarios ot this study. Also, the utilization of biogas digestate as organic fertilizer contributes considerably

	to savings of greenhouse gas emissions. The results indicate that about 130542t of carbon dioxide equivalents can be saved annually in Ethiopia. Indoor air pollution could be also avoided, emissions can be reduced considerably when using biogas instead of dung cakes for the provision of household cooking energy.
Ethiopia [65]	This paper quantified milk production systems' environmental performances differing in degree of intensification in the Mekelle milk shed area, Ethiopia. Life Cycle Assessment (LCA) methodology was used to estimate Land Use (LU), Fossil Energy Use (FEU) and Global Warming Potential (GWP) of the cattle sub-systemin 8 large-scale, 8 (peri-)urban and 8 rural farms. The milk production per average cow per year was much lower in rural farms(730 kg) than in large-scale (2377 kg) and (peri-)urban farms (1829 kg) => The GWP estimates per kg milk (1.75, 2.25 and 2.22 kg CO2-equivalents per kg milk in the large-scale, (peri-)urban and rural farms, respectively) were slightly higher than GWP values for the same types of farms in other developing countries, due to the relatively large amounts of low quality feeds fed. The quality of cattle management practices seems more important than the choice for a specific cattle keeping system in reducing the environmental impacts of milk production.
Ethiopia [66]	The overall aim of this study was to contribute to the creation of LCA database on electricity generation systems in Ethiopia. This study specifically estimates the environmental impacts associated with wind power systems supplying high voltage electricity to the national grid => The average midpoint environmental impact of Ethiopian wind power system per kWh electricity generated is for climate change: 33.6 g CO2eq., fossil depletion: 8 g oil eq., freshwater ecotoxicity: 0.023 g 1,4-DCB eq.,freshwater eutrophication: 0.005 g N eq., human toxicity: 9.9 g 1,4-DCB eq., metal depletion: 18.7 g Fe eq., marine ecotoxicity:0.098 g 1,4-DCB eq., particulate matter formation: 0.097 g PM10 eq., photochemical oxidant formation: 0.144 gNMVOC, and terrestrial acidification: 0.21 g SO2eq. The pre-operation phase that includes the upstream life cycle stage is the largest contributor to all the environmental impacts, with shares ranging between 82 and 96%. The values of cumulative energy demand (CED) and energy return on investment (EROI) for the wind power system are 0.393 MJ and 9.2, The results of this study should be interpreted within the context of the data limitations encountered during the course of the research, namely, lack of local datasets for electricity, transport, and waste treatment activities relevant to local conditions.
Ghana [67]	This study evaluated the life-cycle costs and environmental impacts of fuels used in Ghanaian households for cooking. The analysis covered all the common cooking energy sources, namely, firewood, charcoal, kerosene, liquefied petroleum gas, electricity, and even biogas, whose use is not as widespread as the other => The results indicate that firewood, one of the popular woodfuels in Ghana and other developing countries, with an annual environmental damage cost of US$36,497 per household, is more than one order of magnitude less desirable than charcoal, the nearest fuel on the same scale, at US$3120.

Ghana [68]	This study performed a comparative environmental and economic assessment of four different façade systems for low-cost residential buildings in Ghana. Shotcrete Insulated Composite Façade(Shotcrete ICF), Galvanised Steel Insulated Composite façade (G. Steel ICF) and Stabilised Earth Block Façade(SEBF) against the conventional Concrete Block and Mortar Façade (CBMF) were considered. => This study covers the entire life cycle of all four façade except the end-of-life stage where reliable data are not available for Ghana. The comparative assessment revealed that SEBF can save up to 39.13 % of CED, 18.07 % of GWP and 47.87 % of the cost. Also, for all facades, the operational stage accounts for the largest life cycle impact whereas material production accounts for most of the embodied impact.Scenario analyses indicate that the impact of transportation is significant,as sourcing materials locally can reduce CED and GWP of shotcrete IFC by over 18%.
Ghana [69]	The case of chocolate is a remarkable example, owing to the increasing demand and the complex production process from cocoa beans to final bars. The present study aimed at assessing the environmental impacts related to three chocolate types (dark, milk, and white) through life cycle assessment (LCA) methodology => Along the chocolate supply chain, different phases are evaluated according to LCA methodology. Among analyzed producer countries: Indonesia monoculture case results to be the most impacting situation, due to an intensive use of agrochemicals; pesticides give a wide contribution in Ecuador, whereas Ghana is penalized by the highest water consumption. The transport of beans to manufacturing plant influences mostly the GWP, owing to long travelled distances. Considering the whole production process, cocoa derivatives and milk powder are the main contributors to every impact category. In both cases, dark chocolate globally presents the best environmental performance, whereas the other two types have similar environmental impacts. These results are also qualitatively confirmed in the case of calories as functional units.
Ghana [70]	This study reviewed the relevance of existing impact categories and LCIA approaches, and uses the most relevant for the timber sector of Ghana. This study uses an earlier LCI study of the timber industry as a starting point for an additional LCIA. A correlation and regression analysis was performed to learn whether wood wastes may function as a single reasonable indicator for land use as a proxy for biodiversity loss and the other impact categories. => The correlation analysis indicated that wood waste is strongly correlated with land use as proxy for biodiversity loss and positively correlated with the other five potential impacts results. It can be concluded that wood waste production is the major driving force for biodiversity loss and a sufficiently good single indicator for all other potential environmental impacts in Ghana's timber sector. This correlation will be very useful for preliminary screening of potential environmental impacts, waste minimization analysis, or an evaluation of emerging technologies at early stages of decision-making in Ghana's timber sector.

Ghana [72]	When complexed in ore gold needs to undergo metallurgical extraction processes to eliminate unwanted ions before being smelted and used as the metal. Cyanide is used during these metallurgical processes. Sodium cyanide is imported into Ghana in wooden intermediate bulk containers for further distribution to the mining companies. A life cycle assessment was completed to determine the burden of this packaging, which includes the wooden intermediate bulk container, a polyethylene liner and a polypropylene liner placed on the environment when they are disposed. =>The LCA conducted in this research project proved to be effective in identifying the impact that the IBC and the two liners have on the Ghanaian environment though the limitations experienced in the quantification of these impacts, such as the use of European databases and confidentiality clauses, cannot be discounted or underestimated
Ghana [74]	The country also processes some of its beans into finished and semi-finished cocoa products for both the local and international markets. This paper was aimed at providing a comprehensive picture of the environmental impacts associated with cocoa production and processing in Ghana by applying the life cycle assessment(LCA) methodology. => In this study, data pertaining to electricity generation, fuels and agrochemicals production and transportation were taken from European databases, since specific local or regional databases are lacking. At the industrial processing stage, the use of natural gas instead of diesel oil for roasters and boilers is recommended due to its relatively low emissions.
Ivory Coast [75]	Life-cycle assessment was used to quantify the benefits of J. curcas biofuel production in West Africa in terms of greenhouse gas emissions and fossil energy use, compared with fossil diesel fuel and other biofuels.L => Biodiesel from J. curcas has a much higher performance than current biofuels, relative to oil-derived diesel fuels. Under West Africa conditions, J. curcas biodiesel allows a 72% saving in greenhouse gas emissions than conventional diesel fuel. Its energy yield (the ratio of biodiesel energy output to fossil energy input) is 4.7. Compared with previous work on other continents, the good performance of Jatropha may be mainly explained by the perennial nature of the crop and by the decentralized,non motorized and low-input production system.
Kenya [77]	This paper quantified environmental and economic life cycle impacts of biochar production and agricultural use in six developing and middle-income countries (Ethiopia, Indonesia, Kenya, Peru, Vietnam, and China). Two types of production technologies typical for rural and urban areas were investigated(flame curtain kiln and gasifier, respectively), and comparisons were made with composting (either home composting or windrow composting) as alternative biowaste management systems. => The results showed that both pyrolysis systems performed better than composting and both were expected to bring environmental benefits. The largest environmental benefits were observed for the gasifier systems, mainly due to the substitution of electricity production from the grid. Damage to ecosystems and human health ranged from -1×10^{-7} to -2×10^{-8} species×yr and from -1×10^{-5} to -5×10^{-6} DALY per kg of biowaste treated, respectively (negative scores indicating environmental benefits).

Kenya [78]	Smaller versions of electricity grids, known as microgrids, have been developed as a solution to energy access problems. Using attributional life cycle assessment, this project evaluates the environmental and energy impacts of three photovoltaic (PV) microgrids compared to other energy options for a model village in Kenya. => When normalized per kilowatt-hour of electricity consumed, PV microgrids, particularly PV−battery systems, have lower impacts than other energy access solutions in climate change, particulate matter, photochemical oxidants, and terrestrial acidification. When compared to small-scale diesel generators, PV−battery systems save 94−99% in the above categories. When compared to the marginal electricity grid in Kenya, PV−battery systems save 80−88%. Contribution analysis suggests that electricity and primary metal use during component, particularly battery manufacturing are the largest contributors to overall PV−battery microgrid impacts. Accordingly, additional savings could be seen from changing battery manufacturing location and ensuring end of life recycling.
Kenya [79]	This study used existing data to provide a diet-level perspective on environmental impact from food production in the case study countries of Vietnam and Kenya => The AWARE characterization model was used to offer a diet-associated water scarcity footprint. Trends in diet-associated environmental impacts were interpreted in light of diet shifts, economic development trends, and other factors. Increasing per capita food supply in Vietnam and increasing in meat, have led to rising diet associated per capita GHGE. While supply of beef remains 5.2 times smaller than pork—the dominant meat—increases in beef demand in the past decade have resulted in it becoming second only to rice in contribution to dietGHGE. The water use and water scarcity footprint in Vietnam follow an increasing trend comparable to food supply. On the other hand, historically consistent levels of dairy and beef in Kenya dominate diet-level GHGE.
Lesotho [81]	The environmental sustainability of wastewater treatment through phosphate (P) and ammonia (N) chemical precipitation (struvite) was examined using the life cycle assessment methodology. => The optimal conditions, from the environmental perspective, were found to be 0.2 g L1 feed dosage and 10 min mixing, at ambient temperature and pH (total environmental footprint 60.9 mPt per treated L of wastewater). To improve N removal efficacy, which is desirable in real-world applications, higher feed dosages and mixing durations are required, albeit at the expense of environmental sustainability (e.g. the 180 min and 16 g L1 environmental footprint sharply rises to1.87 mPt L1). Overall, results complement the existing body of knowledge on such systems' techno-economic performance and provide insight to decision- and policy-makers to sustainably scale up the process, at village- or industrial-level, in rural South Africa Lesotho, and further afield.
Libya [82]	This paper introduced a novel environmental Life Cycle assessment of Libyan petroleum refining processes. => The results of the assessment showed that crude oil production and distillation have first significant impacts (Fossil fuels). The assessment leads to the following main conclusions. The analysis demonstrates two major stages of crude oil life cycle: the read code is for crude oil extraction, production, and transportation to the refinery. The green color code is refinery processes to make diesel. It is evident from the analysis that the

	amount of environmental impacts at both stages is the same in regard to fossil fuels. The second major impacts are the respiratory inorganic impacts. Flaring and venting issues must be reduced and gases should be used efficiently for preheating and energy generation.
Libya [83]	The aim of this study was to analyze and evaluate the LCA and real impact of the first wind farm to be installed in Libya considering the whole life cycle => The analysis revealed that the energy payback period is 0.475 year (5.7 months), and then the payback ratio is 42.1, which confirms very well with other literature results. The electricity generated by one wind turbine 1.65 MW (model M. Torres (TWT 1.65/82)) land-based in this wind farm is expected to emit approximately 10.42g per kWhCO2. The results obtained in this study confirm that wind energy produces the lowest CO2 emissions per kWh of electricity compared to fossil fuel and other renewable energy sources. Comprehensive studies concerning the determination of the local electricity emission factor should be supported.
Madagascar [84]	The paper explained the advantages and disadvantages of solar cooking and the challenges faced to change traditional cooking habits, in order to fight the ongoing deforestation, preserve the environment and fight poverty. To optimize the success of this project, the use of solar cooker has been compared to two alternatives - firewood and charcoal cooking and on the topics of primary energy utilization and CO2 gas emission => As results, parabolic solar cooker is less usable in cloudy or rainy weather. A reduction of about half the environmental impact has been obtained with this technology. Some backup heat source must still be available to cook meal at these times. Solar cooker, charcoal and firewood can work in a complementary fashion to meet a variety of cooking needs.
Malawi [86]	This paper reviewed the material and energy flows of the Malawian tea industry in order to identify opportunities and reduce its environmental impacts. => Results indicate that green leaf consumption in the studied factories ranged from 4.19 to 6.33kg greenleaf/kg made tea(MT), with an average of 4.96kg per kg of made tea compared to 4.5 and 4.66 kg green leaf for tea factories in Kenya and SriLanka, respectively. Average wood consumption in Malawian tea factories is 3.35kg/kg made tea and specific water consumption ranged from 1.92 to 8.32kg/kgMT. The average value of greenhouse gas(GHG)emissions for eight fac-tories is 4.32kg of CO2-eq/kgMT compared to 2.27 and 2.7kgCO2-eq/kg in similar factories in Kenya and SriLanka, respectively. The major sources emitting GHG are from boiler fuel combustion and stand-by diesel power generation system.
Malawi [87]	The rising demand for bricks baked in wood-fuelled kilns in Malawi is raising concerns due to its contribution to fluctuations of climatic conditions locally and globally. To obtain lifecycle inventory, process inventory analysis was used, focusing on energy inputs and carbon outputs at the initial construction stage. A functional unit of a 1m2 wall was used for calculating energy and carbon emissions. => The results demonstrate that, for individual blocks, kiln burnt bricks (KBBs) consume 0.531 GJ/m2 compared to 0.138 GJ/m2 and 0.106 GJ/m2 for stabilized soil-cement blocks (SSBs) and solid cement blocks (SCBs), respectively. Similarly, KBBs have a higher global warming potential than the SCBs and SSBs. When cement or

	lime joint and plaster mortars are included, the KBBs contain the highest values for the energy consumed and CO2 emitted. The results suggest the need to switch from KBBs to other energy and carbon-efficient materials and a call to sound sectoral policy to tackle the effects of climate change in Malawi and beyond.
Mali [89]	The system is modeled and simulated with TRNSYS program for Bamako, Mali and the results show that 6,648 MJ of energy can be provided per year and the solar contribution is 0.96, i.e., 96% of the needs for hot water for a 4-6 persons family are satisfied with solar energy => The results show that such a system can provide 6,648 MJ of energy per year and the solar contribution is 0.96, i.e.,96% of the needs for hot water are satisfied with solar energy. By considering a rate for electricity equal to 0.16 US$/kWh, the payback time is 2 years and the life cycle savings, representing the money saved because of the use of the system throughout its life (20 years)instead of using conventional energy (electricity), is US$ 2,200. With respect to the life cycle assessment, the pollution created for the production of the system is estimated by calculating the embodied energy invested in the manufacture, assembly and installation of the collectors and other parts of the system. For the present thermosyphon system the embodied energy is found to be equal to 4,283 MJ.
Mali [90]	In this case-study located in Southern Mali, a comparative lifecycle assessment was perfomed to highlight the influence of smallholder participation and yield fluctuations on the global warming potential, fossil resource depletion and energy demand of Jatropha-based rural electrification in comparison to a fossil fuel-based reference. => The energy efficiency and fossil depletion of Jatropha-based electricity are favourable relatively to the equivalent fossil-based electricity generation. However, whether or not the Jatropha system attains lower global warming potential (GWP) than fossil energy depends on the yield level. On average, under the conditions that lead to the smallest harvest, the GWP of fossil electricity is lower than the GWP of Jatropha bioenergy. With higher yields, the GWP decreases, and from circa 2t/ha, it becomes low enough for Jatropha to become a viable and sustainable alternative to fossil fuels. It can be concluded that the environmental sustainability of a centrally operated system inclusive of smallholder cultivation depends on the success of the harvest and the productivity of the crop.
Mali [91]	While the concept of insect-based feeds (IBFs) promises great potential, especially in developing countries, the sustainability performance of IBF production remains widely underexplored. => The results show that the input efficiency in the production of IBF is largely determined by the quality of rearing substrates, the larval development time, and the employed inoculation practises, i.e., the method by which eggs or larvae are added to rearing substrates. The H. illucens system ranked highest for conversion efficiency (substrate input per IBF output), but showed substantially higher inputs in labor, fossil energy, and wastewater output.
Mali [92]	This study improved the global application of methods and analyses, especially Life Cycle Assessment (LCA), that properly incorporates environmental impacts of firewood and a social sustainability indicator (human energy) as

	tools for sustainable human development. => Human energy (entirely from women) contributed 25–100% of shea butter production processes(2000–6100 kJ/kg of shea butter) and mechanized production processes had reduced human energy without considerably greater total energy. Firewood accounted for 94–100% of total embodied energy (103 and172 MJ/kg of shea butter for improved and traditional shea butter production processes, respectively) and global warming potential and 18–100% of human toxicity of the production processes. Implementation of improved cookstoves modeled in this study could reduce: (1) global warming potential by 78% (from 18 to 4.1 kg CO2eq/kg and 11 to 2.4 kg CO2 eq/kg of shea butter for the traditional and improved processes respectively), (2)the embodied energy of using firewood by 52% (from 170 to 82 MJ/kg and 103 to 49 MJ/kg for the traditional and improved processes respectively), and (3) human toxicity by 83% for the non-mechanized traditional and improved processes (from 0.041 to 0.0071 1,4 DB eq/kg and 0.025 to 0.0042 1,4 DB eq/kg respectively).
Mali [93]	Cotton is the most produced natural fibre in the world, with an annual output of 23 million t of lint in the period2000–2013. Africa produced in average 6% of that output, and despite being a relatively minor contributor to global cotton supply chains, it has been estimated that a large percentage of the continent's population depends on cotton cultivation for their livelihood. Most published cotton LCAs focused on the main global producers (India, China, USA), a few consider African cotton, and none to date Malian cotton. => A single score–based contribution analysis confirms that pesticide application is the main contributor to impacts, followed by mineral fertilizers, for conventional cotton. For organic cotton, the main drivers of impacts are natural pesticides and organic fertilisation. The overwhelming contribution of pesticides is largely due to the provision of organophosphorus compounds, specifically the insecticide profenofos. Moreover, the ginning phase contributed very little to theoverall impacts (up to 3%). When data uncertainty is considered, the impacts per t of lint are always lower for organic cotton. Conclusions Impacts were generally larger for conventional than from organic cotton. The main hotspots are related to pesticide use,and therefore, efforts should focus on that factor, despite pesticide inputs being already relatively lower than elsewhere.Climate change indicators for Malian cotton products were compared with literature values, having similar orders of magnitude. Malian cotton production features lower yields than the main global producers do, which is mainly due to low soil fertility and, to a lesser extent,to its dependence on rainwater. A shift towards organic cotton would be desirable only if the yield gap can be overcome.
Mauritania [94]	This article presented a Life Cycle Assessment (LCA) methodology to assess and compare the environmental impacts related to the capture, processing and exportation of packed frozen octopus from this fishery to the main importing nations. => Environmental results show that common frozen octopus presented a remarkable dominance of the fishing vessel activities due to the fishery's high energy intensity and the fact that the activities include harvesting, processing, and preliminary packaging. Post-harvesting activities presented low relative contributions in all impact categories, minimizing the food mile effect of exporting to Japan, thanks to the slow transportation through marine freight of frozen octopus.

Mauritius [96]	This case study aimed to identify and review the significant areas of potential environmental impacts across the whole life cycle of cane sugar on the island of Mauritius. => The inventory of the current sugar production system revealed that the production of one tonne of sugar requires, on average, a land area of 0.12 ha, the application of 0.84 kg of herbicides and 16.5 kg of N-fertilizer, use of 553 tons of water and 170 tonne-km of transport services. The total energy consumption is about 14235 MJ per tonne of sugar, of which fossil fuel consumption accounts for 1995 MJ and the rest is from renewable bagasse. 160 kg of CO2 per tonne of sugar is released from fossil fuel energy use, and the net avoided emissions of CO on the island due to the use of bagasse as an energy source is 932,000 tonnes. 1.7 kg TSP, 1.21 kg SOz, 1.26 kg NOx and 1.26 kgCO are emitted to the air per tonne of sugar produced. 1.7 kg N,0.002 kg herbicide, 19.1 kg COD, 13.1 kg TSS and 0.37 kg PO4 3-are emitted to water per tonne of sugar produced. Cane cultivation and harvest account for the largest environmental impact(44%) followed by fertilizer and herbicide manufacture (22%),sugar processing and electricity generation (20%), transportation (13%) and cane burning (1%).
Mauritius [97]	Mauritius generates around 1200 tonnes of municipal solid wastes on a daily basis, out of which more than 60% is of organic nature. The objective of this paper was to evaluate two different strategies for the treatment of organic wastes on a life cycle perspective, namely: composting and Anaerobic Digestion (AD). => The gaseous emissions of NH3, H2S and HC were very low compared to emissions of CO2 and CH4 for both composting and AD. The photochemical oxidant formation had a highest score of 0.0742 (a* 10–12) for AD, whereas for composting, the largest score obtained was for global warming. Including the energy recovery from methane in the system, boundaries decreased the overall environmental index for the AD process from 0.135 to 0.013.For island states such as Mauritius where land is a severe limitation, an impact category such as land use would be a valuable parameter to consider in decision-making about the choice of biological waste treatment technologies.
Mauritius [99]	Disposal of the increasing volume of used Polyethylene Terephthalate (PET) bottles has been a cause for concern for the Mauritian Government. Three disposal scenarios, namely (100%) landfilling; (100%) incineration; and50% landfilling and 50% incineration, were compared => The results showed that about 90% of the total environmental impact happened during the assembly and use phase of PET bottles. 100% incineration was found to be the most preferred option
Mauritius [100]	This study aimed to assess the environmental impacts associated with the disposal of Municipal Solid Waste (MSW) in Mauritius through incineration and landfilling from a life cycle perspective. Two scenarios were considered; scenario baseline, which considered the landfilling of the waste and Scenario 1 which considered waste incineration. => The study showed that incineration of MSW brought significant avoided impacts in many categories, particularly in the category of resource damage due to the process of energy production. Incineration of 300,000 tonnes of MSW was found to avoid the depletion of 1 × 108 MJ of energy reserves. Scenario (S1) was

	found to contribute the least in terms of environmental damage.
Mauritius [101]	In this respect, the present study investigated and compared the environmental and social impacts of four selected disposal alternatives of used PET bottles. => Environmental impacts of the four disposal alternatives, namely: 100 % landfilling, 75 % incineration with energy recovery and 25 % landfilling, 40 % flake production(partial recycling) and 60 % landfilling and 75 % flakeproduction and 25 % landfilling.highest environmental impacts occurred when used PET bottles were disposed by 100 %landfilling while disposal by 75 % flake production and25 % landfilling gave the least environmental load.
Mauritius [102]	This paper investigated the environmental impact of five waste management scenarios (100%landfill; 100% incineration with energy recovery; 50% incineration and 50% landfill; 34% flake production and 66% landfill;100% flake production) for used PET bottles in Mauritius. => The comparison also indicated that there were least impacts on the environment when all used PET bottles were incinerated and the corresponding energy was recovered. Both the scenarios that incorporated incineration (Scenarios 2 and 3) performed better than the actual scenario, i.e. Scenario 4.However, pending the introduction of incineration plant in Mauritius and policy measures to enable 100% separate collection, Scenario 4 becomes the most appropriate waste management option for used PET bottles.
Mauritius [103]	The annual rise in population growth coupled with Mauritius's flourishing tourism industry has led to a considerable increase in the amount of solid waste generated. This study investigated the environmental impacts and the cost-effectiveness of four selected disposal alternatives for used PET bottles in Mauritius. The four disposal routes investigated were: 100% landfilling;75% incineration with energy recovery and 25% landfilling; 40% flake production (partial recycling) and 60% landfilling; and 75% flake production and 25% landfilling. => Thus, the hierarchy from most preferred to the least preferred scenario is established as follows: Scenario 4 (75% flake production and 25% landfilling); Scenario 2 (75% incineration and 25% landfilling); Scenario 3 (40% flake production and 60% landfilling);and Scenario 1 (100% landfilling). Damage costs or externalities had important bearings on two scenarios (scenario 1 and 2) and made them economically non-viable, while inclusion of damage costs in scenarios 3and 4 (the recycling scenarios) resulted in increasing the respective NPVs and lowering their payback period.
Mauritius [104]	The current paper evaluated for the first time the life cycle environmental impacts of electricity generation in Mauritius aiming to inform electricity generators and policy makers on how the impacts could be reduced => The electricity from coal had a much higher impact than in other counties (the global warming potential(GWP) of electricity from coal is estimated at 1444 kg CO2 eq./MWh, about 6 times the minimum value obtained in the literature). This is explained by the low efficiency of the plants, the lack of abatement technology for PM2.5, SO2, and NOx, as well as the higher Sulphur content of the coal used. The GWP of the

	electricity mix in Mauritius was estimated at 868 kg CO2 eq./MWh. Impacts could be descreased by reducing the share of fossil fuels in the electricity mix through an increased use of renewables as well as by improving the efficiency of the fossil power plants and stimulating a reduction in energy demand.
Morocco [106]	The case study focused on off-season tomatoes produced in Morocco under unheated greenhouses in a water-scarce area, which covers 68% of the fresh tomatoes imported to France. => Freshwater use had greater impacts under the arid Moroccan climate: 28.0 L H2Oeq/kg of Moroccan tomato and 7.5 L H2Oeq/kg of French tomato. Conversely, the higher level of artificialisation of the French production resulted in greater impacts on total energy consumption, global warming, eutrophication, even including transport to France for the Moroccan tomato. The comparison of the environmental impacts of the Moroccan and the French tomatoes shows that the inclusion of the impacts of freshwater use is critical, revealing a trade-off between usual impact categories, mostly energy-related, and freshwater use impacts. The current freshwater impact assessment method is not complete and probably leads to underestimating the impacts for the Moroccan tomato study case. Aquifer overuse causing water depletion and salinization is not properly addressed. In addition, impact assessment methods should be based on a reliable inventory.
Morocco [107]	In most published LCA on perennial crops, the agricultural production is based on data sets for just one productive year. This may be misleading since performances and impacts of the system may greatly vary year by year and the evolution of the stand over the cycle induces specific mechanisms (nutrient re-mobilization, yield alternating, resistance etc.) that must be included. Three modeling choices for the perennial crop cycle were tested in parallel in two contrasted LCA case studies: oil palm fruits from Indonesia, and small citrus from Morocco => The baseline scenario included a complete modeling of the crop cycle while a 3-year average scenario and 3 single year scenarios were also tested. Key insights from these two analyses were consistent:1. non-productive years have a large share in the environmental impacts of orchards and should be included;2. choosing one single year from the full production phase leads to highly uncertain results and should be avoided especially for strongly alternating yield crops;3. even a 3-year average scenario is not sufficient to capture properly the full perennial crop cycle and can be misleading 4. an effort should therefore be made to include the whole crop cycle ideally based on real data when available or at least on expert knowledge
Morocco [108]	Fruits are under growing scrutiny regarding their environmental impacts. However, fruit cropping systems have seldom been studied using life cycle assessment (LCA). As part of the Agribalyse project,the cropping systems for apple and peach in France, clementine in Morocco, and mango in Brazil were evaluated with a cradle-to-farm-gate LCA in order to include the manufacturing, transportation and utilization of all inputs used on the farm. => It can be observed that except for terrestrial acidification and marine eutrophication, the results are higher for all the other impacts categories in Morocco. Several reasons explain these results: at first, the higher amount of fertilizer used (6 kgN/kg). The high amount of water needed to grow clementine (8000 m3/hectare compared

	with 2.767 for Apple grown in France), despite the fact that water is scarce in Morocco and it has to be withdrawn from more than 100 meter-deep wells. The energy required to pump this water is also important (22,830 MJ per hectare compared with 2,946 for Mango grown in Brazil). Moreover, the Moroccan electricity mix is more than 50% based on fossil energy (coal), which explains why the impact of climate change is also high. Morocco is concerned about the environmental impact of energy consumption. Therefore, it pushes for a shift to renewable energy, with Ouarzazate Solar Power Station opening in 2016, a 510MW capacity solar power station located in the country's central part.
Morocco [109]	This paper aimed to evaluate the environmental impact of a commercial High concentrated photovoltaic (HCPV) plant located in Morocco by determining its impact on a wide range of environmental categories. => Climate change impact was found 53.3 kg CO2 eq/MWh, with most of the impacts were associated with the extraction of raw materials and manufacturing of components, being aluminum and steel materials with higher impacts. The power plant components manufacturing and the electricity consumption from the grid presented a high impact in the plant's life cycle, implying a significant importance of the local electricity mix ((electricity mix in Morocco is highly dependent on fossil fuels)). The country of location can significantly affect the impact of the plant's life cycle, not only because of the local solar irradiance, but also due to the nature of the electricity mix thatis consumed onsite during plant operation and in the local manufacturing of certain components. Extending the life expectancy of the HCPV plant improves the environmental performance of the plant.
Morocco [111]	Three modeling choices for the perennial crop cycle were tested in parallel in two contrasted LCA case studies: oil palm fruits from Indonesia, and small citrus from Morocco. => In both case studies, the modelling choices to account or not for the whole perennial cycle drastically influenced LCA results. The differences could be explained by the inclusion or not of the yearly variability and the accounting or not of the immature phase, which contributed to 7–40 or 6.5–29 % of all impact categories for oil palm fruit and citrus, respectively. The chosen approach to model the perennial cycle influenced the final LCA results for two contrasted case studies and deserved specific attention.
Morocco [113]	The objective of this article was to evaluate the environmental impacts of a sector of the automotive industry. => The impacts of climate change and human health representing the same impact value 27% to produce a headrest. The transportation category accounts for a larger share of all impacts. Followed by the use and manufacture of polyurethane foam, after the other components of the headrest.
Morocco [114]	In this study, a sustainability assessment have been applied to a facility comprising a hybrid solar/biomass micro-cogeneration organic ranking cycle system located in Morocco => Regarding environmental results, LCA shows a climate change potential of 11.8 g CO2 eq/kWhel (For instance, if GHG results are compared to the NREL harmonization of CSP, results are in line with those compiled

	(10–50 g CO2/kWhel) (NREL, 2018)),of which more than 70% comes from the boiler operation and specifically from the emissions due to biomass transportation. These results can help in promoting micro solar-biomass systems in Morocco as they identify the socioeconomic and environmental benefits that can counterbalance the higher costs of such systems compared to fossil technologies.it would also lead to a decrease of fossil fuel imports, increasing the energy security of Morocco reducing the economic dependency.
Morocco [115]	A thermal analysis of the performance of a solar water heater system installed for domestic use to satisfy the hot water needs of a family composed of five members is studied. => The results demonstrate that the solar energy systems prevent the release of significant amounts of greenhouse gas emissions (around 75%). The total embodied energy needed to manufacture a flat plate collector using the embodied energy index (MJ/kg) is calculated at 2875 MJ . The total embodied energy needed for the manufacture and installation of the complete solar system was calculated at 7245 MJ.
Morocco [116]	A life cycle assessment (LCA) was carried out to evaluate the environmental impact of a wastewater treatment plant (natural lagoon) located in Ain-Taoujdate city in Morocco. Construction and operation phases were assessed, only the decommissioning phase was not included => The most important potential impacts were global warming, terrestrial acidification, marine and freshwater eutrophication, terrestrial ecotoxicity, freshwater and marine ecotoxicity. This is justified by the microbiological activity coming from the different ponds of the plant. The second simulated scenario showed that a WWTP with aerated lagoon contributes in the same way as a WWTP with natural lagoon type at "discharges and emissions" phase, except at operation phase where the second scenario takes part in a more significant way to the environmental impacts. This study highlightedthe importance of opting for renewable energies as an alternative source for wastewater treatment plants, since the second scenario (AL) would be favorable for such situation, since on-site systems are mainly based on electricity and this treatment technique is well known, more efficient in terms of purification efficiency and less productive of greenhouse gases.
Mozambique [117]	In order to assess whether biofuels truly have a higher water use than do fossil fuels, a life cycle assessment study of a low input jatropha plantation in northern Mozambique was conducted. In addition to different water use indicators, the fossil energy use and global warming potential were assessed for 1 MJ of jatropha oil. => The green water footprint indicates that the water use of jatropha oil is much higher than that of fossil diesel, since it is nil for fossil diesel. The blue water formation, however, is so high for jatropha oil that it by far outweighs its bluewater footprint. Furtherermore, is it shown that the jatropha yield may heavily influence the result for different water use indicators. This finding implies that comparisons of different biofuels and comparisons with fossil fuels need to be done carefully, retaining the specific site's connection. The results also showed that the global warming potential of jatropha oil is similar or lower than that of fossil diesel, and that the fossil energy use of jatropha oil is lower than that of fossil diesel.

Mozambique [118]	By using surplus land for biomass production, Mozambique could produce wood pellets for domestic use or export to the European market to meet increasing demand. => The results showed an initial cooling effect of the pellet systems studied due to carbon sequestration in soil and biomass, counteracting the temperature warming effect from greenhouse gas emissions associated with the production system. The temperature cooling effect of carbon sequestration increased most in the beginning of the studied time period, while the temperature warming effect from the production system continued to increase, resulting in a net temperature warming effect overtime.
Nigeria [120]	Developing countries throughout the world currently fuel kitchen stoves for cooking by burning wood responsible for many health and environmental problems. Multiple biodigester designs were tested under conditions specific to various third-world countries; the countries tested were Nicaragua, Bolivia, Nigeria, India and Indonesia. => TEA results indicated that tube digesters are the most cost-effective method of anaerobic digestion in all countries tested; tube digestion at a family scale ranged from approximately $0.24 per meal to $0.73 per meal. The LCA showed that operation of anaerobic digestion required much more water than previously considered, which may cause it to not be a sustainable method. However, it did emit a much lower amount of carbon dioxide than burning wood. The CO2emissions per meal ranged from 0.97 kg per meal to 1.29 kg per meal. The water impacts ranged from 76 L/meal to 100 L/meal.
Nigeria [121]	This paper examined the environmental implications of residential building construction in a Nigerian context using embodied energy as an index of measurement with a view to identifying areas that could benefit from innovative strategies. => Nevertheless, the results obtained point to the areas that need intervention in order to reduce embodied energy intensity. In this respect, the building frame and the recurring embodied energy component were identified. For the former, the use of low energy materials will suffice while for the latter, low energy and durable materials would be preferred. Specifically, the contribution of portland cement, steel reinforcement and painting should be targeted for embodied energy reduction. Cement substitutes and the use of low energy composite panels as well as durable materials are recommended.
Nigeria [122]	In this study, life cycle assessment (LCA) methodology was used to determine municipal solid waste (MSW)management strategy for Minna, Nigeria. Three scenarios were modeled as alternatives to the current waste management system in Minna. The baseline scenario was the existing open dumping waste management strategy operating in Minna presently and this was used as the reference and chosen as the benchmark in which all the three modeled scenarios were measured and compared. => In the context of the five impact parameters considered, scenario 1 with 17.05% Recycling (9.36%plastics, 1.30% metals and 6.39% glass), 50.04%Compost and 32.91% Landfill is the best and most favorable alternative in term of ecotoxicity, eutrophication, acidification, carcinogen and global warming potentials in Minna. This research work showed that scenario 1 had the greatest reduction in global warming, carcinogen, ecotoxicity and

	acidification potentials of Minna city when the recycling was increased from baseline of 1.5% to total recycling of 17.05%(9.36% plastics, 1.30%metals and 6.39% glass).
Nigeria [123]	This paper proposed the use of Jatropha biodiesel as a substitute fuel to petroleum diesel. It examines the energy efficiency and environmental life cycle impact of the production and use of 1MJ of Jatropha biodiesel in a typical126 MW (ISO rating) industrial gas turbine power plant with multi-fuel capability using life cycle assessment methodologies and principles. => A net energy ratio of 2.37, 1.54, and 1.32 and fossil fuel savings of 58%, 36% and 27% were achievable under three farming system scenarios: a) base-case rain-fed, b)base-case irrigated and c) large scale farming system. Also, an environmental benefit with GHG savings of 19% was attainable under the three farming scenarios. The results demonstrate that the contribution of GHGs and effect on climate change is most significant with the end-use of the fuel.
Nigeria [124]	The study was designed to assess each unit's production processes of shea butter to identify hotspots using life cycle assessments (LCA) in South-western Nigeria. Scenarios were drawn for the impact assessments. Material sourcing from Kaiama, Scenarios 1, 3 and Minna Scenarios 2, 4 but different heat supply sources (Liquefied Petroleum Gas „LPG‟ Scenarios 1, 2 and 10.8 kW Diesel Heater, scenarios 3, 4) => Main processes affecting GWP, AP and EP were the milling, churning and packaging unit processes, and the inclusion of the clarification process in Scenarios 3 and 4. Diesel fuel was predominantly the major fuel used in operating all machines except in some cases when liquefied petroleum gas was used. A comparison among the four scenarios indicated that scenario 4 (S.BHeaterMinna) gave the greatest impact on the environment for all midpoint impact categorisation while Scenario 1 (S.BGasKaiama) showed the lowest impact. The highest impact category among others in shea butter production was GWP. Since petrol was the major fuel used in the transportation of raw shea kernels purchased, Minna transportation distances about 3.5 times Kaiama distances showed a great effect of shea kernel purchasing distance to the production site.
Nigeria [125]	This paper provided the environmental impact of integrating renewable energy systems to the utility-grid based on a baseline optimized energy production data from "HOMER" forrenewable systems modelling of a site in northern Nigeria. => On the specific environmental impact categories analyzed, it could be
Nigeria [126]	Existing dams in Nigeria have in recent times been considered for retrofit to generate hydroelectricity to meet the energy needs of its growing population. => The life cycle environmental impacts according to 1 MWh of electricity to be produced were appraised for all three options and range between 1.60 and 5.52 kg CO2eq. of GWP, 32 and 66 MJ of ADP fossil, 0.0004

	and0.0150 kg SO_2 eq. of AP, 0.41 and 1.80 kg DCB eq. of HTP, and 0.022 and 0.030 kg DCB eq. of FAETP. The construction stage accounts for the largest share of overall environmental impacts. As the global imperative for sustainable energy builds and with hydroelectricity proposed as one aspect of a sustainable energy profile, the upgrading of existing dams for hydropower installations is by far the lowest cost renewable energy available today. It can sometimes provide additional energy at far lesser cost than the cost of a new project.
Nigeria [127]	This paper assessed the environmental impacts associated with the production, storage, and disposal of cowpea grains in Ilorin, Kwara State, Nigeria,and offer ways of improving and reducing some of the environmental impacts associated with the system. Three scenarios were created in the cowpea study; production and storage in an inert atmosphere silo, hermetic storage, and cold shock (freezer) storage, respectively. => It was obtained that the Global Warming Potential (GWP) for the three scenarios were 6.7, 6.46, and 8.82kg CO_2-equivalent for inert, hermetic and cold shock, respectively. Acidification Potential (AP)values for the three scenarios were: 0.0105, 0.01 and 0.0121kgSO_2 equivalent respectively,Eutrophication Potentials (EP), were 1.68, 1.56, and 2.012e-3kg phosphate equivalent respectively.Ozone layer depletion potential (ODP) gave same values each in the scenarios with 9.99e-13kgR11equivalent, and human toxicology potential (HTP) values for each were 0.181, 0.151 and 0.24kgDCB equivalent respectively. Diesel and petrol fuel used for tillage and post farm operations respectively were major hotspots in the scenarios.
Nigeria [128]	In this research, the energy consumption pattern in cassava production, and its environmental burden were considered. => The results from the findings showed that crop protection, planting operation, land preparation, harvesting and packing consumed 16764.83, 5057.32, 5011.46 and 294MJ/ha which represented 61.80%, 18.64%, 18.48%and 1.08% respectively of the total energy consumption. Other energetic parameters and their value determined in cassava production were, energy productivity (1.47 kg/MJ),energy ratio (8.95) and net energy gain (215672.39 MJ/ha). The percentage non-renewable energy and renewable energy consumed were 78.40% and 21.60%, respectively. The environmental impacts associated with cassava production include global warming potential (GWP) (8.025E+01 kg CO_2 equiv.), acidification potential (AP) (1.8892E-02 kgSO_2 equiv), eutrophication potential (EP) (6.7375E-01 kg NO_3 equiv.), and ozone layer depletion potentials (OLDP) (2.9981E-04 kg RII equiv.)
Nigeria [129]	The study was undertaken to investigate the energy input and output of a group of citrus research farms in Nigeria. => About 87% of the total energy inputs used in sweet orange production was from direct sources (seeds, fertilizers, manure, chemicals, machinery) and 13% was from indirect sources (human labor, diesel). Mean orange yield was about 41000 kg ha-1. The net energy and energy productivity value was estimated to be 31.3 GJ ha-1 and 0.88 kg MJ-1, respectively. The ratio of energy outputs to inputs was found to be 1.67. This indicated an intensive use of inputs in sweet orange production not accompanied by an increase in the final product.

Nigeria [130]	This paper presented the life cycle environmental impacts and economic costs of the passenger transport sector in Nigeria for 2003–2030. => Increasing the use of buses would reduce the environmental impacts on average by 15–20% compared to BAU; simultaneously,the total fuel costs would be 25–30% lower. It has also been shown in this study that gas flaring contributes up to 15% of the life cycle environmental impacts from passenger transport.
Nigeria [131]	Agricultural operations have been indicated to be some of the major emitters of greenhouse gases (GHG), particularly methane (CH4) and nitrous oxide (N2O) around the globe, and it is important to determine the quantity emitted and how they can be reduced. The environmental impacts associated with field production and industrial processing of soybean into crude vegetable oil in Nigeria. => The functional unit was defined as one kilogram of soy bean. This study's environmental impact categories are global warming, acidification, eutrophication, and ozone layer depletion. Of these four environmental impacts, global warming has the highest impact score of 4.7516E-01 kg CO2 equivalent, followed by eutrophication (1.6414E-04 kgNO3 equivalent). Ozone layer depletion has the lowest environmental impact score of –2.8207E-07 kg R11 equivalent. The high impact score of global warming is due to the high emission of CO2 gas from fossil fuel and biomass combustion during field operations and processing of soybeans. To reduce the environmental impact of soybean production and processing, the use of fuel derived from biological sources such as biodiesel in internal combustion engines instead of fossil fuels is recommended. This will in turn reduce the emission causing global warming associated with fertiliser production and transportation.
Rwanda [133]	Based on the cradle-to-farm-gate LCA results of the tomato in Rwamagana district in Rwanda commissioned by the European Union, the main objectives of the paper were to validate statistically the differences in environmental impacts among expert-based types for this crop based on location and season and identify the key drivers of these impacts => Consequently, for most impact categories, the first group with mainly plots in marshland during wet season had the least impacts, the third group with plots in hillside showed the worst impacts. The second group composed of plots in marshland during the dry season generally showed intermediate impacts due to water withdrawing for irrigation. The second group obtained a greater freshwater ecotoxicity due to a greater use of toxic insecticides. Compared to existing datasets, all groups showed high freshwater ecotoxicity impacts due to toxic insecticides and excessive use of mancozeb. The third group also showed a high freshwater eutrophication in relation to P losses due to erosion and low yield.
Senegal [134]	Southern pink shrimp (Penaeus notialis) are an important Senegalese export commodity. Artisanal fisheries in rivers produce 60%. Forty percent are landed in trawl fisheries at sea. => Results for typical LCA categories include that artisanal fisheries have much lower inputs and emissions in the fishing phase than does the industrial fishery. For the product from artisanal fisheries, the main part of the impact in the standard LCA categories occurs during processing on land, mainly due to the use of heavy fuel oil and refrigerants with high global warming and ozone depletion potentials. If developing countries can ensure biological sustainability of their fisheries and design the chain on land in a resource-efficient way, long-distance

	to markets is not an obstacle to sustainable trading of seafood products.
Somalia [135]	According to UNICEF and World Health Organization (UNICEF and WHO, 2009) diarrhoeal109 diseases are the second major reason of mortality of children under five years old, killing around 1.5110 million of them every year. This situation is extremely aggravated in Africa, where the mortality111 rate due to unsafe water, hygiene and sanitation services is triple that of the global rate; e.g., in112 Somalia, more than 60,000 cases of suspected cholera have been reported between January and113 August 2017 and more than 800 people have died =>
South Africa [137]	The aim of this paper was to evaluate and compare the applicability of these European LCIA procedures within the South African context, using a case study. The five European methods have been evaluated based on the applicability of the respective classification, characterisation, normalization and weighting approaches for the South African situation. => In most cases impact categories and procedures defined in the LCIA methods for air pollution, human health and mined abiotic resources are applicable in South Africa. However, the relevance of the methods is reduced where categories are used that impact ecosystem quality, as ecosystems differ significantly between South Africa and the European continent. The methods are especially limited with respect to water and land resources. Normalization and weighting procedures may also be difficult to adapt to South African conditions, due to the lack of background information and social, cultural and political differences.
South Africa [138]	The environmental life cycle assessment (LCA) methodology was used in this study to calculate and compare the environmental burdens resulting from two different methods employed in the production of potable water in South Africa. One method employs conventional processes for the treatment of water and the other one is based on membrane filtration. =>
South Africa [139]	Various LCIA methods have been developed in Europe, which can be applied directly to provide a comparatively quick indication of the environmental influences of the industrial and economic systems evaluated. However, problems have been experienced with these methods in South Africa in terms of their comprehensiveness and modelling approaches. The scope, therefore, exists to develop a specific LCIA method for South Africa. => The resource impact indicators that are calculated through the framework aim to provide a simpler means to compare equally the impacts of a lifecycle system on the four main natural resource groups of water, air, land, and mined abiotic resources. The impact indicators on water, air and land resources take into account the current and target burdens on human health and ecosystem quality in four defined regions. The mined abiotic resource indicators consider the current and projected mineral and energy reserves a national level.
South Africa [140]	The LCIA procedure is dependent on a comprehensive life cycle inventory (LCI) of the evaluated life cycle system. Water usage is included in LCIs, and is incorporated in LCIA procedures as direct extraction from available resources. However, the environmental burdens associated with water supply extend beyond

	extraction and include non-renewable energy use, materials use, land use, and pollution of air, soil and water resources. An LCA study was subsequently undertaken to identify key environmental aspects that should be considered where water is used in the manufacturing sector of South Africa, and to identify possible shortcomings in the LCA tool. => An introduced LCIA framework for South Africa was used to determine the extent of different environmental impacts. Based on the interpretation of the LCIA it is concluded that the actual extraction of the water from the ambient environment is in fact the most important consideration. The toxicity potential impacts on water resources, mainly due to the water supply system's required electricity, are of secondary importance. However, the extent of the impact due to water extraction is not accurately reported in the water use category of the LCIA profile, due to the lack of appropriate categorisation factors.
South Africa [141]	The objective of this study was to generate information on the environmental profile of the life cycle of water, including treatment, distribution and collection and disposal (including recycling), in an urban context. As a case study the eThekwiniMunicipality (with its main city Durban) in South Africa was used. Another aim of the study was to compare the environmental consequences for the provision of normal, virgin potable water vs. recycled water to the industry in Durban. => This study shows that energy consumption and the losses in urban water systems are the most important factors contributing to these systems' environmental burdens. Reducing the losses is important, not only because of the savings associated with the treatment and distribution of water but in a water-stressed country and in a catchment where demand is projected to outstrip supply, water is a resource that no longer can be wasted. Therefore, quantification of losses and active measures to reduce them is a priority action in order to increase the environmental performance of urban water systems in South Africa. As the improvement analysis showed, there are different options to address these 2 priority areas and each option or combinations thereof have different outcomes. It has to be underlined that energy efficiency is directly linked to the pumping requirements of the system and in turn these requirements are determined by the local conditions in which distances and elevations play an important role. Therefore, energy assessments of urban water systems can not be generalised and efficiency of systems/processes has to be researched ina case-by-case approach.
South Africa [143]	The present study provided the first example of a Life Cycle Assessment (LCA) quantifying the future environmental benefit of i-Site for support of a radio base station in South Africa. =>Specially avoidance of diesel combustion and the electricity efficient air cooling solution for i–Site (loopthermosyphone and DC Fan) and are behind these positives. The payback times for energy and CO2 are reasonable. The effect on the financial payback time results of added CO2 costs beyond increased diesel/electricity costs is a 2% reduction.
South Africa [144]	This study presented the results of a comparative life cycle assessment (LCA) on the energy requirements and greenhouse gas (GHG) emission implications of recycling construction and demolition (C&D) rubble and container glass in Cape Town, South Africa. =>The results indicated that recycling container glass instead of landfilling can achieve an energy savings of 27%

	and a GHG emissions savings of 37%, with a net savings still being achieved even if collection practices are varied. The C&D waste results, however, showed net savings only for certain recycling strategies. Recycling C&D waste can avoid up to 90% of the energy and GHG emissions of landfilling when processed and reused onsite but, due to great dependence on haulage distances, a net reduction of energy use and GHG emissions could not be confidently discerned for off-site recycling. It was also found that recycling glass achieves significantly greater savings of energy and emissions than recycling an equivalent mass of C&D waste.
South Africa [145]	Quantified environmental impacts associated with clay brick production are notvery well researched for the South African context. This paper, based on a study undertaken for the Clay Brick Association of South Africa, where clay bricks arestill the predominant wall construction material, identifies processes within thevarious clay brick firing techniques, where environmental impacts are the mostsevere, with the intention to make producers aware of where they may improve production processes and reduce adverse environmental impacts
South Africa [146]	A screening of LCA for the evaluation of the damage arising from the life cycle of a bi-layer film bag for food packaging was carried out. Such packages are made of films obtained matching a layer of PA (Polyamide)with one of LDPE (Low-Density Polyethylene) and are mainly used for vacuumor modified atmosphere packaging and preservation of food. =>The study allowed to demonstrate what we already expected, namely that the total damage, due to the bag production, can be reduced by thinning the thickness of the films. In particular, the use of 65 µm thick films would lead to a reduction of the total damage by about 25%: the eventual production and marketing of this type of bag would prove the Firm's interest of making a significant mark in implementing environmental sustainability
South Africa [147]	Three alternative processes for the production of liquid transportation biofuels from sugar cane bagasse were compared, on the perspective of energy efficiencies using process modelling, Process Environmental Assessments and Life Cycle Assessment. Separate Hydrolysis and Fermentation (Process 1) and Simultaneous Saccharification and Fermentation(Process 2), in comparison to Gasification and Fischer Tropsch synthesis for the production of synthetic fuels (Process 3) => The more advanced bio-ethanol process was Process 2 and it had a higher energy efficiency at 42.3%. Heat integration was critical for the Process 3, whereby the energy efficiency was increased from 51.6% to 55.7%. For both the Process Environmental and Life Cycle Assessment, Process3 had the least potential for detrimental environmental impacts, due to its relatively high energy efficiency. Process 2 had the greatest Process Environmental Impact due to the intensive use of processing chemicals. Regarding the Life Cycle Assessments, Process 1 was the most severe due to its low energy efficiency.
South Africa [148]	A life cycle assessment approach was used to model primary fossil fuel energy inputs and greenhouse gas emissions associated with the production of sugarcane in South Africa. => Despite higher energy inputs in the irrigated North, greenhouse gas emissions are similar for sugarcane

	produced in each region. Green cane harvesting reduces energy inputs and greenhouse gas emissions by 4% and 16%, respectively, in both regions however impacts of mechanization soil compaction and stool damage result in lower yields and proportionally higher energy inputs and greenhouse gas emissions.
South Africa [150]	This paper presented the results of a study comparing the life cycle environmental impacts and cumulative energy demands of reading printed books (print system) with those of reading e-books from anApple Air iPad (digital system), with a specific focus on production of books and use of both options in South Africa. => When the two systems are compared in terms of impact potentials, the digital system emerges as the environmentally preferred system for certain impact categories, including climate change, ozone depletion,terrestrial acidification, marine eutrophication,human toxicity, photochemical oxidant formation,particulate matter formation, terrestrial ecotoxicity,ionising radiation, agricultural land occupation,urban land occupation, natural land transformation,water depletion and fossil depletion. The stages with the highest contribution to the impact potentials and cumulative energy demand for the print system are the printing and paper stages. Electricity produced in South Africa using hard coal also features as a one of the main contributing processes in these stages. Mining also features prominently in fossil depletion potential and urban land occupation, and the disposal of coal mining waste is the main contributing process for freshwater eutrophication potential.The other major finding is that the print systemhas much larger land-based impacts than the digital system, because of the large amount of wood needed to produce books. The impact potentials for agricultural land occupation, urban land occupation,and natural land transformation are significantly higher for the print than the digital system
South Africa [151]	Lactic acid (LA) is considered for the diversification and value addition to sugar industry in South Africa. => The total environmental savings of the major impact categories obtained upon replacing a tonne of fossil-based LA with biobased LA are: 3925.65 kg CO2eq. of global warming potential; 1742.05 kg fossil fuel eq. of abiotic depletion potential; 1296.16 kg 1,4-DB eq. of human toxicity potential; 397.79 kBq U235eq.of ionizing radiation potential; 253.97 kg Fe eq. of metal depletion potential; 43.48 kg 1,4-DBeq. of marine aquatic ecotoxicity potential; 42.97 kg 1,4-DB eq. of freshwater aquatic eco-toxicity potential and 18.23 kg SO2eq. of acidification potential. Auxiliary chemicals used in the biobased LA production are most relevant to the total environmental impacts. Thus, biobased LA production has significantly reduced the impact on the environment, giving 80–99% environmental savings compared to fossil-derived LA.
South Africa [152]	South Africa was the first country in Africa to implement a locally developed green building rating tool and has a growing number of rated green building projects. At present, more than 70% of all sawn timber in South Africa is used in buildings, mainly in roof structures. several roof truss systems were compared (South African pine, Biligom and light gauge steel) found in low- and medium-income house designs in South Africa using a simplified life-cycle assessment approach. => Both cradle-to-gate and cradle-to-grave analyses, the two timber alternatives – Biligom and South African pine truss systems – showed significantly lower environmental impact than LGS. For the smaller truss system,

	LGS had about twice the GWP impact of the timber systems, and the normalised impact overall environmental indicators was about 40% higher. The benefit of biogenic carbon dioxide and low embodied energy present in timber proved to play a significant role in the GWP impact and could be further reduced if wood were used at its end-of-life to generate energy and substitute for fossil fuel use.
South Africa [153]	The aim of this study was to determine the environmental mitigation potential of replacing grid-powered irrigation in South African maize production with photovoltaic irrigation systems using Life Cycle Assessment. The study included the value chain of maize production from cultivation to storage. => Replacing grid electricity with photovoltaic-generated electricity leads to a 34% reduction in the global warming potential of maize produced under irrigation, and—applied at a national level—could potentially reduce South Africa’s greenhouse gas emissions by 536,000 t CO_2-eq. per year. Non-renewable energy demand, freshwater eutrophication, acidification, and particulate matter emissions are also significantly lowered
South Africa [154]	This study investigated biogas plant potentialities to reduce emissions from poor waste management both at the feedlot and at the abattoir stage of the South Africa beef and pork value chain. => Electricity generation from the biogas and possibly usage of co-produced heat would further reduce GHG emissions by about 1.56 Mt CO_2eq per year, reducing beef and pork's carbon footprints by 10% and 30%, respectively. Even more significant reductions of both AC and EU impacts should be achievable by avoiding mostly landfilling of wastes and over-fertilization of soils.
South Africa [155]	Detailed techno-economic evaluationand Life Cycle Assessment (LCA) were applied to model alternative routes for converting sugarcane residues(bagasse and trash) to selected biofuel and/or biochemicals (ethanol, ethanol and lactic acid, ethanol and furfural,butanol, methanol and Fischer–Tropsch synthesis, with co-production of surplus electricity) in an energy self-sufficient biorefinery system. => LCA results demonstrated that sugarcane cultivation was the most significant contributor to environmental impacts in all of the scenarios, other than the furfural production scenario in which a key step, a biphasic process with tetrahydrofuran solvent, had the most significant contribution.
South Africa [156]	In this study, alternative lignocellulose biorefineries annexed to a typical Sugarmill were investigated to co-produce ethanol (EtOH), lactic acid (LA), and/or electricity, utilizing bagasse and a component of harvesting residues (brown leaves) as feedstock. Studied scenarios included EtOHas the sole product from glucose and xylose (Scenario 1), LA as the sole product from these two sugars(Scenario 2), EtOH from glucose and LA from xylose (Scenario 3), and EtOH from xylose and LAfrom glucose (Scenario 4), all of which were associated with some level of export electricity production. => To service the combined energy demands of a sugar mill and annexed biorefinery, a 35 to 40% bypass of lignocellulose directly to the boiler section was required to achieve integrated scenarios that were energy self-sufficient, i.e., not dependent on external (fossil)energy sources. Scenario 2 was economically most attractive

	with the highest internal rate of return(IRR) of 31.1%, whereas Scenario 1 had the lowest IRR of 10.0%. Scenarios 2 and 4 were economically the most robust, with the least sensitivity to variations in the key economic drivers, i.e., EtOH, LAand enzymes. The LCA suggested that LA producing scenarios introduced environmental burdens that were marginally higher than Scenario 1, due to higher consumption of processing chemicals. Overall, Scenario 4 was found to be the most desirable biorefinery scenario.
South Africa [157]	Different biorefinery scenarios were investigated in this work concerning the co-production of bioethanol and electricity from available lignocellulose at a typical sugar mill, as possible extensions to the current combustion of bagasse for steam and electricity production and burning trash on-filed. In scenario 1, the whole bagasse and brown leaves is utilized in a biorefinery, and coal is burnt in the existing inefficient sugar mill boiler. Scenario 2 & 3 are assumed with a new centralized CHP unit without/with coal combustion, respectively. Also, through scenarios 4 & 5, the effect of water-insoluble loading were studied. => Based on LCA results, all scenarios have environmental benefits over the combustion of bagasse in the Sugarmill for steam/electricity production, while zero coal consumption (bypass of 35% of feedstock to the boiler) delivered the lowest environmental burdens.
South Africa [159]	The life cycle assessment of several zinc oxide (ZnO) nanostructures, fabricated by a facile microwave technique, was presented. => It was found that synthesis temperature and microwave power are inversely proportional to environmental sustainability, i.e. high temperature and microwave power lead to reduced environmental footprint. The reason is that with a small increase in the total electricity consumption the ZnO nanostructures surface area. It was found that the main environmental weaknesses identified during the production process were; (a) the use of ethanol for purifying the produced nanomaterials and (b) the electricity consumption for the ZnO calcination, provided by South Africa's fossil-fuel dependent electricity source.
South Africa [161]	This study used life cycle assessment (LCA) tool to evaluate the overall impact of artisanal sandstone mining (ASAM) on the environment and human health. => Transportation phase consumed most energy and non-renewable resources and contributed the most to global warming, climate change and ozone layer depletion. The combustion of diesel fuel contributed highest to energy use (about 97%) and ozone layer depletion. The amount of global warming and climate change potential was estimated to be 12.164 kg CO_2 per tonne of sandstone produced. Acidification potential was estimated to be 0.01632 kg SO_2 per tonne of sandstone produced as a result of the combustion of diesel fuel in truck engine. ASAM water use impact was determined as 12 l per tonne of sandstone produced. Since no standardized characterization method for water use is available in the LCA framework, the assessment for this impact category was not performed. Impacts on land use are limited because quarrying takes place in area with sparse vegetation and limited biodiversity.

South Africa [163]	A “cradle-to-grave” life cycle assessment(LCA) approach was adopted to study the use of NMT in comparison with conventional pour-flush toilet (PFT)and urine-diverting dry toilet (UDDT) => The human health impact category of the system,with and without the inclusion of the environmental credits related to the generatedash, against that of the UDDT system has been, respectively, 144% and 154% higher, whereas against that of the PFT system it has been 54%and 43% lower. In the case of the resources impact category, the value of the aforementioned NMT systems is 95% and 105% higher than that of the UDDT system. On the contrary, when compared with the PFT system the respective value of the two examined NMTsystems is 103% and 97% lower, correspondingly. Lastly, in terms of the ecosystems impact category, the NMT system scenarios, with and without the inclusion of ash as fertilizer, exhibit a higher value by 90% and 101% as compared to the UDDT system and a lower value by 99% and 106% that that of PFT system.
South Africa [164]	This study used secondary data from literatures to develop a life cycle inventory on farming, crushing and conversion capacity of soybean and then conduct LCA of soybean biodiesel production in South Africa. => The FER of soybean biodiesel was estimated to be 2.25, i.e. biodiesel yields 125% more energy than the energy required to produce it. This shows that biodiesel has more useful energy than the energy used to make it. The production and use of soybean biodiesel reduced GHG emissions by 31.5% compared to that of fossil diesel. their value of 1.49 indicates that making biodiesel on average returns 1.49 times the cost of the energy input.
South Africa [166]	Two of the methods currently considered are desalination of seawater and reuse of mine-affected water based on the use of reverse osmosis (RO) membranes. => A detailed investigation of both water treatment processes revealed that the desalination process has a greater overall environmental impact than the mine-water reuse process, mainly due to the increased energy requirements. As the results indicate that plant impacts are highly dependent on the electricity supply source, further investigations of the substitution of fossil fuel–based energy with renewable energy were undertaken. It was calculated that the use of solar or wind energy could significantly reduce the climate change effect (i.e. reduce GHG emissions) of using seawater and mine-affected water to levels that are comparable to conventional water treatment processes currently employed in the eThekwini Municipality.
South Africa [169]	This study compared the environmental impacts associated with five straw material options available in South Africa. The straw materials compared include disposable options (polypropylene, paper and polylactide) and reusable straws(glass and steel). Plastic straws were the only locally produced option from local materials, whereas glass and steel straws are manufactured from imported materials and paper and polylactide straws are imported. => Material production was the major contributor to straw emissions, for all material options. The relative contribution of transportation, including import of materials and straws, was dependent on the form of transportation used whereby higher variations were observed for changes in road transportation distances. In the case of reusable straws, washing water temperature was found to significantly influence emissions. From a

	marine pollution perspective, reusable straws were deemed to have the least risk due to their unlikelihood to be littered.
South Africa [170]	Using the current state of life cycle assessment (LCA), carbon and water footprinting, and EPDs in South Africa, this work explored the challenges and opportunities for scholarly development in these areas in the country => 27 LCA studies, 17 water and 12 carbon footprinting, and 10 EPD studies were found. Although these studies have potential advantages for policymaking and business, their number, implementation, and impact remain limited.
South Africa [171]	The environmental sustainability of wastewater treatment through phosphate (P) and ammonia (N)chemical precipitation (struvite) was examined using the life cycle assessment methodology. => Therefore, this work suggests that when using the low dosage, struvite precipitation can act as a fast, efficient, and environmentally friendly pre-treatment method, particularly in cases where raw wastewater is directly released to the environment. In these cases, which include rural and peri-urban SouthAfrica and Lesotho, struvite recovery systems could be a very efficient and fast alternative to effectively treat wastewater, instead of releasing it untreated to the environment. However, for village- or industrial-scale applications higher feed dosages and contact times might be required.
South Africa [172]	In this study, life cycle assessment (LCA) methodology and mechanistic modeling were used to quantify the environmental benefits of improved management of water and fertilizer N by sugar cane farmers in a case study in Pongola, South Africa. => The overall environmental impact of sugar cane production can be reduced significantly not only at crop production stages but also through the co-generation of electricity using sugar cane fibre and bio-ethanol generation.
South Africa [173]	This study compared a life cycle assessment (LCA) of pork production in the Western Cape with pork production in Flanders. => Flemish GWP, eutrophication potential, acidification potential and energy use are 56%, 65%, 62% and 59% respectively of the Western Cape equivalents. The exporting of pork accounts for less than 8% of environmental impacts in all impact categories.
South Africa [174]	Two processes were compared by means of Life Cycle Assessment (LCA) to determine which one causes less environmental impact for the treatment of saline mining wastewater: Eutectic Freeze Crystallisation (EFC) or Evaporative Crystallisation (EC). => According to the LCA results for the modelled 4 wt.% Na2SO4 solution, the EFC process is strongly preferred to EC as it uses 6–7 times less non-renewable energy to produce the same set of products. There was a decrease of [70–95%] for the “global warming” impact category (independent of the geographical context) when

	comparing EFC to EC. But the impacts of "ionizing radiation" may be 15% higher for EFC if the source of electricity used is dominated by nuclear power.
South Africa [175]	Two different raw water desalination technologies, an existing ion exchange plant, and a proposed reverse osmosis intervention, were compared by life cycle assessment for the production of 1 Mℓ of boiler feed water. => A significant finding from the LCA includes that, despite sourcing electricity from a power station that desalinates highly saline mine water, the RO intervention would strongly reduce salinisation risks in the studied system, without shifting salts problems from one place to another. However, for impact categories relating to abiotic resource depletion and greenhouse gas emissions, the RO intervention is associated with an approximately 22% poorer environmental performance compared to IX system.
South Africa [176]	Life cycle assessment has been used to investigate the global warming potential (GWP) and fossil-energy requirements of the production of biodiesel from canola (oilseed rape), soybean, and sunflower oils in South Africa. => This research showed that the GWP and fossil-energy requirements of biodiesel produced in South Africa vary widely, depending upon predominantly the crop yield, the requirement for irrigation, and the ploughing of uncultivated land. For the best case scenario, where no uncultivated land is newly ploughed and irrigation is not required, biodiesel has a GWP 20-36% lower than that of the fossil dieselmix currently used in South Africa and a fossil-energy requirement 50-62%.
South Africa [177]	The scope of the paper focused on the seed extraction biodiesel production scenarios of the strategy. => Water usage is a highly variable parameter, which emphasises the importance of rainfall and irrigation to the overall burden of the biodiesel system on water resources. Crop yields may differ by a factor of two, which is a significant difference in terms of land and non-renewable energy resources requirements.
South Africa [179]	The environmental life cycle assessment (LCA) methodology was used in this study to calculate and compare the environmental burdens resulting from two different methods employed in the production of potable water in South Africa => In conclusion, for both methods of producing potable water, the life cycle is dominated by the operational stage. This stage has the highest material and energy consumption and the highest environmental scores for all the impact categories considered. The decommissioning stage is the least important one and the construction stage has an intermediate, but minor position. The most important process to which most of the environmental burdens for producing potable water are traced is the generation of electricity. This process dominates all environmental impact categories for the operation stage, for both methods considered.
Tanzania [181]	This paper presented the environmental assessment of the centralized grid-connected electricity production in Tanzania using a life cycle approach for the years 2000,2015, 2020, 2026, and 2030, according to the Tanzania Electricity Supply Company Limited, TANESCO's, plans for power system expansion (power system master plan of the year 2009)

	=> The proposed power system master plan would have considerably higher environmental impacts compared to year 2000. The environmental burden in all categories could be reduced through increased energy efficiency and increased participation of renewables, especially hydropower, for which there is an ample potential in Tanzania, as well as other renewables such as wind power. If the power system master plan is followed about 1530 MW of hydro resource potential will still remain unused.
Tanzania [182]	This paper evaluated GHG emissions and energy balances (i.e. net energy value (NEV), net renewable energy value (NREV) and net energy ratio (NER)) of jatropha biodiesel as an alternative fuel in Tanzania by using life cycle assessment (LCA) approach. The functional unit (FU) was defined as 1 tonne (t) of combusted jatropha biodiesel. => The findings of the study prove wrong the notion that biofuels are carbon-neutral, thus can mitigate climate change. A net GHG equivalent emission of about 848 kg/y was observed. The processes which account significantly to GHG emissions are the end-use of biodiesel (about 82%)followed by farming of jatropha for about 13%. Sensitivity analysis indicates that replacing diesel with biodiesel in irrigation of jatropha farms decreases the net GHG emissions by 7.7% while avoiding irrigation may reduce net GHG emissions by 12%.
Tanzania [183]	This study assessed the environmental toxicity potential of the centralized grid-connected electricity-generating systems for the years 2000, 2015, 2020, 2026 and 2030, according to the Tanzania Electricity power system master plan of the year 2009. => The result shows an increase in environmental toxicity potential within the time frame mainly due to an increase in the share of electricity generation from fossil fuels. From the study, fossil fuel-based power plants have a higher contribution of impacts per megawatt-hour. This suggests that the proposed power system master plan would have significantly high environmental toxicity potential that would certainly have serious implications on environmental profile and the public health.. Furthermore, since this study had to rely much on secondary data, there is scope for improving future studies results.
Tanzania [184]	A case study comparing extensive, low-yielding smallholder maize production with an intensified, high-yielding production system (‘sustainable intensification’) was used to illustrate potential trade-offs between agricultural product carbon footprints (PCFs) and land use (LU). => A comparison of the LU indicators of the different systems can highlight the risk of LUC and help interpret PCF results. If this is not done, there is a risk that PCF results may be misinterpreted, and agricultural systems that have low PCFs but exert a large pressure on land resources may be encouraged, unintentionally causing significant carbon emissions due to land conversion to agriculture.In conclusion, the success and benefits of sustainable intensification on existing agricultural land should not be assessed based on direct impacts only.
Tunisia [187]	Here, the system is not only anthropogenic, but also includes both natural behaviours and pollution aspects from human activity: it is a coastal lagoon with varied activities and waste disposals nearby. => The concentrations of the phosphorus and nitrogen compounds were considered for the calculation of the

	AEP and their spatial and temporal variations in the lagoon. The results showed that the AEP of the phosphorus exceeds the AEP of nitrogen systematically and that the contents of both are systematically higher in summer than in winter. Nitrogen is the limiting factor for the algae growth. Ammonia and phosphates are the most important nutrients for the AEP in summer, whereas nitrates dominate in winter.
Tunisia [188]	Life cycle assessment (LCA) methodology was applied in order to compare two growing facility systems: a traditional raceway (TR) and a cascade raceway (CR) in Tunisia. => The analysis revealed that the major part of the energy consumption was due to rearing phase through water pumping and oxygen injection and production, with 175,000 MJ/tonne and 280,000 MJ/tonne, for TR and CR, respectively. For all the studied impacts, the assessment revealed that CR presented more environmental burden than TR. The current study has shown that feed processing is the main contributor to a number of impact categories in the life cycle of the intensive land-based systems. Any measures decreasing and optimising the use and the process of feed, will have an impact on the overall environmental performance. Most important is to optimise the diet formulation, since high effects of feed composition(marine sources) combined with a poor feed conversation rate induces high nutrient loading into the sea and high primary production requirement
Tunisia [189]	The purpose of this paper was to evaluate the energy performance and potential of Jatropha Curcas for biodiesel production in Tunisia. => Clearly, most energy consumption occurs at the transesterification stage, which accounts for 53% of the total energy use. This step is expensive and increases the cost of biodiesel production. Technical advancement and R&D progress could reduce the high cost of this stage. Additionally, they could increase the competitiveness of JCL biodiesel vis-à-vis the alternative fuels. To conclude, the total energy mobilised by JCL biodiesel reached 29,889.5 MJ/ha, whereas the energy output is about 12580 MJ/ha. Therefore,–17,309.5 MJ/ha is the net energy deficit (NED). The energy balance of JCL biodiesel is negative; JCL biodiesel production required 42% more fossil energy than the biodiesel fuel produced.
Tunisia [190]	LCA tool was implemented to quantify the potential environmental impacts associated with the activated carbon (AC) production process from olive-waste cakes in Tunisia. => The results showed that impregnation using H_3PO_4 presented the highest environmental impacts for the majority of the indicators tested: acidification potential (62%), eutrophication (96%), ozone depletion potential (44%), human toxicity (64%), fresh water aquatic ecotoxicity(90%) and terrestrial ecotoxicity (92%). One of the highest impacts was found to be the global warming potential (11.096 kg CO_2 eq/kg AC), which was equally weighted between the steps involving impregnation, pyrolysis, and drying the washed AC. The cumulative energy demand of the AC production process from the by-product olive-waste cakes was 167.63 MJ contributed by impregnation, pyrolysis, and drying the washed AC steps. The use of phosphoric acid and electricity in the AC production were the main factors responsible for the majority of the impact.
Tunisia [191]	This paper aimed at using LCA to assess the environmental impacts of contrasted groundwater pumping systems in semi-arid central Tunisia. The results confirm that for groundwater pumping, energy has the highest

	environmental impacts on human health, the ecosystem, and resource depletion. => In line with previous studies, our results confirm that for groundwater pumping, energy has the highest environmental impacts on human health, the ecosystem, and resource depletion. This work also highlighted that along with pump efficiency, the type of power source must be considered when ranking pumping systems based on environmental performance. Indeed, diesel-powered pumping systems are more harmful than electric pumps when electricity is generated from natural gas and diesel-powered pump efficiency is low. However, the diesel pumping system becomes the best option when electricity is derived from coal and diesel-powered pump efficiency exceeds 12%.
Tunisia [192]	This paper presented an environmental impacts during hydraulic fract shale gas in Tunisia. => The two steps contribute 68.2% to 98.25% of the potential impacts evaluated. Stages of site preparation and closing wells contribute marginally to the potential impacts evaluated. The production stage (including the activities of compression and dehydration) and distribution stage (including production, transportation and installation of gas pipes to connect the compressor station to the distribution system) affect slightly(1.6% to 31.77%) the environmental profile of shale gas.
Tunisia [193]	This study used footprint indicators, the water, land and carbon footprint, to assess natural resources use and greenhouse gas emissions for sheep and chicken meat produced in Tunisia in different farming systems in the period 1996–2005 => Poultry production is relatively large and based on imported feed. The farming systems considered are: the industrial system for chicken, and the agro-pastoral system using cereal crop-residues, the agro-pastoral system using barley and the pastoral system using barley for sheep. Chicken meat has a smaller water footprint (6030 litre/kg), land footprint (9 m2/kg) and carbon footprint (3 CO2-eq/kg) than sheep meat (with an average water footprint of 18900 litre/kg, land footprint of 57 m2/kg, and carbon footprint of 28 CO2-eq/kg).
Tunisia [194]	The study aimed to understand the influence of rearing practices and the contributions of production phases of fish farming to their environmental impacts and determine which practices and technical characteristics can best improve the farms' environmental performance. The approach consisted of three major steps: (i) of the 24 aquaculture farms in Tunisia, 18 were selected which follow intensive rearing practices in sea cages of European seabass (Dicentrarchus labrax) and gilthead seabream (Sparusaurata), and then a typology was developed to classify the studied farms into rearing practice groups using HCPC; (ii)LCA was performed on each aquaculture farm and (iii) mean impacts and contributions of production phases were calculated for each group of farms. => The study revealed that rearing practices and fish feed were the greatest contributors to the impacts studied. FCR, which is directly influenced by feeding practices, contributed most to most impacts. Low efficiency of fish feed use emits large amounts of N and P into the environment. Based on this finding, it was concluded that optimising fish feed use and production would positively influence overall environmental performance,

	especially because protein and lipids required by cultured fish are principally provided by fish meal and oil.
Tunisia [195]	Life Cycle Assessment (LCA) was applied to assess potential environmental impacts generated by production of1 ton of European seabass (Dicentrarchus labrax) and gilthead seabream (Sparus aurata) on a sea-cage aquaculture farming in Tunisia => Fish feed is the main contributor to most of the impacts studied,which is directly related to production of fish meal and oil as feed ingredients and the large amounts of nitrogen and phosphorus released into the environment. Fish reared on the farm require large amounts of protein and lipids, whichare provided mainly by fish meal and fish oil from wild-fish stocks.
Tunisia [198]	The Gulf of Gabes is one of the most productive fishery areas in the southern Mediterranean Sea. Life Cycle Assessment (LCA) was applied to assess the environmental performance landing1 t of seafood with wooden demersal trawlers in the Gulf of Gabes. => Results showed that 70% of the vessels had relatively low impacts. Impact intensity was proportional to the amount of fuel consumed to land 1 t of seafood. Ships that fished less had the highest impacts per ton, due to lower fishing effort and catch per unit effort. This is likely to typify vessels that target highly valuable species such as shrimp. Onboard vessel activities contributed most to different environmental impacts (AP, EP, GWPand POFP), related to the high energy use of this fishery. Several impacts (ADP, ODP, METP, LOP, andTCED) were associated mainly with fuel and lubricating oil production.
Tunisia [200]	A multi-criteria environmental impact assessment based on life cycle analysis (LCA) was conducted at the regional level on the Kairouan Plain (Tunisia) where groundwater withdrawals for irrigation purposes are constantly increasing. => Results highlight that the main processes contributing to the impacts on resources—when overlooking impacts on water depletion—are: energy used for groundwater pumping (23%), fertilization (30%), i.e. road transportation of manure (21%), ammonium nitrate manufacturing (9%), and also the manufacturing of irrigation pipes (13%).
Tunisia [201]	Despite the advantages that tomato production has on the economic balance of Tunisia, it may present an environmental pressure on the natural ecosystem. => The results obtained showed that fertilizers and energy sub-systems were the most contributing in the majority of the impacts.The production of 1 ton of tomato emits about 954 kg CO_2-eq. Moreover, waste treatment sub-system engendered an avoided global warming, land use, water resources depletion and abiotic resources depletion potential impacts. Finally, the studied system presented a relatively low water footprint due to the use of geothermal water for irrigation. The sensitivity analysis showed that substituting electricity source from natural gas to renewable sources (biomass, photovoltaics, and hydropower) could improve the tomato

	production system's environmental performance. A total of 1.33 m3 of freshwater resources were used to produce1 ton of tomatoes. Fertigation sub-system was behind 73% of water use. The acidification potential of the studied system is about 8.09 molc H + eq. Around 79% of the total impact is caused by energy sub-system. The terrestrial eutrophicating emissions are about10.17 molc N-eq per ton of tomato produced. The sub-systems that contribute the most to this impact category are fertigation (41%) and energy (39%).
Tunisia [202]	A renewable electricity system hybrid concentrated solar power/biomass power plant in Tunisia was assessed. => Application of these methodologies allowed computing environmental footprint, and the total economic stimulation produced by the increase in the demand for goods and services needed to build and operate this kind of plant.Results show for system operates in closed digester conditions value of 18.5 gCO2eq per kWh.
Tunisia [205]	The aim of the study was to assess the environmental footprint of the most representative olive growing systems of the actual production of olive fruit in Tunisia, from the planting phase to the full production phase, during a reference period of the life cycle of the olive growth of 50 years. => Fertilizers and soil management were the field agricultural practices that presented the highest contributions in most of the categories evaluated. Especially, fertilizers presented high impacts in all categories in the innovative systems. Therefore, aiming to improve the environmental performance of olives production in Tunisia, the implementation of an integrated management, as well as good practice guides and training programs for farmers, should be considered a priority. The possibility of increasing the planting density in this region may be considered to increase crop production. The organic systems showed the lowest environmental impacts with respect to the traditional and conventional systems in all categories per both FUs. Optimizing the use of compost or using biological foliar fertilizers could be effective in improving the productivity in the organically grown olives.The most innovative olive production systems (intensive and super-intensive) resulted in less environmental impacts.
Uganda [206]	Assessing the life cycle of a specific sanitary pad, MakaPads, in Uganda defines unique and vital social equity measurements, especially for women laborers. => In terms of environmental consequences to cottage-based production of the African sanitary pad, MakaPads, it was found to be more environmentally friendly. These results were compared to Libresse specifically, but could be expanded to compare with other imported sanitary pads
Uganda [208]	This study aimed to quantify greenhouse gases(GHGs) from the production, transportation, and utilization of charcoal and to assess the possibilities of decreasing greenhouse gases (GHGs) from the charcoal industry in general in Uganda => The results showed that greenhouse gases emitted due to charcoal supply and use of traditional production technique in Kampala was 1,554,699 tCO2eq, with the transportation phase accounting for approximately 0.15 %of total greenhouse gases emitted. The utilization phase (charcoal cookstoves) emitted 723,985 tCO2eq (46.6 %), while the charcoal production phase emitted 828,316 tCO2eq (53.3 %).Changing the charcoal production technology from a traditional method to an improved production method (PYREGcharcoal process)

	resulted in greenhouse gases reductions for the city of 230,747 tCO2eq; however, by using sustainably sourced biomass, this resulted in reductions of801,817 tCO2eq.
Uganda [209]	In this study, the lifecycle assessment (LCA) method and qualitative data collected from household interviews were used to determine the environmental impacts associated with water sources and household treatment methods. => The dominant impact categories in the life cycle assessment were land use and climate change when considering perceived water quality because charcoal was used for boiling during the household treatment stage. On the other hand, the fossil fuels category is the dominant impact category for measured water quality because the source (centralized treatment)was the largest contributing stage. In contrast, rainwater posed the opposite scenario. When considering perceived water quality, survey respondents generally explained that rainwater was a clean, pure source with a preferable taste. As a result, there was no treatment practiced at the household level, thus yielding a very low environmental impact.
Zambia [212]	A lifecycle assessment including ecological, health, and resource impacts has been conducted for field sites in Zambia to evaluate biochar's overall impacts for agricultural use. The life cycle impacts from conservation farming using cultivation growth basins and precision fertilization with and without biochar addition were in the present study compared to conventional agricultural methods. Three different biochar production methods were evaluated: traditional earth-mound kilns, improved retort kilns, and micro top-lit updraft (TLUD)gasifier stoves. => The results confirm that the use of biochar in conservation farming is beneficial for climate change mitigation purposes. However, when including health impacts from particle emissions originating from biochar production, conservation farming plus biochar from earth-mound kilns generally results in a larger negative effect over the whole life cycle than conservation farming without biochar addition. The use of cleaner technologies such as retort kilns or TLUDs can overcome this problem, mainly because fewer particles and less volatile organic compounds, methane and carbon monoxide are emitted.
Zambia [213]	A lifecycle assessment including ecological, health and resourceimpacts has been conducted for field sites in Zambia to evaluatethe overall impacts of biochar for agricultural use. The life cycleimpacts from conservation farming using cultivation growthbasins and precision fertilization with and without biocharaddition were in the present study compared to conventional agricultural methods. Three different biochar production methods were evaluated: traditional earth-mound kilns,improved retort kilns, and micro top-lit updraft (TLUD)gasifier stoves. => The results confirm that the use of biochar in conservation farming is beneficial for climate change mitigation purposes. However, when including health impacts from particle emissions originating from biochar production, conservation farming plus biochar from earth-mound kilns generally results in a larger negative effect over the whole life cycle than conservation farming without biochar addition. The use of cleaner technologies such as

	retort kilns or TLUDs can overcome this problem, mainly because fewer particles and less volatile organic compounds, methane and carbon monoxide are emitted
Zimbabwe [214]	This research was aimed at assessing theinteraction between the High Density Polyethylene (HDPE) plastic carrier bag life cycle and theenvironment, hence identifying specific life cycle stages that pose significant threats to theenvironment =>
Zimbabwe [215]	This paper discussed the Life Cycle Assessment of newsprint paper in Zimbabwe. The product system used for the study covers the production of raw materials, the pre-combustion effects of coal and of electricity production. The data from the production of newsprint at Mutare Board and Paper Mills, the largest paper mill in Zimbabwe, is used. => The greatest contributor to carbon dioxide emission was the pulping and paper making processes due to the combustion of coal in the boilers. This results in a major contribution to the overall global warming. The pulping processes assume a predominant role in global warming impactcategory as a result of carbon dioxide emissions. Transportation is the main contributor to the eutrophication and contributes significantly to the acidification impact categories. The contribution of the disposal stage of the life cycle of the paper to environmental impacts needs to be explored.
Zimbabwe [216]	This paper discussed an application of the LCA methodology on the vehicle leaf spring, used on trucks, buses and trailers in Zimbabwe. => The main recommendations are on the need to use electrical energy more, particularly power from renewable sources. The use of energy-efficient modern technology, plant and process improvements and cleaner production activities will go a long way to prevent, reduce or eliminate environmental pollution in specific processes.
Zimbabwe [217]	This paper generated data that can be used to quantify total life cycle environmental impacts of cement production in Zimbabwe. Emissions of carbon dioxide, sulfur dioxide, nitrous oxides and solid waste occur. => The finish grinding section consumed more electrical energy than all the other stages. Respiratory inorganics produced mainly from cement kiln dust were found to have the greatest potential damage to health. This study has confirmed cleaner production assessment results which were presented in the paper showing that clinker production has the most impact on the environment followed by the cement milling, the final stage of cement production. Environmental improvements can be focused in these two areas to get the most benefit.
Zimbabwe [218]	In this paper a life cycle assessment (LCA) for steel balls used as grinding media in mines that are produced at Craster International in Zimbabwe was discussed. Knowing the life cycle environmental impacts of the steel balls is very important since they produce greenhouse gases in their production => Trace elements are in all the processes and their effects have been highlighted. Employees were also exposed to hazardous emissions during the production of steel and of the steel balls. Accidents affect not only the environment but also can cause human damage. Recommended damage mitigation steps include preventive

	maintenance of all machinery, regular medical checkups for employees and the community and use of sensing and alarm systems.
Zimbabwe [219]	Six municipal solid waste management (MSWM) options (A1–A6) in Harare were developed and analyzed for their global warming, acidification, eutrophication, and human health impact potentials using life cycle assessment methodology to determine the least impactful option in Harare. A1 and A2 considered the landfilling and incineration, respectively, of indiscriminately collected MSW with energy recovery and byproduct treatment. Source-separated biodegradables were anaerobically treated with the remaining non-biodegradable fraction being incinerated in A3 and landfilled in A4. A5 and A6 had the same processes as in A3 and A4, respectively, except the inclusion of the recovery of 20% of the recoverable materials. => The life cycle stages considered were collection and transportation, materials recovery, anaerobic digestion, landfilling and incineration. A5 emerged as the best option. Materials recovery contributed to impact potential reductions across the four impact categories.
Zimbabwe [220]	Composting and anaerobic digestion (AD) of biodegradable waste were assessed for their benefits from literature and environmental impacts using the life cycle impact assessment (LCIA) procedure. => LCIA results show that both AD and composting lead to increases across the four impact categories considered, namely, global warming, human health, eutrophication, and acidification. AD however, showed lower contributions than composting to global warming, human health, and acidification. Composting only showed lower contribution than AD with regards to eutrophication.

APPENDIX 1.2: Overview of the LIME3 method

Impact Category	Human Health DALY	Social Asset US$	Biodiversity EINES	Primary Production NPP	Important Parameters	G20 IF Low	G20 IF High
Climate Change	Malnutrition, diarrhea, cardiovascular disease, malaria, coastal flooding, and inland flooding	-	Terrestrial ecosystem (vascular plants)	-	Diseases Relative Risk against temperature, Average mortality per disease, Future population, Current and Future species distribution, Ratio of Area decrease	Same for all countries	
Air pollution	Chronic death, acute death, respiratory diseases	-	-	-	Total population, Population density, Age distribution, Pollutant dispersion	ARG BRA MEX	IND
Photochemical Oxidant	Chronic death, acute death, respiratory diseases	-	-	-	Total population, Population density, Age distribution, Pollutant dispersion	CAN USA	IND
Water	Waterborne infectious diseases, nutritional deficiency	-	-	-	Water scarcity, Economic adaptation capacity, International trade	ARG	KOR
Land Use	-	-	Terrestrial ecosystem (vascular plants)	Terrestrial ecosystem	National population of threatened species, Species distribution	CAN	IDN
Mineral resources	-	User cost	Terrestrial ecosystem (vascular plants)	Terrestrial ecosystem	Reserve to extraction ratio, International trade	BRA	GBR
Fossil resources	-	User cost	Terrestrial ecosystem (vascular plants)	Terrestrial ecosystem	Reserve to extraction ratio, International trade	SAU	GBR

APPENDIX 1.3: LIME3 integration factors used to calculate the external cost of electricity (Inside each category from dark green (Low integration factor) to dark red (High integration factor)).

	ARG	AUS	BRA	CAN	CHN	DEU	FRA	GBR	IDN	IND	ITA	JPN	KOR	MEX	RUS	SAU	TUR	USA	ZAF
CO2 ($/kg)	$1.71x10^{-2}$	$1.71x10^{-2}$	$1.71x10^{-2}$	$1.71x10^{-2}$	$1.71x10^{-2}$	$1.71x10^{-2}$	$1.71x10^{-2}$	$1.71x10^{-2}$	$1.71x10^{-2}$	$1.71x10^{-2}$	$1.71x10^{-2}$	$1.71x10^{-2}$	$1.71x10^{-2}$	$1.71x10^{-2}$	$1.71x10^{-2}$	$1.71x10^{-2}$	$1.71x10^{-2}$	$1.71x10^{-2}$	$1.71x10^{-2}$
SO2 ($/kg)	$6.18x10^{-1}$	1.02	$6.18x10^{-1}$	$7.87x10^{-1}$	4.33	2.84	2.84	2.84	1.02	5.11	2.84	1.58	4.33	$6.18x10^{-1}$	1.85	2.52	1.85	$7.87x10^{-1}$	1.240
NOX ($/kg)	$3.01x10^{-1}$	$4.47x10^{-1}$	$3.01x10^{-1}$	$4.02x10^{-1}$	4.96	2.11	2.11	2.11	$4.47x10^{-1}$	8.66	2.11	1.37	4.96	$3.01x10^{-1}$	1.16	1.31	1.16	$4.02x10^{-1}$	$5.23x10^{-1}$
NMVOC ($/kg)	$5.57x10^{-3}$	$9.41x10^{-3}$	$5.57x10^{-3}$	$4.63x10^{-2}$	$1.28x10^{-1}$	$8.11x10^{-2}$	$8.11x10^{-2}$	$8.11x10^{-2}$	$9.41x10^{-3}$	$6.69x10^{-2}$	$8.11x10^{-2}$	$4.25x10^{-2}$	$1.28x10^{-1}$	$5.57x10^{-3}$	$4.10x10^{-2}$	$3.15x10^{-2}$	$4.10x10^{-2}$	$4.63x10^{-2}$	$1.12x10^{-2}$
PM2.5 ($/kg)	1.80	4.14	1.80	3.22	$2.51x10^{1}$	$1.02x10^{1}$	$1.02x10^{1}$	$1.02x10^{1}$	4.14	$3.64x10^{1}$	$1.02x10^{1}$	$1.20x10^{1}$	$2.51x10^{1}$	1.80	4.21	9.15	4.21	3.22	4.05
Oil_R ($/kg)	$3.63x10^{-1}$	$1.57x10^{-1}$	$1.76x10^{-1}$	$1.32x10^{-1}$	$2.17x10^{-1}$	$2.12x10^{-1}$	$1.43x10^{-1}$	$4.08x10^{-1}$	$2.58x10^{-1}$	$5.50x10^{-2}$	$1.03x10^{-1}$	$3.23x10^{-2}$	$3.72x10^{-2}$	$3.62x10^{-1}$	$1.68x10^{-1}$	$2.49x10^{-3}$	$3.52x10^{-1}$	$2.21x10^{-1}$	$4.84x10^{-2}$
Coal_R ($/kg)	$2.12x10^{-3}$	$1.35x10^{-3}$	$1.98x10^{-3}$	$3.98x10^{-3}$	$2.92x10^{-2}$	$1.04x10^{-3}$	$1.76x10^{-3}$	$3.92x10^{-2}$	$6.84x10^{-2}$	$2.03x10^{-3}$	$1.77x10^{-2}$	$1.30x10^{-2}$	$2.42x10^{-2}$	$1.75x10^{-3}$	$6.12x10^{-4}$	$2.12x10^{-2}$	$3.41x10^{-2}$	$1.82x10^{-3}$	$1.78x10^{-3}$
NG_R ($/kg)	$4.13x10^{-2}$	$4.68x10^{-3}$	$1.75x10^{-2}$	$3.56x10^{-2}$	$1.28x10^{-2}$	$1.80x10^{-2}$	$3.68x10^{-3}$	$3.18x10^{-2}$	$1.02x10^{-2}$	$1.28x10^{-2}$	$1.13x10^{-2}$	$7.65x10^{-3}$	$7.61x10^{-3}$	$3.70x10^{-2}$	$1.98x10^{-3}$	$5.99x10^{-4}$	$1.60x10^{-3}$	$3.40x10^{-2}$	$8.76x10^{-3}$
Water ($/m3)	$1.60x10^{-4}$	$5.83x10^{-2}$	$2.95x10^{-2}$	$2.75x10^{-2}$	$3.04x10^{-1}$	$1.15x10^{-1}$	$9.98x10^{-2}$	$7.03x10^{-1}$	$1.02x10^{-1}$	$5.69x10^{-1}$	$1.90x10^{-1}$	$9.34x10^{-1}$	1.40	$2.43x10^{-1}$	$3.68x10^{-2}$	$8.35x10^{-4}$	$2.69x10^{-1}$	$3.32x10^{-1}$	$4.01x10^{-1}$
Ag ($/kg)	$5.64x10^{2}$	$2.01x10^{2}$	$6.40x10^{2}$	$8.88x10^{2}$	$7.62x10^{2}$	$5.04x10^{2}$	$6.65x10^{2}$	$6.65x10^{2}$	$6.47x10^{2}$	$5.64x10^{2}$	$6.65x10^{2}$	$1.19x10^{2}$	$5.56x10^{2}$	$9.46x10^{2}$	$5.10x10^{2}$	$5.64x10^{2}$	$5.64x10^{2}$	$5.95x10^{2}$	$5.95x10^{2}$
Al ($/kg)	$3.44x10^{-1}$	$1.02x10^{-1}$	$2.28x10^{-2}$	$2.43x10^{-2}$	1.07	$4.97x10^{-2}$	$1.22x10^{-1}$	1.14	2.45x10-1	$3.74x10^{-1}$	1.44	$2.25x10^{-1}$	$2.29x10^{-1}$	$6.37x10^{-1}$	1.03	$4.65x10^{-1}$	1.67	$3.37x10^{-2}$	$5.49x10^{-1}$
Au ($/kg)	$4.13x10^{4}$	$2.13x10^{4}$	$1.51x10^{4}$	$6.43x10^{4}$	$7.84x10^{4}$	$2.13x10^{4}$	$3.91x10^{4}$	$3.97x10^{4}$	$3.50x10^{4}$	$4.01x10^{4}$	$3.91x10^{4}$	$4.11x10^{4}$	$6.32x10^{4}$	$2.79x10^{4}$	$2.95x10^{4}$	$4.37x10^{4}$	$3.95x10^{4}$	$5.31x10^{4}$	$2.43x10^{4}$
Ce ($/kg)	$2.44x10^{-3}$	$2.43x10^{-3}$	$3.24x10^{-3}$	$2.42x10^{-3}$	$2.40x10^{-3}$	$2.42x10^{-3}$	$2.41x10^{-3}$	$2.43x10^{-3}$	2.43x10-3	$2.96x10^{-3}$	$2.42x10^{-3}$	$2.42x10^{-3}$	$2.41x10^{-3}$	$2.42x10^{-3}$	$2.41x10^{-3}$	$2.43x10^{-3}$	$2.41x10^{-3}$	$2.43x10^{-3}$	$2.43x10^{-3}$
Co ($/kg)	$1.01x10^{1}$	$1.05x10^{-2}$	3.03	$1.94x10^{1}$	4.89	$2.62x10^{1}$	$2.76x10^{-2}$	$1.01x10^{1}$	6.34	$2.20x10^{-1}$	$1.01x10^{1}$	$1.66x10^{1}$	$1.01x10^{1}$	$1.01x10^{1}$	$1.57x10^{1}$	$1.01x10^{1}$	$1.01x10^{1}$	$6.18x10^{1}$	4.91
Cr ($/kg)	9.93	9.94	9.95	$1.0x10^{1}$	$1.02x10^{1}$	$1.01x10^{1}$	$1.0x10^{1}$	9.96	9.94	$1.39x10^{1}$	9.97	$1.22x10^{1}$	$10-x10^{1}$	9.97	5.48	9.42	9.93	9.93	9.93
Cu ($/kg)	3.13	$1.99x10^{-1}$	4.48	8.26	3.39	3.12	3.22	6.74	4.28	3.20	3.19	3.84	3.22	$5.85x10^{-1}$	2.46	3.62	3.32	4.40	3.97
Eu ($/kg)	$1.30x10^{-1}$	$1.29x10^{-1}$	$1.24x10^{-1}$	$1.48x10^{-1}$	$1.23x10^{-1}$	$1.29x10^{-1}$	$1.26x10^{-1}$	$1.30x10^{-1}$	$1.30x10^{-1}$	$1.53x10^{-1}$	$1.27x10^{-1}$	$1.26x10^{-1}$	$1.25x10^{-1}$	$1.28x10^{-1}$	$1.24x10^{-1}$	$9.87x10^{-2}$	$1.25x10^{-1}$	$1.27x10^{-1}$	$1.30x10^{-1}$
Fe ($/kg)	$2.73x10^{-3}$	$8.87x10^{-3}$	$2.73x10^{-3}$	$7.50x10^{-4}$	$8.69x10^{-2}$	$5.71x10^{-3}$	$3.24x10^{-3}$	$1.57x10^{-2}$	$1.81x10^{-3}$	$4.74x10^{-2}$	$8.27x10^{-3}$	$1.32x10^{-2}$	$1.10x10^{-2}$	$1.10x10^{-2}$	$2.88x10^{-4}$	$5.28x10^{-2}$	$3.50x10^{-3}$	$1.15x10^{-3}$	$8.21x10^{-2}$
Gd ($/kg)	$4.56x10^{-1}$	$4.54x10^{-1}$	$4.42x10^{-1}$	$5.26x10^{-1}$	$4.41x10^{-1}$	$4.52x10^{-1}$	$4.46x10^{-1}$	$4.55x10^{-1}$	$4.54x10^{-1}$	$4.55x10^{-1}$	$4.49x10^{-1}$	$4.47x10^{-1}$	$4.45x10^{-1}$	$4.50x10^{-1}$	$4.43x10^{-1}$	$3.43x10^{-1}$	$4.44x10^{-1}$	$4.49x10^{-1}$	$4.55x10^{-1}$
La ($/kg)	$9.02x10^{-2}$	$8.96x10^{-2}$	$1.16x10^{-1}$	$8.93x10^{-2}$	$8.89x10^{-2}$	$8.95x10^{-2}$	$8.92x10^{-2}$	$8.97x10^{-2}$	$8.96x10^{-2}$	$1.08x10^{-1}$	$8.93x10^{-2}$	$8.93x10^{-2}$	$8.92x10^{-2}$	$8.94x10^{-2}$	$8.90x10^{-2}$	$8.98x10^{-2}$	$8.91x10^{-2}$	$8.97x10^{-2}$	$8.97x10^{-2}$
Li ($/kg)	$3.44x10^{-4}$	1.15	$3.80x10^{-1}$	$2.24x10^{-14}$	$1.03x10^{-1}$	$6.74x10^{-1}$	$5.16x10^{-1}$	$5.20x10^{-1}$	$6.10x10^{-1}$	$1.62x10^{-1}$	$2.43x10^{-1}$	$4.25x10^{-1}$	$6.10x10^{-1}$	$1.19x10^{-2}$	$1.50x10^{-1}$	$6.10x10^{-1}$	$6.10x10^{-1}$	$7.64x10^{-1}$	$1.32x10^{-1}$
Mn ($/kg)	$3.78x10^{-2}$	$8.86x10^{-1}$	$1.08x10^{-2}$	$6.55x10^{-1}$	1.62	$3.87x10^{-1}$	$1.07x10^{-1}$	$3.87x10^{-1}$	$9.43x10^{-1}$	$5.11x10^{-1}$	$4.03x10^{-1}$	$5.12x10^{-1}$	$7.07x10^{-1}$	2.11	$3.52x10^{-1}$	$4.93x10^{-1}$	$4.34x10^{-1}$	$5.48x10^{-1}$	$3.47x10^{-1}$
Mo ($/kg)	5.22	5.22	7.04	8.54	4.45	5.99	6.38	4.43	5.22	6.38	5.22	8.75	5.86	3.88	3.22	5.22	5.22	6.73	7.91
Nd ($/kg)	$1.05x10^{-1}$	$1.05x10^{-1}$	$1.37x10^{-1}$	$1.04x10^{-1}$	$1.04x10^{-1}$	$1.05x10^{-1}$	$1.04x10^{-1}$	$1.05x10^{-1}$	$1.05x10^{-1}$	$1.27x10^{-1}$	$1.04x10^{-1}$	$1.04x10^{-1}$	$1.04x10^{-1}$	$1.05x10^{-1}$	$1.04x10^{-1}$	$1.05x10^{-1}$	$1.04x10^{-1}$	$1.05x10^{-1}$	$1.05x10^{-1}$
Ni ($/kg)	$1.43x10^{1}$	$5.80x10^{-2}$	$8.67x10^{-2}$	$1.40x10^{1}$	$2.13x10^{1}$	$1.43x10^{1}$	1.33	$1.43x10^{1}$	$1.43x10^{1}$	$1.43x10^{1}$	$1.43x10^{1}$	$2.15x10^{1}$	1.33	$1.43x10^{1}$	$1.78x10^{1}$	$1.43x10^{1}$	$1.43x10^{1}$	$1.43x10^{1}$	$3.16x10^{-1}$
Pb ($/kg)	3.09	$7.33x10^{-1}$	2.75	3.21	3.35	2.97	2.75	3.09	2.94	1.89	2.75	1.55	1.46	1.09	3.09	2.75	3.09	2.53	4.34
Pd ($/kg)	$2.66x10^{4}$	$2.66x10^{4}$	$4.46x10^{3}$	$2.47x10^{4}$	$1.23x10^{4}$	$6.90x10^{3}$	$6.07x10^{3}$	$1.87x10^{4}$	$2.66x10^{4}$	$2.66x10^{4}$	$1.63x10^{4}$	$1.48x10^{4}$	$1.24x10^{4}$	$2.66x10^{4}$	$2.66x10^{4}$	$2.66x10^{4}$	$2.66x10^{4}$	$1.42x10^{4}$	$2.66x10^{4}$
Pr ($/kg)	$3.00x10^{-1}$	$2.98x10^{-1}$	$3.89x10^{-1}$	$2.97x10^{-1}$	$2.95x10^{-1}$	$2.97x10^{-1}$	$2.96x10^{-1}$	$2.98x10^{-1}$	$2.98x10^{-1}$	$3.60x10^{-1}$	$2.97x10^{-1}$	$2.97x10^{-1}$	$2.96x10^{-1}$	$2.97x10^{-1}$	$2.96x10^{-1}$	$2.98x10^{-1}$	$2.96x10^{-1}$	$2.98x10^{-1}$	$2.98x10^{-1}$
Pt ($/kg)	$2.88x10^{4}$	$3.88x10^{4}$	$2.25x10^{3}$	$2.37x10^{4}$	$2.37x10^{3}$	$1.21x10^{4}$	$3.46x10^{3}$	$5.62x10^{4}$	$2.88x10^{4}$	$2.88x10^{4}$	$1.88x10^{4}$	$1.52x10^{4}$	$1.75x10^{4}$	$2.88x10^{4}$	$1.19x10^{5}$	$2.88x10^{4}$	$2.88x10^{4}$	$8.72x10^{3}$	$2.88x10^{4}$
Re ($/kg)	$8.14x10^{2}$	$8.14x10^{2}$	$8.14x10^{2}$	$2.42x10^{3}$	$8.14x10^{2}$	$8.14x10^{2}$	$8.14x10^{2}$	$8.14x10^{2}$	$8.14x10^{2}$	$8.14x10^{2}$	$8.14x10^{2}$	$8.14x10^{2}$	$8.14x10^{2}$	$8.14x10^{2}$	$3.75x10^{-1}$	$8.14x10^{2}$	$8.14x10^{2}$	$1.90x10^{2}$	$8.14x10^{2}$
Sn ($/kg)	$2.01x10^{1}$	$2.01x10^{1}$	6.13	1.25	$2.44x10^{1}$	$2.01x10^{1}$	1.25	$2.01x10^{1}$	$2.34x10^{1}$	1.25	$2.01x10^{1}$	$2.01x10^{1}$	$2.01x10^{1}$	1.25	$4.08x10^{-1}$	$2.01x10^{1}$	$2.01x10^{1}$	$2.01x10^{1}$	1.25
Sr ($/kg)	$3.96x10^{-1}$	$4.48x10^{-1}$	$4.48x10^{-1}$	$4.48x10^{-1}$	$4.24x10^{-1}$	$6.00x10^{-1}$	$4.69x10^{-1}$	$4.79x10^{-1}$	$4.48x10^{-1}$	$4.48x10^{-1}$	$4.86x10^{-1}$	$5.49x10^{-1}$	$5.58x10^{-1}$	$6.53x10^{-1}$	$4.48x10^{-1}$	$4.48x10^{-1}$	$4.48x10^{-1}$	$6.28x10^{-1}$	$4.48x10^{-1}$
Ta ($/kg)	$1.07x10^{1}$	$1.80x10^{-1}$	$4.30x10^{-1}$	$1.62x10^{-1}$	$7.68x10^{-1}$	$1.07x10^{1}$	$3.49x10^{-1}$	$2.26x10^{-1}$	$3.49x10^{-1}$	$3.49x10^{-1}$	$3.49x10^{-1}$	$1.80x10^{-1}$	$3.49x10^{-1}$	$3.49x10^{-1}$	3.49x10-1	$1.07x10^{1}$	$1.07x10^{1}$	9.06	$1.56x10^{1}$
U ($/kg)	$4.46x10^{1}$	$1.94x10^{-1}$	$1.57x10^{-1}$	$3.02x10^{1}$	$2.18x10^{1}$	$1.27x10^{1}$	$2.35x10^{1}$	$2.80x10^{1}$	$2.82x10^{1}$	2.61	3.57	$3.05x10^{1}$	$3.05x10^{1}$	$2.80x10^{1}$	$7.50x10^{-1}$	$2.80x10^{1}$	$2.80x10^{1}$	6.88	$1.56x10^{-1}$
Zn ($/kg)	2.29	$7.77x10^{-1}$	2.74	3.46	2.97	2.72	1.50	2.29	2.29	2.65	2.31	1.54	1.53	$8.81x10^{-1}$	1.25	2.29	2.29	2.59	2.29
Zr ($/kg)	$1.19x10^{-1}$	$8.73x10^{-2}$	$5.13x10^{-1}$	$1.19x10^{-1}$	$1.61x10^{-1}$	$6.84x10^{-2}$	$5.35x10^{-2}$	$6.21x10^{-2}$	$4.39x10^{-1}$	$1.31x10^{-1}$	$7.53x10^{-2}$	$8.68x10^{-2}$	$9.75x10^{-2}$	$1.19x10^{-1}$	$1.53x10^{-1}$	$1.19x10^{-1}$	$1.19x10^{-1}$	$7.43x10^{-2}$	$3.84x10^{-2}$

APPENDIX 1.4. Inventory items having an influence on the external cost for each system.

	HC	Lignite	NG C/CC	Oil	Wind ON/OFF	GEO	Hydro RR	Hydro PS	Hydro R	Nuclear BW/PW	Solar OG	Solar Roof
AUS	1-CO_2 2-SO_2	1-CO_2 2-SO_2	1-CO_2 2-SO_2	1-Oil_R 2-CO_2 3-SO_2	Mineral	-	Various	1-CO_2 2-SO_2	-	-	1-LandO 2-Mineral	1-Mineral 2-Oil_R
BRA	1-CO_2 2-SO_2	1-CO_2 2-PM2.5 3-SO_2	1-CO_2 2-NG_R	1-Oil_R 2-CO_2 3-SO_2	Mineral	-	-		1-Water 2-LandT	Mineral	1-LandO 2-Mineral	1-Mineral 2-CO_2 3-Oil_R
CAN	1-CO_2 2-SO_2	1-CO_2 2-PM2.5	1-CO_2 2-NG_R	1-Oil_R 2-CO_2	Mineral	Various	Various	1-CO_2 2-Oil_R	1-Water 2-Mineral	Mineral	1-Mineral 2-LandO	Mineral
CHN	1-SO_2 2-CO_2 3-PM2.5	-	1-CO_2 2-NG_R	1-Oil_R 2-SO_2 3-NOx	Mineral	1-PM2.5 2-Mineral	Various	1-SO_2 2-CO_2 3-PM2.5	-	Mineral	1-Mineral 2-PM2.5	1-Mineral 2-PM2.5
DEU	1-CO_2 2-SO_2 3-NOx	1-CO_2 2-SO_2 3-NOx	1-CO_2 2-NG_R	1-Oil_R 2-CO_2 3-SO_2	Mineral	1-Mineral 2-CO_2 3-PM2.5	Mineral	1-CO_2 2-SO_2 3-Mineral	Water	Mineral	1-Mineral 2-LandO 3-CO_2	1-Mineral 2-CO_2 3-SO_2
FRA	1-CO_2 2-SO_2 3-NOx	-	1-CO_2 2-NOx	1-Oil_R 2-SO_2 3-CO_2	Mineral	1-CO_2 2-PM2.5 3-Mineral	Various	1-Mineral 2-CO_2	Water	Mineral	1-Mineral 2-LandO 3-CO_2	1-Mineral 2-CO_2 3-SO_2
GBR	1-Coal_R 2-SO_2 3-CO_2	-	1-CO_2 2-NG_R	1-Oil_R 2-SO_2 3-CO_2	Mineral	1-Mineral 2-CO_2	Various	1-Coal_R 2-CO_2 3-SO_2	-	1-Water 2-Mineral	Mineral	Mineral
IDN	-	1-PM2.5 2-CO_2	CO_2	1-Oil_R 2-SO_2 3-CO_2	Mineral	1-Coal_R 2-Mineral 3-CO_2	-	-	1-Land T 2-Mineral	-	-	Mineral
IND	1-PM2.5 2-NOx 3-CO_2	1-PM2.5 2-NOx 3-CO_2	CO_2	1-NOx 2-SO_2	Mineral	Various	-	1-PM2.5 2-NOx 3-CO_2	-	Various	-	1-Mineral 2-PM2.5
ITA	1-CO_2 2-SO_2 3-NOx	-	1-CO2 2-NOx	1-Oil_R 2-SO_2 3-CO_2	Mineral	1-CO_2 2-PM2.5 3-Mineral	Various	1-Mineral 2-CO_2	Water	Mineral	1-Mineral 2-LandO 3-CO_2	1-Mineral 2-CO_2 3-SO_2
JPN	1-CO_2 2-SO_2 3-NOx	1-PM2.5 2-CO_2 3-SO_2	CO_2	1-CO_2 2-SO_2 3-Oil_R	Mineral	1-Mineral 2-CO_2 3-PM2.5	Various	1-CO_2 2-SO_2 3-Coal_R	Water	Water Mineral	-	1-Mineral 2-Water
KOR	1-CO_2 2-NOx 3-CO_2	1-PM2.5 2-SO_2 3-CO_2	CO_2	1-SO_2 2-NOx 3-SO_2	Mineral	-	Various	1-PM2.5 2-CO_2 3-NOx	Water	Water	Water Mineral	Mineral Water
MEX	CO_2	1-CO_2 2-PM2.5	1-CO2 2-NG_R	1-Oil_R 2-CO_2	Mineral	-	Various	-	-	Mineral	Mineral	Mineral
RUS	1-CO_2 2-SO_2	1-PM2.5 2-CO_2	CO_2	1-Oil 2-CO_2	Mineral	Various	Various	1-CO_2 2-PM2.5	Various	Mineral	-	Mineral

		3-SO_2		3-SO_2				3-SO_2				
SAU	-	-	CO_2	1-CO_2 2-SO_2 3-NOx	-	-	-	-	-	-	-	Mineral
TUR	1-Coal_R 2-CO_2	1-PM2.5 2-CO_2 3-SO_2	CO_2	1-Oil_R 2-SO_2 3-CO_2	Mineral	Various	Various	-	Water	-	-	Mineral
USA	CO_2	1-PM2.5 2-CO_2	1-CO_2 2-NG_R	1-Oil_R 2-CO_2	Mineral	Various	Various	1-CO_2 2-PM2.5	Water	Mineral	Mineral	Mineral
ZAF	1-CO_2 2-SO_2	-	CO2	1-CO_2 2-Oil 3-SO_2	Mineral	1-Mineral 2-CO_2	Various	1-CO_2 2-SO_2	Water	Mineral	-	Mineral

APPENDIX 3.1: DALYs/Death for each disease (WHO data)

	Stroke	IHD	LC	COPD	ALRI
Afghanistan	28	28	33	29	91
Albania	17	18	24	19	93
Algeria	22	21	30	28	91
Angola	25	24	30	30	91
Antigua and Barbuda	22	21	28	21	94
Argentina	22	18	25	18	92
Armenia	21	17	26	18	92
Australia	16	15	21	18	95
Austria	18	14	23	18	99
Azerbaijan	23	21	31	24	92
Bahamas	23	22	27	27	92
Bahrain	33	27	25	40	95
Bangladesh	25	26	27	24	91
Barbados	18	18	24	18	95
Belarus	22	18	27	24	95
Belgium	17	15	23	18	93
Belize	23	22	28	23	92
Benin	27	24	34	29	91
Bhutan	29	30	33	30	92
Bolivia	27	22	25	20	91
Bosnia and Herzegovina	20	18	25	21	95
Botswana	23	23	31	28	91
Brazil	23	24	25	21	92
Brunei Darussalam	29	26	25	29	93
Bulgaria	18	18	27	21	92
Burkina Faso	28	25	32	31	91
Burundi	27	26	34	29	91
Cambodia	25	25	28	34	92
Cameroon	26	24	39	28	91
Canada	21	17	22	18	95
Cape Verde	21	18	32	22	91
Central African Republic	25	25	33	28	91
Chad	29	26	35	30	91
Chile	21	20	23	17	92
China	23	19	23	20	92
Colombia	23	21	25	18	92
Comoros	27	26	31	29	91
Republic of Congo	25	23	29	29	91
Costa Rica	19	21	22	16	93
Ivory Coast	31	28	31	31	91
Croatia	18	16	24	18	94
Cuba	19	19	23	19	92
Cyprus	17	18	23	15	94
Czech Republic	19	16	23	22	93
North Korea	23	21	27	21	92
Democratic Republic of the Congo	25	24	31	28	91

Denmark	18	17	21	18	93
Djibouti	27	25	32	30	91
Dominican Republic	24	23	25	22	91
Ecuador	22	20	23	16	91
Egypt	24	25	30	28	92
El Salvador	24	20	23	20	92
Equatorial Guinea	27	25	34	30	91
Eritrea	25	24	34	27	91
Estonia	23	15	22	21	98
Ethiopia	25	24	34	28	91
Fiji	33	27	28	31	92
Finland	19	15	21	23	94
France	17	15	24	14	98
Gabon	22	20	32	27	91
Gambia	27	24	31	28	91
Georgia	19	17	27	20	92
Germany	18	15	23	19	94
Ghana	25	23	31	29	91
Greece	15	16	22	18	92
Grenada	19	21	24	22	92
Guatemala	21	20	25	20	91
Guinea	27	25	37	29	91
Guinea Bissau	27	24	32	30	91
Guyana	25	26	27	24	91
Haiti	26	25	27	25	91
Honduras	25	22	26	21	92
Hungary	21	17	26	23	94
Iceland	17	14	21	19	-
India	26	27	30	27	91
Indonesia	26	26	28	32	92
Iran	21	20	26	24	92
Iraq	25	22	27	31	91
Ireland	19	17	22	18	93
Israel	19	16	23	19	93
Italy	14	14	20	14	94
Jamaica	18	17	24	20	93
Japan	17	15	17	17	93
Jordan	23	25	28	28	92
Kazakhstan	24	20	27	24	92
Kenya	25	24	28	31	91
Kiribati	30	30	30	35	91
Kuwait	29	32	26	37	92
Kyrgyzstan	24	19	29	21	92
Laos	26	25	29	32	91
Latvia	18	16	24	24	95
Lebanon	23	20	26	23	93
Lesotho	22	22	31	24	91
Liberia	25	23	35	29	91
Libya	25	24	28	28	92

Lithuania	18	15	24	22	96
Luxembourg	19	17	23	18	96
Madagascar	27	25	29	28	91
Malawi	23	22	31	27	91
Malaysia	25	23	28	36	92
Maldives	24	20	29	26	92
Mali	27	24	34	28	91
Malta	17	16	22	18	91
Mauritania	26	23	35	28	91
Mauritius	24	23	26	26	92
Mexico	21	20	24	18	92
Micronesia (Federated States of)	25	24	28	30	91
Mongolia	29	25	27	30	92
Montenegro	17	18	30	19	102
Morocco	20	19	31	24	91
Mozambique	25	23	27	30	91
Myanmar	25	24	28	28	91
Namibia	23	22	30	27	91
Nepal	24	24	30	26	91
Netherlands	18	16	22	20	92
New Zealand	17	16	22	19	92
Nicaragua	25	20	26	20	91
Niger	28	25	33	29	91
Nigeria	28	25	34	30	91
Norway	18	15	22	18	93
Oman	31	27	29	48	92
Pakistan	24	24	30	28	91
Panama	19	20	23	18	92
Papua New Guinea	28	28	30	35	91
Paraguay	24	22	25	21	92
Peru	26	21	23	21	92
Philippines	29	27	29	33	91
Poland	21	17	25	20	93
Portugal	16	16	24	15	92
Qatar	42	31	34	69	93
South Korea	22	19	21	26	97
Moldova	21	18	28	21	92
Romania	18	17	27	22	92
Russia	20	18	27	24	93
Rwanda	25	23	33	28	91
Saint Lucia	19	21	30	25	92
Saint Vincent and the Grenadines	21	18	29	23	92
Samoa	24	22	31	31	92
Sao Tome and Principe	23	20	26	22	91
Saudi Arabia	25	26	30	33	91
Senegal	25	22	36	27	91
Republic of Serbia	20	18	27	21	94
Seychelles	27	24	27	35	92

Sierra Leone	31	28	36	31	91
Singapore	22	21	22	27	92
Slovakia	22	17	25	24	92
Slovenia	18	15	24	18	109
Solomon Islands	26	25	31	31	92
Somalia	28	27	33	29	91
South Africa	24	24	28	28	92
South Sudan	26	25	31	30	91
Spain	16	15	23	14	93
Sri Lanka	23	23	27	32	93
Sudan	28	28	31	29	91
Suriname	24	24	26	25	92
Swaziland	24	23	31	27	91
Sweden	17	15	20	20	93
Switzerland	18	14	22	20	93
Syria	27	22	27	28	91
Tajikistan	22	20	32	22	92
Thailand	25	22	26	28	92
Macedonia	20	21	28	22	92
East Timor	26	25	30	36	91
Togo	28	25	33	29	91
Tonga	22	22	25	26	92
Trinidad and Tobago	21	23	26	22	92
Tunisia	21	20	29	24	92
Turkey	23	21	30	22	92
Turkmenistan	28	23	35	31	91
Uganda	27	25	34	29	91
Ukraine	21	17	28	23	93
United Arab Emirates	38	34	33	58	94
United Kingdom	18	17	20	18	92
United Republic of Tanzania	26	23	30	29	91
United States of America	22	18	22	23	93
Uruguay	19	17	25	18	92
Uzbekistan	25	21	32	29	92
Vanuatu	26	24	30	31	92
Venezuela	22	22	27	22	92
Vietnam	23	19	27	29	92
Yemen	28	28	29	28	91
Zambia	26	25	29	31	91
Zimbabwe	26	22	27	29	91

APPENDIX 4.1: Code MATLAB to obtain production-based and consumption-based emissions in Chapter 4

```
clear

Y2015= readmatrix('Y2015.csv'); %load Y matrix
T2015= readmatrix('T2015.csv'); %load T matrix
Q2015= readmatrix('Q2015bis.xlsx'); %load Q matrix



%Making (I-A)^-1
Ysum2015 = sum(Y2015, 2);   %Final Demand(all country)
Ysum2015 = diag(Ysum2015);  %Final Demand(all country)(14839*14839)
Tsum2015 = sum(T2015, 2);  %sum up T matrix
Tsum2015 = diag(Tsum2015);  %T matrix (14839*14839)
G2015 = Tsum2015 + Ysum2015;%Gross input(14839*14839)
Gsum2015 = sum(G2015,1);    %Gross input(1    *14839)
A2015 = T2015* inv(G2015);  %A matrix
I = eye(14839, 14839);      %I matrix
IA2015 = I- A2015;          %I-A
IA2015inv = inv(IA2015);    %(I-A)^-1 matrix

clear Y2015;
clear T2015;
clear Tsum2015;
clear A2015;
clear I;
clear IA2015;
clear G2015;

% Making Q(satellite emission)
Q2015airNOx =Q2015;
Q2015airNOx( 1499:2619 ,:) = [];
Q2015airNOx( 1:1443 ,:) = [];
Q2015airNOx = sum(Q2015airNOx , 1); %airNOx emission matrix (1*14839)

Q2015airNH3 = Q2015;
Q2015airNH3( 1609:2619 ,:) = [];
Q2015airNH3( 1:1553 ,:) = [];
Q2015airNH3 = sum(Q2015airNH3 , 1); %airNH3 emission matrix (1*14839)

Q2015airSO2 = Q2015;
Q2015airSO2( 1664:2619 ,:) = [];
Q2015airSO2( 1:1608 ,:) = [];
Q2015airSO2 = sum(Q2015airSO2, 1);  %airSO2 emission matrix (1*14839)

Q2015airPM10 = Q2015;
Q2015airPM10( 1719:2619 ,:) = [];
Q2015airPM10( 1:1663 ,:) = [];
```

```
Q2015airPM10 = sum(Q2015airPM10, 1);  %airPM10 emission matrix (1*14839)

clear Q2015;

%Making direct coefficient(14839*14389)
d2015airNOx = Q2015airNOx  ./ Gsum2015; %NOx intesity matrix
d2015airNH3 = Q2015airNH3  ./ Gsum2015; %NH3 intesity matrix
d2015airSO2 = Q2015airSO2  ./ Gsum2015; %SO2 intesity matrix
d2015airPM10 = Q2015airPM10  ./ Gsum2015; %PM10 intesity matrix

% clear Q2015airNOx;
% clear Q2015airNH3;
% clear Q2015airSO2;
% clear Q2015airPM10;



%Making intensity (14839*14389)
e2015airNOx = diag(d2015airNOx)*IA2015inv;
e2015airNH3 = diag(d2015airNH3)*IA2015inv;
e2015airSO2 = diag(d2015airSO2)*IA2015inv;
e2015airPM10 = diag(d2015airPM10)*IA2015inv;



% clear d2015airSO2;
% clear IA2015inv;
% clear d2015airNOx;
% clear d2015airNH3;

% clear d2015airPM10;

% Making esum2015(14839*1)
eSum2015airNOx = sum(e2015airNOx,1);
eSum2015airNH3 = sum(e2015airNH3,1);
eSum2015airSO2 = sum(e2015airSO2,1);
eSum2015airPM10 = sum(e2015airPM10,1);



%Intensity*Final Demand (14839*14839)
EF2015airNOx = e2015airNOx * Ysum2015;
EF2015airNH3 = e2015airNH3 * Ysum2015;
EF2015airSO2 = e2015airSO2 * Ysum2015;
EF2015airPM10 = e2015airPM10 * Ysum2015;

% clear e2015airNOx;
% clear e2015airNH3;
% clear e2015airSO2;
% clear e2015airPM10;

% Making Esum2015(14839*1), sum of the consumption-based emissions for each country
```

```
EFSum2015airNH3 = sum(EF2015airNH3,1);
EFSum2015airNOx = sum(EF2015airNOx,1);
EFSum2015airSO2 = sum(EF2015airSO2,1);
EFSum2015airPM10 = sum(EF2015airPM10,1);
```

APPENDIX 4.2: Production-based impact per African sector (DALYs)

	Algeria	Angola	Benin	Botswana	Burkina Faso	Burundi	Cameroon	Cape Verde	Chad	Congo
Agriculture	27,999	16,064	190,478	4,813	102,039	18,417	663,528	7,290	1,007,666	46,898
Fishing	6,858	6,012	8,767	3,081	9,423	9,432	10,148	7,376	8,007	10,054
Mining and Quarrying	22,920	17,779	11,536	3,697	16,539	16,249	13,125	7,202	13,067	18,030
Food & Beverages	7,042	6,057	8,734	3,107	9,419	9,277	10,298	7,288	8,025	10,016
Textiles and Wearing Apparel	6,801	5,948	8,635	3,071	9,292	9,172	10,173	7,284	7,967	10,008
Wood and Paper	6,885	5,959	8,670	3,084	9,343	9,201	10,269	7,285	8,002	10,013
Petroleum, Chemical and Non-Metallic Mineral Products	18,209	7,293	9,351	3,077	9,264	8,891	11,924	7,156	7,892	9,974
Metal Products	8,823	6,082	8,676	5,972	9,369	9,200	10,778	7,285	8,009	10,015
Electrical and Machinery	7,406	6,355	8,782	3,141	9,541	9,279	10,556	7,291	8,092	10,026
Transport Equipment	7,125	6,128	8,698	3,105	9,400	9,224	10,342	7,286	8,021	10,015
Other Manufacturing	6,840	5,961	8,637	3,081	9,282	9,177	10,184	7,284	7,972	10,009
Recycling	6,807	5,912	8,622	3,068	9,261	9,162	10,143	7,283	7,957	10,007
Electricity, Gas and Water	11,612	11,110	10,288	4,538	12,902	10,233	16,378	7,410	8,699	10,014
Construction	7,634	6,301	8,766	3,180	9,423	9,280	10,523	7,290	8,107	10,025
Maintenance and Repair	6,916	6,031	8,805	3,084	9,493	9,571	10,187	7,377	8,072	10,062
Wholesale Trade	8,545	6,677	9,691	3,178	13,619	11,799	11,304	7,382	9,037	10,326
Retail Trade	8,476	6,506	9,650	3,134	11,458	11,436	11,173	7,381	8,741	10,257
Hotels and Restaurants	8,167	6,601	9,611	3,155	12,350	11,612	11,098	7,381	8,796	10,308
Transport	24,130	16,286	18,444	5,494	17,264	13,840	24,310	7,011	11,037	16,289
Post and Telecommunications	7,984	6,700	9,609	3,126	10,833	10,517	11,186	7,380	9,290	10,305
Financial Intermediation and Business Activities	8,318	11,021	13,967	3,230	11,846	11,585	16,916	7,333	14,621	11,488
Public Administration	10,742	7,866	10,414	3,330	15,924	13,521	11,902	7,392	11,122	10,489
Education, Health and Other Services	8,531	8,020	11,499	3,230	13,223	13,699	13,080	7,396	11,201	10,655
Private Households	6,913	6,023	8,804	3,083	9,445	9,535	10,182	7,377	8,082	10,059
Others	7,033	6,069	8,837	3,085	9,508	9,478	10,235	7,377	8,095	10,075
Re-export & Re-import	0	0	0	0	0	0	0	0	0	0

	Cote dIvoire	DR Congo	Djibouti	Egypt	Eritrea	Gabon	Gambia	Ghana	Guinea	Lesotho
Agriculture	98,737	1,212,281	3,173	140,224	4,240	23,703	27,260	1,327,005	1,239,293	7,462
Fishing	8,958	6,604	3,234	14,114	3,267	10,104	7,341	9,191	7,570	5,457
Mining and Quarrying	23,129	8,357	3,393	66,510	3,784	12,932	8,012	18,431	12,089	6,918
Food & Beverages	9,328	6,912	3,309	22,760	3,253	10,641	7,309	10,307	7,636	5,401
Textiles and Wearing Apparel	8,863	6,495	3,231	17,243	3,248	10,128	7,295	9,183	7,489	5,397
Wood and Paper	9,135	6,698	3,259	17,195	3,250	10,532	7,300	9,668	7,526	5,397
Petroleum, Chemical and Non-Metallic Mineral Products	10,833	7,789	3,300	85,968	3,226	11,076	7,178	10,631	7,574	5,302
Metal Products	9,028	10,052	3,266	22,955	3,250	10,531	7,299	9,272	7,528	5,397
Electrical and Machinery	9,358	7,243	3,361	24,746	3,255	11,432	7,310	10,375	7,676	5,403
Transport Equipment	9,073	6,815	3,282	19,584	3,251	10,679	7,301	9,773	7,575	5,398
Other Manufacturing	8,857	6,524	3,232	15,685	3,249	10,173	7,295	9,256	7,501	5,395
Recycling	8,806	6,429	3,218	14,762	3,248	10,036	7,293	9,143	7,479	5,394
Electricity, Gas and Water	11,630	9,999	7,496	160,057	5,728	16,346	7,544	52,770	12,142	5,504
Construction	9,171	7,124	3,322	23,842	3,253	11,405	7,308	11,084	7,693	5,406
Maintenance and Repair	8,993	6,802	3,235	14,246	3,275	10,106	7,344	9,377	7,617	5,469
Wholesale Trade	10,665	14,108	3,250	19,915	3,412	10,164	7,418	17,339	9,024	5,745
Retail Trade	10,479	13,073	3,247	21,816	3,389	10,145	7,408	12,421	9,046	5,684
Hotels and Restraurants	10,467	13,546	3,245	20,804	3,392	10,143	7,424	13,652	8,748	5,689
Transport	23,476	28,430	3,909	189,711	4,166	14,440	7,655	36,389	12,574	5,691
Post and Telecommunications	10,362	14,400	3,243	17,364	3,392	10,159	7,412	10,497	8,511	5,609
Finacial Intermediation and Business Activities	13,075	54,492	3,609	29,830	4,153	13,623	7,982	12,513	11,464	5,830
Public Administration	11,917	17,152	3,279	23,421	3,789	10,214	7,527	14,360	10,001	6,052
Education, Health and Other Services	12,062	26,563	3,287	25,308	3,847	10,247	7,661	12,440	11,414	5,956
Private Households	8,981	6,743	3,235	14,244	3,275	10,106	7,344	9,294	7,615	5,464
Others	9,058	7,180	3,235	14,565	3,279	10,109	7,347	9,425	7,687	5,469
Re-export & Re-import	0	0	0	0	0	0	0	0	0	0

	Liberia	Libya	Madagascar	Malawi	Mali	Mauritania	Morocco	Mozambique	Namibia	Niger
Agriculture	29,942	5,770	11,830	30,427	285,781	7,235	27,721	7,783	6,813	23,282
Fishing	7,705	3,359	2,781	2,759	4,797	4,724	6,317	2,898	3,094	8,008
Mining and Quarrying	10,345	4,766	8,360	5,263	5,942	6,687	8,255	5,214	3,498	15,510
Food & Beverages	7,542	3,368	2,783	2,772	4,808	4,925	7,203	2,937	3,077	8,200
Textiles and Wearing Apparel	7,513	3,316	2,797	2,744	4,754	4,702	6,888	2,846	3,052	7,972
Wood and Paper	7,524	3,339	2,748	2,751	4,776	4,729	6,540	2,859	3,055	8,014
Petroleum, Chemical and Non-Metallic Mineral Products	7,451	6,223	2,806	2,735	4,715	4,727	14,335	2,983	2,969	8,037
Metal Products	7,531	3,394	2,782	2,753	4,780	4,654	8,584	3,640	9,752	8,002
Electrical and Machinery	7,564	3,457	2,841	2,786	4,842	4,819	7,789	2,969	3,070	8,143
Transport Equipment	7,604	3,378	2,794	2,761	4,793	4,762	6,806	2,905	3,060	8,056
Other Manufacturing	7,514	3,320	2,764	2,740	4,757	4,704	6,374	2,851	3,052	7,981
Recycling	7,509	3,305	2,750	2,737	4,748	4,693	6,242	2,845	3,049	7,958
Electricity, Gas and Water	9,339	42,196	4,303	3,103	5,435	10,254	66,336	3,375	3,087	11,183
Construction	7,544	3,439	2,837	2,775	4,828	4,788	7,300	3,020	3,080	8,240
Maintenance and Repair	7,724	3,362	2,804	2,769	4,820	4,725	6,316	2,908	3,094	8,037
Wholesale Trade	8,364	3,450	3,462	3,054	5,334	4,879	6,562	3,651	3,132	9,097
Retail Trade	8,248	3,421	3,389	3,044	5,282	4,860	6,520	3,751	3,112	8,889
Hotels and Restraurants	8,969	3,434	3,294	3,056	5,267	4,891	6,497	3,640	3,118	9,247
Transport	10,862	12,728	6,162	4,093	6,373	8,405	20,231	8,964	4,918	14,020
Post and Telecommunications	8,362	3,443	3,279	3,044	5,315	4,821	6,459	4,077	3,118	8,718
Finacial Intermediation and Business Activities	11,158	4,153	6,048	4,506	7,844	5,014	6,976	4,200	3,115	10,442
Public Administration	9,120	3,478	3,624	3,193	5,975	5,281	6,827	4,450	3,143	10,935
Education, Health and Other Services	10,070	3,544	4,347	3,629	6,398	4,999	6,509	4,581	3,111	10,686
Private Households	7,721	3,360	2,799	2,768	4,820	4,720	6,316	3,110	3,094	8,026
Others	7,732	3,368	2,830	2,781	4,838	4,724	6,328	2,941	3,094	8,069
Re-export & Re-import	0	0	0	0	0	0	0	0	0	0

	Nigeria	Rwanda	Senegal	Sierra Leone	Somalia	Swaziland	Togo	Tunisia	Uganda	Tanzania
Agriculture	3,854,674	13,540	216,961	231,641	9,328	7,888	194,596	9,174	1,275,924	31,507
Fishing	21,178	9,152	7,504	7,485	3,339	5,430	8,849	3,403	10,020	4,464
Mining and Quarrying	81,033	15,005	14,125	12,225	7,331	5,944	15,812	5,543	31,222	16,097
Food & Beverages	25,822	9,076	7,870	7,522	3,308	5,328	8,702	3,479	10,152	4,576
Textiles and Wearing Apparel	21,416	8,980	7,442	7,375	3,279	5,340	8,689	3,519	9,921	4,445
Wood and Paper	21,839	9,012	7,516	7,395	3,289	5,306	8,694	3,424	10,011	4,445
Petroleum, Chemical and Non-Metallic Mineral Products	48,803	8,898	8,636	7,378	3,258	5,251	8,911	11,003	10,396	4,964
Metal Products	22,421	9,011	7,520	7,386	3,290	5,343	8,695	3,418	9,882	4,505
Electrical and Machinery	26,623	9,092	7,777	7,467	3,314	5,350	8,708	3,663	10,291	4,735
Transport Equipment	24,503	9,025	7,575	7,407	3,293	5,343	8,697	3,489	10,082	4,559
Other Manufacturing	21,670	8,983	7,466	7,375	3,280	5,340	8,690	3,376	9,931	4,452
Recycling	21,448	8,966	7,413	7,358	3,276	5,339	8,687	3,343	9,892	4,399
Electricity, Gas and Water	76,263	10,523	27,311	10,197	3,989	6,809	11,386	9,976	16,586	5,890
Construction	25,830	9,069	7,945	7,493	3,307	5,347	8,705	3,533	10,211	4,636
Maintenance and Repair	21,732	9,205	7,507	7,531	3,357	5,434	8,895	3,410	10,301	4,516
Wholesale Trade	34,954	10,219	8,487	14,651	3,786	5,500	9,947	3,718	18,854	6,620
Retail Trade	51,338	10,288	8,731	7,855	3,754	5,504	9,870	3,666	18,798	6,711
Hotels and Restraurants	43,493	10,271	8,365	9,824	3,698	5,498	9,818	3,643	18,327	6,482
Transport	226,864	12,406	19,636	10,032	4,758	5,462	18,774	6,740	35,331	16,126
Post and Telecommunications	29,352	10,137	8,000	7,828	3,703	5,496	9,891	3,584	18,587	6,201
Finacial Intermediation and Business Activities	45,093	14,964	9,532	7,888	6,089	5,733	14,844	3,922	60,169	13,964
Public Administration	43,562	11,192	8,887	8,704	4,243	5,590	10,822	4,005	23,705	8,423
Education, Health and Other Services	42,389	12,426	9,050	9,167	4,842	5,656	12,129	3,915	34,990	10,136
Private Households	21,377	9,204	7,507	7,564	3,356	5,434	8,892	3,407	10,262	4,519
Others	22,180	9,241	7,542	7,508	3,376	5,435	8,924	3,423	10,682	4,577
Re-export & Re-import	0	0	0	0	0	0	0	0	0	0

APPENDIX 4.3: Consumption-based impact per African sector (DALYs)

	Algeria	Angola	Benin	Botswana	Burkina Faso	Burundi	Cameroon	Cape Verde	Chad	Congo
Agriculture	11,356	4,167	45,878	2,219	30,413	3,618	176,839	1,108	216,815	9,455
Fishing	2,289	1,048	893	1,075	1,220	725	1,426	583	741	979
Mining and Quarrying	722	468	540	787	1,234	1,348	376	258	852	386
Food & Beverages	19,803	16,879	84,166	6,186	49,125	18,567	135,502	11,474	159,730	25,222
Textiles and Wearing Apparel	4,846	3,743	8,271	2,776	8,294	6,159	9,052	4,876	6,844	5,332
Wood and Paper	1,533	957	3,608	637	2,783	1,659	7,103	1,038	5,115	1,555
Petroleum, Chemical and Non-Metallic Mineral Products	6,798	3,418	7,055	1,415	6,570	6,147	6,534	3,630	5,625	3,272
Metal Products	1,926	578	1,005	1,341	1,095	1,124	1,165	786	1,043	899
Electrical and Machinery	11,538	8,219	12,040	7,437	10,827	11,620	13,447	10,760	14,124	11,059
Transport Equipment	11,361	8,087	11,432	5,829	11,226	11,418	13,111	8,383	11,951	10,632
Other Manufacturing	5,023	3,344	6,253	2,207	7,157	5,763	7,388	4,307	5,770	5,807
Recycling	7,857	5,065	7,813	3,636	9,584	7,232	9,375	4,903	6,765	6,773
Electricity, Gas and Water	3,655	3,804	8,331	1,936	12,201	9,010	8,292	3,776	4,439	2,317
Construction	21,091	15,722	26,649	15,772	24,434	22,967	32,011	15,539	51,806	25,474
Maintenance and Repair	4,376	3,607	5,930	2,021	7,368	5,289	7,247	3,885	4,719	5,114
Wholesale Trade	6,317	4,515	8,862	2,781	11,970	11,792	9,974	4,810	8,625	6,778
Retail Trade	10,829	9,175	18,136	3,627	18,635	17,244	20,873	9,114	19,443	12,744
Hotels and Restraurants	12,903	12,275	29,728	6,039	29,331	19,311	36,534	9,404	48,366	19,515
Transport	7,788	6,109	9,441	3,031	12,327	6,461	10,302	2,497	6,078	5,963
Post and Telecommunications	4,938	3,501	7,126	2,258	8,349	6,888	7,783	3,094	8,672	5,101
Finacial Intermediation and Business Activities	8,276	10,969	22,743	3,245	12,842	11,999	26,540	12,401	32,688	12,039
Public Administration	26,425	25,598	25,457	13,075	37,978	30,162	29,569	19,646	82,131	22,205
Education, Health and Other Services	13,845	23,063	35,207	6,579	23,926	26,272	38,980	20,427	74,840	21,875
Private Households	6,864	5,737	7,325	2,564	8,323	5,735	9,567	4,261	5,672	7,851
Others	2,635	2,087	4,474	1,347	5,590	4,435	4,895	3,040	2,670	2,849
Re-export & Re-import	11	40	40	17	48	46	30	58	162	49

	Cote D'Ivoire	DR Congo	Djibouti	Egypt	Eritrea	Gabon	Gambia	Ghana	Guinea	Lesotho
Agriculture	38,258	280,017	956	52,419	782	6,034	2,939	395,133	314,524	1,329
Fishing	982	1,043	316	3,171	327	1,164	356	1,686	1,046	392
Mining and Quarrying	874	708	191	3,779	194	288	620	1,430	998	414
Food & Beverages	25,472	440,074	6,304	107,024	6,236	21,915	15,702	138,668	433,603	9,300
Textiles and Wearing Apparel	6,679	12,269	2,178	26,593	2,292	6,441	4,856	8,515	11,323	7,896
Wood and Paper	1,876	13,553	598	6,065	585	1,797	1,181	5,474	12,836	710
Petroleum, Chemical and Non-Metallic Mineral Products	6,406	11,028	2,163	46,374	2,083	4,235	4,250	7,631	8,218	2,468
Metal Products	773	1,369	493	3,129	368	1,205	730	1,606	1,377	428
Electrical and Machinery	9,080	18,776	4,712	36,909	4,321	14,209	8,446	15,108	14,096	5,650
Transport Equipment	9,686	14,163	4,339	31,997	4,231	13,129	8,197	13,612	11,410	5,399
Other Manufacturing	5,344	9,050	2,162	15,510	2,085	6,222	4,171	7,599	7,802	2,683
Recycling	7,741	7,609	2,150	24,994	2,558	8,359	5,042	10,198	7,571	6,495
Electricity, Gas and Water	7,404	7,486	2,975	97,674	3,306	5,228	4,580	26,196	5,200	2,492
Construction	17,082	57,315	5,780	63,107	5,258	28,863	14,822	34,447	44,685	13,946
Maintenance and Repair	5,746	5,463	1,795	11,936	1,838	6,074	3,665	7,128	4,848	2,584
Wholesale Trade	6,899	18,390	2,339	23,114	2,376	7,046	4,316	16,192	9,586	4,350
Retail Trade	14,002	46,775	4,293	51,023	4,585	13,139	9,151	22,601	28,201	8,575
Hotels and Restraurants	15,118	128,223	4,105	59,108	4,768	14,251	11,096	42,846	72,284	9,471
Transport	11,861	16,840	1,247	100,813	1,662	5,214	3,995	16,553	6,247	3,067
Post and Telecommunications	5,833	15,418	1,337	15,034	1,772	5,726	3,417	7,178	7,271	3,570
Finacial Intermediation and Business Activities	12,483	84,580	5,701	42,478	5,449	14,987	19,801	14,341	40,265	6,665
Public Administration	21,593	65,497	9,298	57,696	10,781	25,866	19,779	37,993	35,919	16,085
Education, Health and Other Services	19,438	109,402	9,917	65,058	10,583	25,046	26,125	23,278	59,822	13,107
Private Households	8,187	7,519	1,919	14,741	2,074	8,920	4,463	8,831	6,052	3,075
Others	3,740	3,947	1,399	8,846	1,477	3,735	3,587	5,027	3,990	1,958
Re-export & Re-import	21	55	47	12	65	25	28	21	27	56

	Liberia	Libya	Madagascar	Malawi	Mali	Mauritania	Morocco	Mozambique	Namibia	Niger
Agriculture	3,994	1,985	5,112	8,969	69,225	993	8,517	3,000	1,579	4,895
Fishing	360	1,017	447	286	526	1,192	3,174	622	835	827
Mining and Quarrying	595	611	350	583	353	368	464	622	169	854
Food & Beverages	11,953	7,907	6,517	8,054	95,747	13,569	31,286	7,962	9,886	23,935
Textiles and Wearing Apparel	3,525	2,201	4,299	3,279	5,596	3,323	18,631	2,393	2,977	6,923
Wood and Paper	1,101	675	603	541	3,203	854	1,519	656	506	2,056
Petroleum, Chemical and Non-Metallic Mineral Products	4,397	3,236	2,078	1,825	4,015	2,301	6,602	2,025	1,794	7,437
Metal Products	445	535	242	361	677	750	996	547	823	973
Electrical and Machinery	4,031	4,750	3,081	2,766	7,776	5,618	12,409	4,386	4,344	9,680
Transport Equipment	8,728	4,624	3,224	3,470	7,096	5,881	10,016	4,106	4,309	9,928
Other Manufacturing	2,844	2,223	1,994	1,680	4,059	3,009	4,909	2,204	2,320	5,949
Recycling	4,104	3,241	2,852	2,730	4,635	4,245	6,013	2,644	3,355	8,047
Electricity, Gas and Water	5,179	10,053	3,545	2,404	2,977	3,418	25,411	2,934	1,676	7,897
Construction	5,081	7,971	6,122	4,881	19,073	8,868	26,701	8,822	8,811	20,366
Maintenance and Repair	3,297	2,027	1,940	1,775	3,377	2,678	4,311	2,252	2,137	5,794
Wholesale Trade	5,288	2,657	2,765	2,334	5,418	3,787	5,932	3,345	2,660	7,452
Retail Trade	10,590	4,838	5,287	4,694	12,065	6,776	11,584	5,865	4,671	12,673
Hotels and Restraurants	12,951	5,864	5,061	5,293	26,211	7,488	14,030	6,002	5,237	17,823
Transport	3,648	4,316	2,586	2,543	3,686	4,136	9,510	4,636	2,840	7,997
Post and Telecommunications	4,076	1,963	1,911	2,062	4,596	2,919	4,580	2,963	2,174	5,830
Finacial Intermediation and Business Activities	13,170	5,685	6,901	6,018	16,238	5,426	9,569	4,613	4,325	14,189
Public Administration	19,174	13,631	6,224	6,035	22,602	13,767	23,992	9,886	9,532	22,816
Education, Health and Other Services	23,573	11,497	8,976	8,645	28,398	8,686	13,391	8,529	8,064	23,617
Private Households	4,562	3,245	2,514	2,255	4,113	3,098	6,238	2,749	2,701	6,654
Others	2,545	1,069	1,421	1,581	2,382	2,415	2,548	1,727	1,627	5,405
Re-export & Re-import	32	9	22	29	37	62	10	16	18	33

	Nigeria	Rwanda	Senegal	Sierra Leone	Somalia	Swaziland	Tanzania	Togo	Tunisia	Uganda
Agriculture	1,880,978	2,614	50,948	38,638	1,377	1,711	9,886	46,262	3,106	539,583
Fishing	5,896	737	2,335	487	203	450	1,291	585	1,327	1,527
Mining and Quarrying	1,172	1,016	572	786	269	206	1,307	621	236	1,656
Food & Beverages	980,693	21,295	88,041	83,369	7,507	10,331	12,942	55,416	9,697	330,882
Textiles and Wearing Apparel	35,694	7,111	6,372	8,991	2,366	4,897	3,812	8,196	9,691	11,843
Wood and Paper	21,228	1,876	2,196	4,354	630	807	990	2,319	707	8,133
Petroleum, Chemical and Non-Metallic Mineral Products	39,764	6,918	5,796	6,300	2,661	2,346	3,714	5,513	3,946	14,594
Metal Products	3,529	929	739	1,183	434	420	447	908	462	1,404
Electrical and Machinery	33,879	11,460	10,477	10,107	5,586	6,047	4,842	9,400	6,340	19,113
Transport Equipment	34,689	11,778	9,465	9,385	4,951	4,559	4,980	9,363	5,533	16,311
Other Manufacturing	22,935	6,269	5,279	6,153	2,194	3,357	5,090	6,315	2,726	8,958
Recycling	30,038	8,061	8,889	5,983	2,547	4,690	5,098	6,704	3,235	11,617
Electricity, Gas and Water	64,459	9,791	13,262	5,467	2,853	4,396	4,612	5,234	4,179	15,720
Construction	66,196	18,167	25,942	22,692	8,367	9,239	8,524	20,420	10,922	47,749
Maintenance and Repair	21,790	6,114	5,435	4,714	1,887	3,337	3,225	5,147	2,291	8,108
Wholesale Trade	38,153	8,893	8,501	14,594	2,902	4,476	5,225	7,917	3,028	19,627
Retail Trade	163,358	16,704	18,582	18,965	5,496	8,512	10,722	16,495	5,910	42,724
Hotels and Restraurants	376,157	18,388	23,456	56,112	5,266	8,527	10,915	21,951	6,628	88,318
Transport	152,194	6,710	8,876	5,104	1,528	3,077	7,781	8,696	3,350	19,952
Post and Telecommunications	25,681	7,015	5,531	5,382	1,854	3,451	3,777	6,280	2,344	15,702
Finacial Intermediation and Business Activities	74,944	19,622	17,681	10,562	8,654	8,486	11,660	22,801	5,058	72,032
Public Administration	79,309	23,157	20,513	30,695	11,066	11,267	16,881	26,371	11,895	54,982
Education, Health and Other Services	75,513	29,585	21,594	39,652	13,123	13,476	20,697	35,110	9,017	90,956
Private Households	21,790	7,388	6,885	5,952	2,584	3,589	3,898	6,085	3,333	10,086
Others	19,107	4,750	3,588	3,669	1,452	2,738	2,326	4,017	1,317	5,966
Re-export & Re-import	10	57	16	42	6	28	1	31	11	25