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ORIGINAL PAPER

Environmental impact assessment of the Egyptian cement industry based on a life-cycle assessment approach: a comparative study between Egyptian and Swiss plants

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Abstract Egypt in 2015 announced the alteration of the fuels used in cement plants without the least regard to minimizing the environmental burden (EB) excesses. This study conducts a life-cycle assessment (LCA) of Egyptian cement-manufacturing unit, which is considered as the first one on LCA cement analysis to be conducted in Egypt. This study investigates 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. Meanwhile, SimaPro software has been used to assess the environmental impacts, and three different cement plants were selected for this study: 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; and an Egyptian hypothetical plant (EHP) in which electricity and coal are assumed to be the main energy feeds, and comparisons of different strategies including midpoint and endpoint methods are outlined. Regarding the midpoint method, ETP recorded higher respiratory inorganics, aquatic acidification, global warming, and nonrenewable energy impacts than ECP, because of using coal, while for SCP, global warming and respiratory inorganics achieved the highest adverse impacts compared to ECP and EHP—due to the different manufacturing technology used. With regard to the endpoint method, the peak possibility of human health deterioration has been recorded due to the use of coal as fuel. This possibility was reduced by 46 % in the case of SCP as a result of the technology applied, which interestingly represents a reasonable reduction in terms of technological application.

Keywords Fuel type · Life-cycle assessment · Egyptian cement industry · Environmental impact assessment · SimaPro software

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Introduction

The environmental profile and sustainability of cement production have witnessed increasing interest in the course of the recent years (García-Gusano et al. 2015b). Many life-cycle assessment (LCA) studies have been introduced on how to mitigate the emissions of greenhouse gases from the cement industry. However, the authors have recorded a remarkable shortage of studies in respect of the Egyptian cement industry (ECI) using the LCA approach. Unfortunately, the Egyptian plants monitor just carbon monoxide (CO) under the auspices of the Egyptian Environmental Affairs Agency (EEAA), without least regard to other emissions and environmental appraisals, as well as negligence in the application of environmental assessments such as LCA to reduce the environmental burden (EB) excesses. This article introduces LCA as a new assessment tool in Egypt, particularly after the decision of the EEAA to change the Egyptian cement fuel type without conducting any studies on environmental assessments. Consequently, the authors have investigated an analysis about the old manufacturing process which was published at the Asian conference, 2014 (Ali et al. 2014a, b). The results of the current study were as well compared to those of the published one for further investigations into the differences between the both.

There are two basic and distinct strategies for calculating environmental impacts: the midpoint and endpoint methods (Blankendaal et al. 2014). These strategies are characterized by a paradox of greater relevancy (endpoints) versus greater reliability (midpoints) (Ramesh et al. 2010). The lifetime of a product/material has a significant impact on its final score, and a small additional investment can potentially increase the lifetime (Parker et al. 2011), and it is of the utmost importance to find optimal environmental solutions over the entire life cycle of a product (Dakwale et al. 2011). Meanwhile, limitations include the higher cases of accesses to environmental databases and the lack of reliable data on the size of the material flows. Research into long-term effects implies uncertainties in terms of the accuracy of results. It would be interesting for the scientific community to have access to a free environmental database so that this database could be used to establish and compare life-cycle assessment methodologies in respect of the industrial production in Egypt which has clearly increased over the recent decades.

Based on the Egyptian Industrial Development Authority (EIDA), there are several offending industries, to be precise, the building material industry which currently is ranked as third after the textile and nutrition material industries, as shown in Table 1 (EIDA 2015). In this respect, the authors focused on the cement industry, as it is the main component of each building. Manufacturing processes of building materials result in emissions of greenhouse gases such as carbon dioxide (CO_2) into the atmosphere. There is immense concern and insistence on reducing emission levels of greenhouse gases into the atmosphere, so as to control the adverse environmental impacts on the world (Sedláková et al. 2015). For example, the authors present a critical analysis of some contemporary studies related to, but not limited to, the cement industry in the world and the adverse impacts caused by such industries on the environment.

Table 1 The distribution of industrial production in Egypt

Nu.	Industry type	Number of projects
1	Textile industries	7413
2	Nutrition material	7212
3	Building material	6657
4	Chemical material	4406
5	Wooden industries	2848
6	Ceramic and refractory materials	2408
7	Paper products, printing and publishing	1943
8	Mineral Industries	701
9	Transformative industries	594
10	Service and maintenance centers	75
11	The exploitation of mines and quarries	53
12	Production and distribution of electricity	34
13	Animal and vegetable production	22
14	Petroleum refining and gas	14
15	Coal mining and processing projects	3
Total		34,383

Margallo et al. (2014) have evaluated and compared ash solidification with recycling within the cement-manufacturing process as a clinker and gypsum substitute, in respect of the natural resources (NR) and environmental burden (EB) factors. The authors came up with the results showing that the substitution of ash fin lieu of clinker resulted in the lower values in respect of the two factors. A comparison of the scenarios has proven that ash solidification is the least auspicious scenario with the highest NR and EB consumption, resulting in the highest impacts on air and water as well.

Mikulčić et al. (2013a) have analyzed the impacts of different amounts of fuel used in and pollutant emissions from a newly designed cement calciner on the environment using the numerical simulation. The numerical models of calcination processes and pulverized coal combustion were implemented into the computational fluid dynamic (CFD)simulations. Ultimately, this study has established that most of the pollutants which are emitted from the calciner are related to the amounts of the fuel used.

Mikulčić et al. (2013b) introduced several measures to reduce the CO_2 emissions: for instance, the use of waste heat CO_2 recovered and storage technologies, the use of alternative and biomass fuels, and the use of alternative raw materials. Using the domain of computational fluid dynamic (CFD) simulations, this study deals with the replacement of fossil fuels with alternative and biomass fuels and recommends three scenarios: (1) particle residence time, (2) the temperature field in a vertical plane, and (3) CO_2 mass fraction in a vertical plane mitigating the influence of cement manufacturing on the environment in Croatia.

Zhang et al. (2010) studied how to control the formation of pollutant gases. This study focused on the combustion environment in the calciner, which is highly considered as a main method to control the formation of pollutant gases based on the combustion mechanism analysis via three aspects: (1) the effects of the flow rate of coal, (2) tertiary air on flue gas compositions, and (3) the effects of staging combustion technology on the NO_x, SO_2, and CO concentrations in flue gas and finally reached the optimal proportion of these factors.

Villar et al. (2012) analyzed the goals in respect of "factories of the future", which are "zero emissions" and "zero material waste" (clean energy technologies) which need the optimal given technologies for waste energy recovery. This paper has introduced a range of new waste-to-energy technologies in continuous process industries such as the cement industry.

For the aforementioned purpose, this study continued to explore the chain of alternatives to reduce extra environmental burdens (EBs) and to fill the gap which occurred when the EEAA decided to change the fuel used in Egyptian cement plants (ECPs). Furthermore, this study takes advantages of the international cement industry in how to eliminate environmental burdens (EBs). Based on these literature studies and many others, the proposed substitution of using coal instead of the conventional fuel type as an energy source has been investigated.

Three different cement production systems have been introduced: two from Egypt and one from Switzerland[1] and were considered for the analysis and comparison. The first was the ECP using electricity, natural gas, diesel, and mazzut (a heavy, low-quality fuel oil, used in generating plants and similar applications), while the second was an Egyptian hypothetical plant (EHP) operated by means of electricity and coal. The third one was a Swiss cement plant[2] (SCP), which is operated using mixed fuels. The main reason behind the comparison between the two Egyptian plants (ECP and EHP) is the fuel feed used: electricity, natural gas, and coal. The most prevailing form of cement is Portland cement, about 93–97 % of which consists of a material called clinker (Feiz et al. 2014). All the details of numbers of clinkers (kilns/plant), the sizes of the cement plants, and the production quantities are shown in Table 2.

On the other hand, it is clear from Fig. 1, the distribution of LCA studies in the world, which were collected by the authors from case 205 of the International case studies. It is reported that Sweden has the largest number of studies, since it has a significant database of building LCA. However, Arab countries do not have any studies, except only one study in Bahrain that too not having anything significant to show from the continent of Africa and especially Egypt. This is clearly owing to the scarcity of life-cycle datasets. This paper sheds light on the results of the environmental impact assessment of new cement technology in Egypt using SimaPro V8.1 (PRé 2015). The commercially available SimaPro has proven its versatility in providing environmental impact factors for energy use in the process stages (Kantardgi et al. 2006). Consequently, this study is presented to partially fill this gap and to encourage the Egyptian industry stakeholders, by aiding them to utilize LCA, then to assess the environmental impacts of their industries, and ultimately, to take the necessary actions to reduce highly adverse impacts.

Materials and methods

Cement manufacturing in Egypt

The ECI has grown in size and capacity during the last 30 years. In 1975, the ECI comprised four factories, which produced 4 million tons per year. Now, there are 14 factories, producing nearly 38 million tons per year of clinker, primarily from dry kilns, with only a small amount from seven wet kilns in two companies. The satellite image in Fig. 2 shows the locations of the 14 cement factories in Egypt. Based on the related studies regarding the Egyptian fortune of the cement industry, Egypt's production is estimated to be 1.5 % of the total world production. Table 2 lists the production and energy consumption of each of the Egyptian cement-producing companies (Askar and Sc 2010); all data refer to the year 2010, and in tandem with these data, the whole dataset has been updated with the latest figures by visiting a few Egyptian plants and doing an on-site survey due to the difficulty of acquiring statistics from a few plants because of breaching confidentiality in data acquisition.

Manufacturing technology

The process of producing cement consists of three core steps: (1) raw material preparation; (2) burning of clinker in the kiln, and (3) cement preparation. Fossil fuel usage is a large contributor to the production of anthropogenic GHG emissions (Qin et al. 2006). Statistically, producing cement requires large amounts of energy in the hearth of the kiln, from 3000 to 6500 mega joule/ton of clinker depending on the process type involved, which requires huge quantities of fossil fuels (García-Gusano et al. 2015a). Regarding fossil fuels, the raw cement needs the suitable amount of the raw materials such as calcium, silicon, aluminum, and iron. By mixing these components, second step, and exposing them to extreme heat (third step), the resulting chemical reactions transform the partially molten raw materials into granules called clinker (García-Gusano et al. 2015a). In other words, the raw materials combined with the fuel as an energy source produces typical cement clinker (Sogut et al. 2009). Figure 3 shows a comprehensive cement-manufacturing process.

[1] The authors choose SCP owing to two reasons: first, the availability of the data, and the second, as it is operated by coal and has the same as that of the Egyptian technology in the cement industry.

[2] All the data and statistical numbers of SCP have copy rights to the Ecoinvent database, and the authors do not have the authorization to publish any of them.

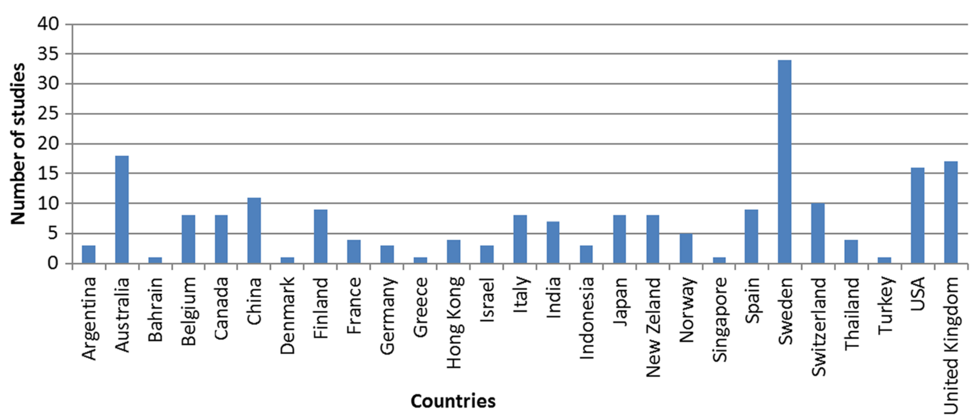
Table 2 Cement plant's clinker production in Egypt

Cement plants	Kiln line	Production (million ton)
Lafarge Cement	Kiln 1, Kiln 2, Kiln 3, Kiln 4, Kiln 5	8.295478
CEMEX (Assiut cement)	Kiln 1, Kiln 2, Kiln 3	4.706112
Helwan (Italcementi group)	Dry Kiln 1 (plant 2), Dry Kiln 2 (plant 2), wet Kiln 2 (plant 1), wet Kiln 3 (plant 1),wet Kiln 5 (plant 1), wet Kiln 6 (plant 1), wet Kiln 1 (plant 3), wet Kiln 2 (plant 3)	4.00934
Sinai cement (Gray)	Kiln 1, Kiln 2	3.350221
National cement	Kiln 1 (wet), Kiln 2 (wet), Kiln 3, Kiln 4	3.031951
Suez Cement (Torah plant) (Italcementi group)	Kiln 5, Kiln 7, Kiln 8, Kiln 9	2.474412
Suez cement (Suez plant) (Italcementi group)	Kiln 1, Kiln 2	2.10071
El Arabeya cement	Kiln 1	2.030428
Amreya cement (Cimpor group)	Kiln 1, Kiln 2	1.900483
Misrbanisuef (TITAN)	Kiln 1	1.573844
Alexandria cement (TITAN)	Kiln 1	1.500005
Amreyacimpor (Cimpor group)	Kiln 1	1.352098
Suez cement (Kattameya plant) (Italcementi group)	Kiln 1	0.84581
El Minia (Italcementi group)	Kiln 1	0.287666
Total		37.45856

N.B. * The table listed in ascending order by production size

* In terms of the kiln process type, primarily from dry kilns, with only a small amount from seven wet kilns in two companies (National cement and Helwan (Italcementi group))

Fig. 1 Summary of the case studies in the 27 countries from the world



The Egyptian environmental regulations regarding the emissions production

The emissions produced from cement manufacturing are chiefly during the combustion stage of fossil fuels that are necessary to heat the kiln and which produces the chemical reaction of raw materials (Brown et al. 2014). A high-temperature kiln/oven heats the raw materials to a partial melt at 1450 °C, converting them into clinker. Clinker is then crushed with gypsum, fly ash, and/or sand to make cement. Figure 4 shows the main sources of pollutants from cement production using the dry process (Askar and Sc 2010).

Egyptian cement firms have been ordered to develop a sound environmental policy to protect and enhance the quality of their local, regional, or national ambient air quality. However, prior to developing an environmental policy, decision makers have to first determine the existing air-quality conditions and the contribution of emission sources (Brown et al. 2014).

Due to the shortage and unavailability of the data, the authors have had to rely on previous studies to get the environmental limits of the cement industry and compare it with the contemporary Egyptian Environmental Standards. In 1994, the Egyptian Environmental Protection Law (EEPL), Law number 4. and its executive regulations were

Fig. 2 Locations of cement factories in Egypt (Google map application)

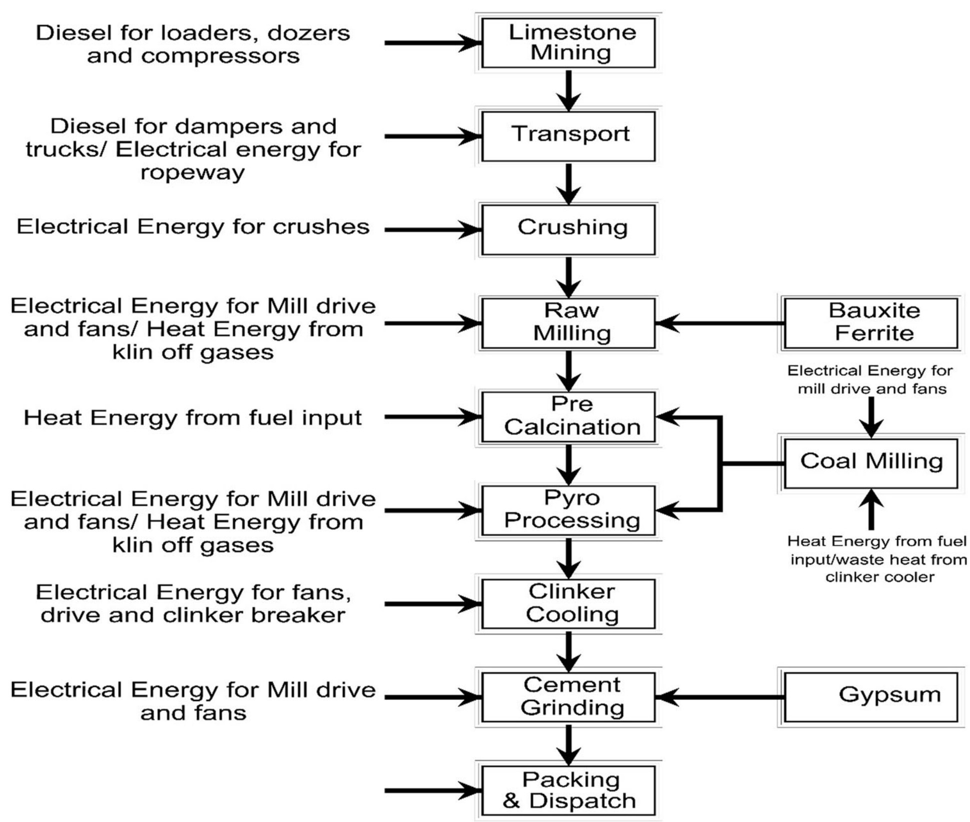


Fig. 3 The life cycle of the cement production (raw material and the consumed Energy)

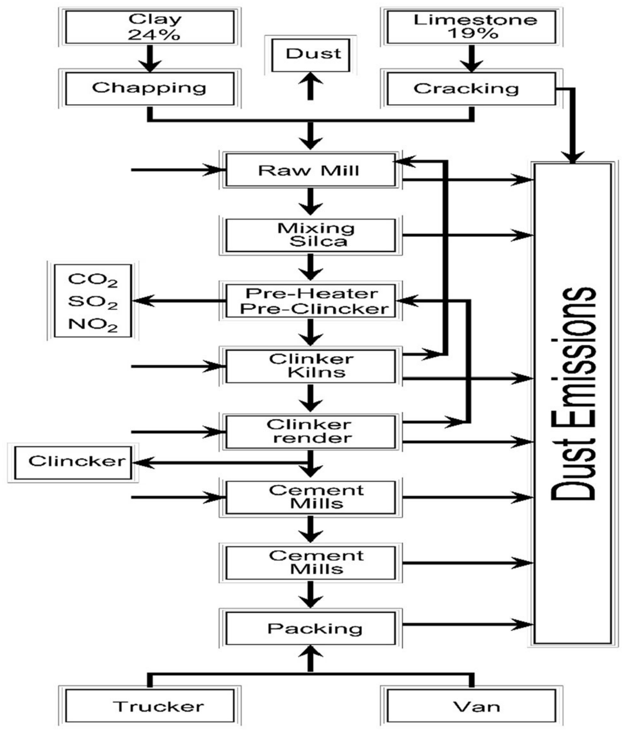


Fig. 4 Pollutions from cement manufacturing—dry process

issued for protecting the Egyptian environment. Limits for particulate matter emissions from cement plants were set at 300 mg/m^3 for plants established before 1995 and 200 mg/m^3 for plants installed after 1995, before the issuance of the new amendments, and 100 mg/m^3 for new plants. Nitrogen oxides (NO_x) and sulfur oxide (SO_x) emission limits were set at 300 mg/m^3 and 4000 mg/m^3, respectively. Following ratification of Law number 9 for the environment in 2009, the Ministry of State for Environmental Affairs and the Egyptian Environmental Affairs Agency (EEAA) developed new air emission standards, which were expected to be ratified by Parliament toward the end of 2010. The new standards for cement plants' particulate matter emissions will, therefore, be more in line with the International Standards of 100 mg/m^3 for old plants and 50 mg/m^3 for new plants, with 400 mg/m^3 for SO_x and 600 mg/m^3 for NO_x (Askar and Sc 2010). Table 3 presents the comparison between the two laws in the two different years as mentioned above (1994 and 2009).

Case study analysis

Due to the presence of several cement plants, cement is one of the competitive products in Egypt, and therefore, to make this study more practical and realistic, the authors formatted a questionnaire to find out the type of cement that is frequently used and to study the adverse impacts of these plants. This questionnaire was given to engineers constructing buildings in Assiut, Egypt. Table 4 shows the questionnaire designed for executive engineers to collect data about the types of cement used in the building construction industry.

Regarding the questionnaire's results (as shown in Table 5), Cement plants were enumerated: CEMEX (Assiut Cement), National Cement, El Minia (Italcementi group), and Lafarge Cement. To obtain a holistic result from this questionnaire, as well as based on production data from Table 2, the authors selected CEMEX plant as a case study on cement manufacturing, given that its high clinker production of 4.7 million ton ranks as the second highest in production volume across the world.

The main components of cement factories are no different from one to another, but there are differences in the amounts of raw materials (limestone, clay, sand, slag, and gypsum) used in each factory. Other data requirements represent energy and resources which consist of mazzut, natural gas, diesel, water, and electricity, and data on the emissions from cement manufacturing, and impacts of particulate matter emissions and gas emissions (SO_2 and NO_2).

A previous study stated that (Ali et al. 2014b), Egypt suffered from a shortage of LCA applications and life-cycle inventory databases; thus, the input–output databases from field visits and surveys of ECPs have been collected. Table 6 shows data collected during field visits from the on-site surveys of the Assiut CEMEX cement plant.

Theory/calculation

Assessing the environmental impacts of the cement industry

LCA allows for the appraisal of processes or products from the 'cradle to the grave' (Margallo et al. 2014). LCA should be implemented according to the four steps of ISO 14040 (ISO 2006a, 2006b) and ISO 14044 (ISO 2006a), (a) definitions of goals and scope; (b) life-cycle inventory (LCI) analysis; (c) life-cycle impact assessment (LCIA) and (d) interpretation. SimaPro V8.1 (PRé Consultants, Amersfoort, The Netherlands) and Ecoinvent database (ECOINVENT 2015), which was established in Switzerland, and the datasets were used in the analysis of the three types of cement industry plants by means of the aforementioned inventory datasets.

Goal and scope

The main objective of this study is to contribute to the assessment of environmental impacts of the cement industry in Egypt, by means of adopting the LCA methodological process. This is to aid stakeholders, decision makers, and building-material manufacturers with

Table 3 Current Regulations and Emissions of Ambient Air quality in Egypt from the cement companies

	Law number 4 in 1994		Law number 9 in 2009	
Particulate matter	Before 1995	300 mg/m^3	New plants	100 mg/m^3
	After 1995	200 mg/m^3 For old plants	Old plants	50 mg/m^3
		100 mg/m^3 For new plants		
Sulphur oxides (SO_x)	300 mg/m^3		400 mg/m^3	
Nitrogen oxides (NO_x)	4000 mg/m^3		600 mg/m^3	

Table 4 The questionnaire of cement types which were used in the buildings

A questionnaire on
Determination of cement types used in constructing the buildings in Egyptian City

This questionnaire is part of the PhD study of Engineer / Ahmed Abdelmonteleb Mohammed – PhD student, Egypt-Japan University of Science and Technology, Alexandria, Egypt. We request you kindly help him to complete this task.

There are various building materials used in Egypt. All such materials have detrimental impacts on the surrounding environments as a direct result of their manufacturing. This is attributed to harmful substances emitted by the chimneys of these plants, such as CO_2, SO_2, particulate matter emissions, etc. So, it was necessary to set a questionnaire to determine materials most commonly used in constructing building in Egyptian City for the purpose of conducting a study to investigate the possibility of reducing such harmful emissions.

Personal information:

- Age: --------------- Gender-------------------- Occupation: -----------------------------------

1- Do you think it is important to study the influence of manufacturing building materials on the surrounding environment?

Yes ☐ No ☐ Somehow ☐

2- Do you live near a plant for manufacturing building materials; particularly the cement plants?

Yes ☐ No ☐

3- If the previous answer was yes; do you feel deterioration of the surrounding environment because of smoke emitted by these plants?

Yes ☐ No ☐

4- If the previous answer was yes; please name the plant(s) near your residence?

....

5- Considering cement, which types of cement do you use when constructing residential buildings?

☐ Amreya cement (Cimpor group) ☐ Sinai cement ☐ Misr bani suef (TITAN) ☐ Alexandria cement ☐ Misr-Qena

☐ Suez Cement ☐ Helwan Cement ☐ El Minia (Italcementi group) ☐ Arabian Cement ☐ CEMEX ☐ LAFARGE ☐ National cement ☐ Others (please specify): ……………………………………

Thanks for your help, response, and precious time. You are welcome to write your notes here:

....

knowledge of the environmental impacts caused by technologies, procedures, or materials that are used in the cement industry. Therefore, a comparison was performed among three different systems: An Egyptian cement plant using electricity, natural gas, diesel, and mazzut for energy consumption; an EHP using electricity and coal; and an SCP using electricity, natural gas, and coal. To ensure a fair comparison among the three different systems, the inputs from the life-cycle inventory databases are of the same quantities in the two case studies in Egypt. Referring to the SCP, the SimaPro LCI database was used on a plant of smaller size. The same technology was used in cement manufacturing, taking into account the minimal error rates of the results between the SCP and the ECPs.

To attain the main goal and scope of this study, the system domain boundary represents the consumed fuels in these processes: raw material acquisition, processing, and product manufacturing (as shown in Fig. 3). All the dataset

Table 5 Presenting the questionnaire results

Number of samples	30 samples from executive engineers from government and private business sectors in Assiut, Egypt
Age question	Age ranges between 27 and 45 years old
First question	14 for Yes, 9 for No, and 7 for Somehow
Second question	9 for Yes, 21 for No, and none for Somehow
Third question	9 for Yes, and none for No
Fourth question	CEMEX (Assiut Cement) and El Minia (Italcementi group)
Fifth question	CEMEX (Assiut Cement), National cement, El Minia (Italcementi group), and Lafarge Cement

N.B. * Been clarified to the executive engineers (the samples), the goal of the questionnaire being that it is related to the scientific research only

Table 6 Cement manufacturing data collected from an Egyptian cement plant (CEMEX plant)

Consumption of raw materials By ton/year	
Lime stone	5978,720
Clay	528,719
Sand	0
Slag/Iron Ore	624,946
Gypsum	207,410
Consumptions	
Electrical (MwH/Year)	641,526
Natural Gas (Ton/Year)	0
Mazzut (Ton/Year)	399,790
Diesel (Ton/Year)	7984,325
Emissions Mg/m^3	
Dust	23,648
CO	512.48
SO_2	25.27
NO_2	130.69

Diesel used in transportation of the materials in each stage by heavy trucks and the excavators in the raw material excavation stage

Natural Gas and Mazzut used in mechanical machines, and others used electric power. (shown in Fig. 2)

collection and calculations in this study have been converted with respect to use of one kilogram of the cement product being the most-known LCA functional unit within research fields, since cement is packaged in sacks and denoted by weight in kilograms or tons.

Life-cycle Inventory database

Life-cycle inventories (LCIs) involved using the data compiled from industry contacts, industry organizations, and precedent studies (Fiksel et al. 2011). Furthermore, the inventory database includes data collection from field visits to count the inputs and outputs of cement manufacturing,such as (1) the raw material from mines (lime stone, gypsum, clay, slag/iron ore, and additions), water use, diesel use, and emissions; and (2) particulate matter emissions of gases and heavy metals. This study used the inventory data which have been collected from visiting the ECP as a case study. It is worth mentioning that the authors have encountered many problems in collecting these data mainly because of several reasons such as the confidentiality of data and the scarcity of monitoring tools for some emissions in some ECPs. That is why the authors have used some assumptions from the Ecoinvent V.3 database to help them fill in some research gaps.

Life-cycle impact assessment (LCIA)

The impact categories enable us to differentiate between the environmental impacts of the different options. Characterization factors or equivalency factors describe the relative impacts of the different environmental flows, i.e., the larger the characterization factor the larger the impact for that flow. Consequently, the characterization factors are definitely multiplied by each of the environmental flows to convert all of them into an equivalent amount for the category indicator. Then, the category indicator is the flow that is usually associated with that particular impact category, for instance, CO_2 for the global warming category, and so forth (Ali et al. 2015). This impact category indicator is assembled into the eight resource categories: fossil, nuclear, hydropower, biomass; and other renewables are, water, minerals, and metals; however, in SimaPro, ten different impact categories are presented: Non-renewables (fossil, primary, metals, minerals, and nuclear); Renewables (kinetic, solar, biomass, water, and potential). The characterization factors for 112 different resources were included in these calculations via SimaPro (2015);

$$CExd = \sum_i m_i \times Ex_{(ch),i} + \sum_j n_j \times r_{ex-e(k,p,n,r,t),j}$$

$CExd$ = cumulative exergy demand per unit of product or process (MJ-eq), m_i = mass of material resource i (kg), $Ex_{(ch,)i}$ is the energy per kg of substance i (MJ-eq/kg), n_j is the amount of energy from energy carrier j (MJ), $r_{ex-e(k,p,n,r,t),j}$ is the energy to energy ratio of energy carrier j (MJ-eq/MJ), ch is the chemical, k is the kinetic, p is the potential, n is the nuclear, r is the radiative, and t is the thermal exergy.

Based on the contemporary literature on the life-cycle impact assessment, two approaches are proposed: the midpoint and the endpoint methods. So far, there is no unanimous verdict in the scientific research community, as to which assessment method is better. The midpoint method impacts on covering issues such as climate change, abiotic resource depletion, and others. The second, i.e., endpoint method impacts on covering issues as follows (Asdrubali et al. 2013):

- Human health damage, expressed as the number of years of human life lost or in suffering from disease, which is defined as Disability-adjusted life years (DALY) and is the sum of years of life lost (YLL) and the years of life disabled (YLD); DALY = $YLL + YLD$ (Goedkoop et al. 2009)
- Quality of ecosystems, which is expressed as the loss of living species in a certain area over a period of time.
- Natural resources, expressed as the surplus of energy necessary for further extraction of minerals and fossil fuels.

Table 7 describes the methodology which is required for the LCI inventory, which is involved in SimaPro V.8.1; this study used the IMPACT 2002+ (Bengoa and Margni 2002) category to assess the environmental impacts of the ECI.

Results and discussion

The network models in Fig. 5 were constructed according to the assumptions and limitations as described in "Theory/calculation" section. Referring to Fig. 6, the

Table 7 IMPACT 2002+ characterization as a life-cycle impact category (version Q2.2) (Bengoa and Margni 2002)

[Source]	Midpoint category	Midpoint reference substance	Damage category (end-Point)	Damage unit	Normalized damage unit
[a]	Human toxicity (carcinogens + non-carcinogens)	kg Chloroethylene into air-eq	Human health	DALY	Point
[b]	Respiratory (inorganics)	kg PM2.5 into air-eq	Human health		
[b]	Ionizing radiations	Bq Carbon-14 into air-eq	Human health		
[b]	Ozone layer depletion	kg CFC-11 into air-eq	Human health		
[b]	Photochemical oxidation (= Respiratory (organics) for human health)	kg Ethylene into air-eq	Human health		
			Ecosystem quality	n/a	n/a
[a]	Aquatic ecotoxicity	kg Triethylene glycol into water-eq	Ecosystem quality	PDF·m^2·y	Point
[a]	Terrestrial ecotoxicity	kg Triethylene glycol into soil-eq	Ecosystem quality		
[b]	Terrestrial acidification/ nutrification	kg SO_2 into air-eq	Ecosystem quality		
[c]	Aquatic acidification	kg SO_2 into air-eq	Ecosystem quality		
[c]	Aquatic eutrophication	kg $PO^4{}_3$- into water -eq	Ecosystem quality		
[b]	Land occupation	m2 Organic arable land-eq · y	Ecosystem quality		
	Water turbines	Inventory in m^3	Ecosystem quality		
[IPCC]	Global warming	kg CO_2 into air-eq	Climate change (life support system)	kg CO_2 into air-eq	Point
[d]	Non-renewable energy	MJ or kg Crude oil-Eq (860 kg/m^3)	Resources	MJ	Point
[b]	Mineral extraction	MJ or kg Iron-eq (in ore)	Resources		
	Water withdrawal	Inventory in m^3	n/a		
	Water consumption	Inventory in m^3	Human health		
			Ecosystem quality		
			Resources		

[a] IMPACT 2002, [b] Eco-indicator 99, [c] CML 2002, [d] Ecoinvent, [IPCC] (IPCC AR5 Report), and [USEPA] (EPA)

daly disability-adjusted life years, *PDF* potentially disappeared fraction of species, *-eq* equivalents, *y* year relationships between the impacts associated with the entire life cycle of two Egyptian cement plants and the significance of alteration within energy feed in the EIA of the cement industry are depicted. According to the figures, significant highly adverse impacts have been recorded which were mainly related to the production of SO_2, which is explicitly confirmed by the Central Pollution Control Board regulations (CPCB 2010), where SO_2 is emitted from the plant chimney during the combustion stage as a result of coal burning (Mittal et al. 2014). Particularly SO_2 emissions chiefly rely on the sulfur content in the coal, operating conditions, and designs of the plant and control devices. Meanwhile, SO_2 pollution damages the prospects of the public in getting clean air quality and endangers the ecosystem and human health as reported earlier (Wang et al. 2015). Indeed, air pollution by SO_2 affects negatively on human beings in terms of corneal haze, breathing difficulty, airways inflammation, eye irritation, psychic alterations, pulmonary edema, heart failure, and circulatory collapse (WHO 2003), (EPA 2011), (Jiang et al. 2015). According to the earlier study (PSR 2015), the impact of coal pollution has primarily caused major adverse effects on the organ systems of the human being, and the report concludes that coal contributes to four of the top five causes of mortality in the world: heart disease, cancer, stroke, and chronic lower respiratory diseases.

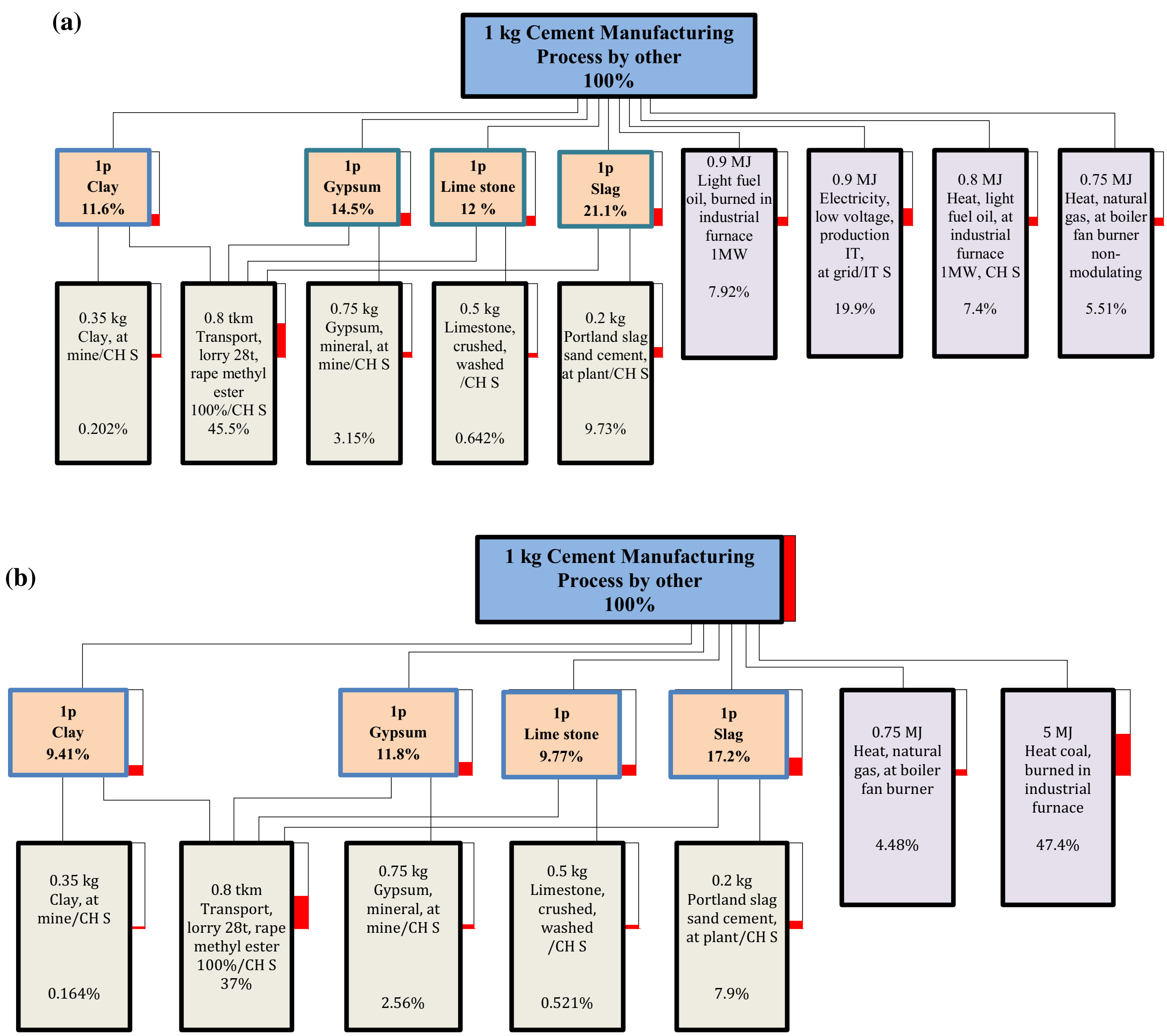


Fig. 5 The network flows of the three cases studies from LCA point of view. **a** Energy consumption in cement industry plant based on electricity, natural gas, diesel, and mazzut as energy sources. **b** Egyptian cement plant using electricity and coal as energy consumers in the plant. **c** Swiss Cement Plant using electricity, natural gas, and coal as energy consumption in the plant

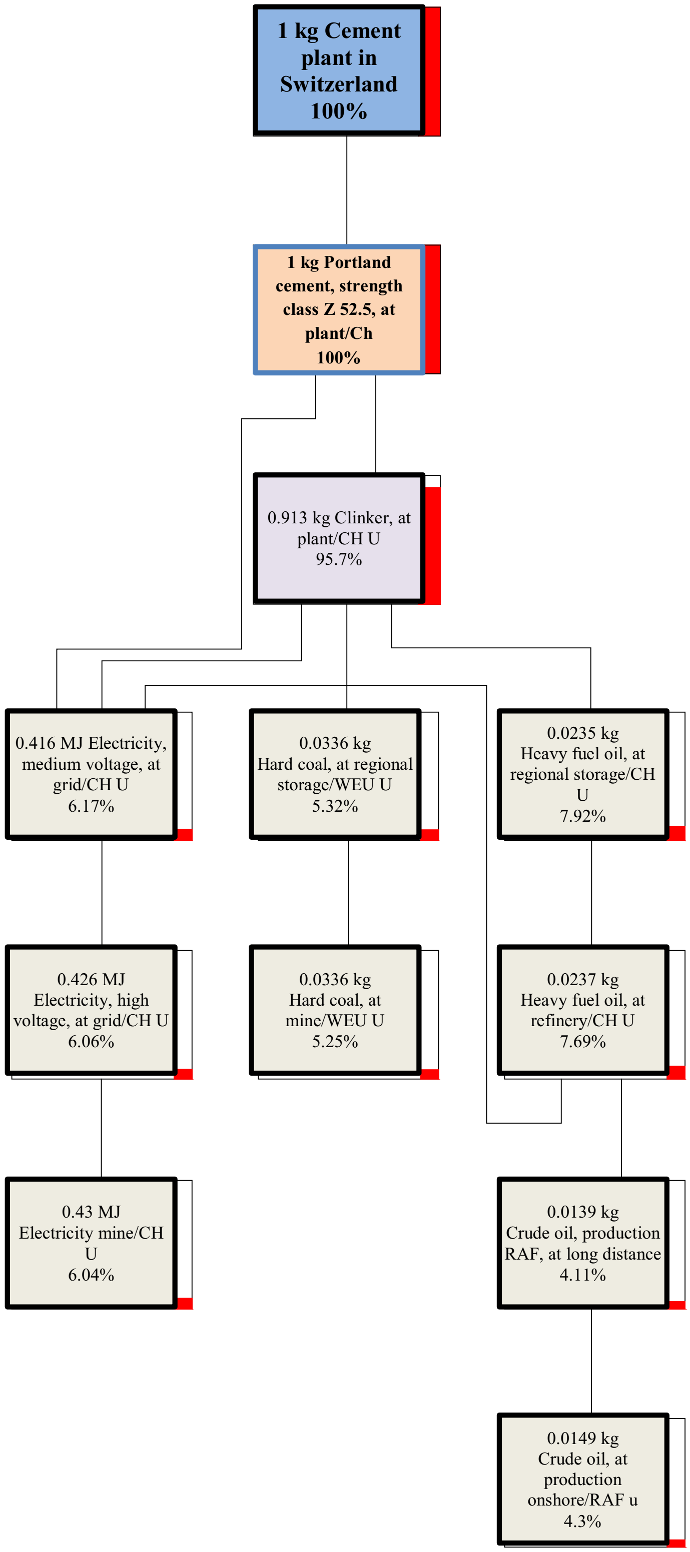


Fig. 5 continued

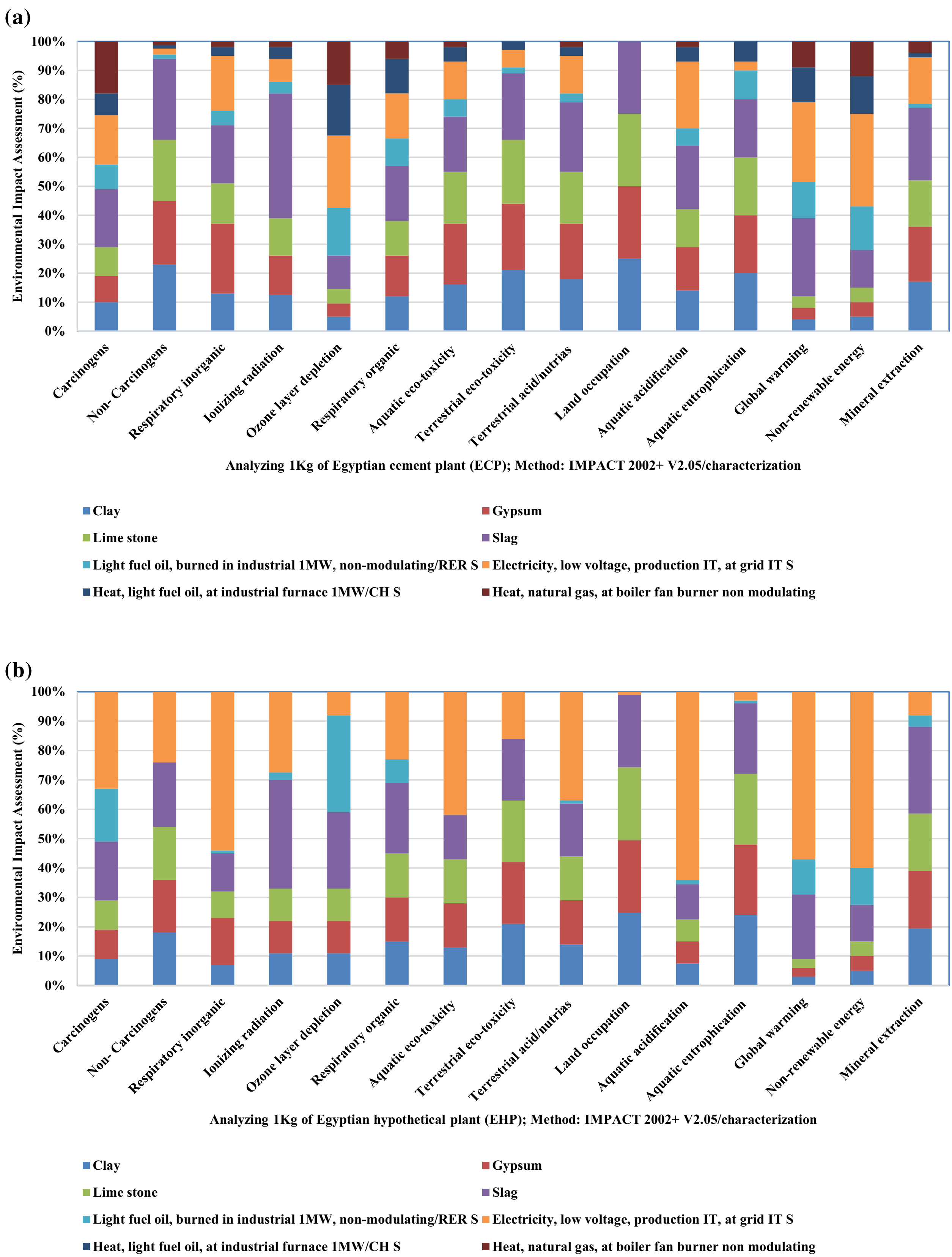


Fig. 6 Environmental impact assessments of the two Egyptian cement plants. **a** Using electricity, natural gas, diesel, and mazzut. **b** Using electricity and coal

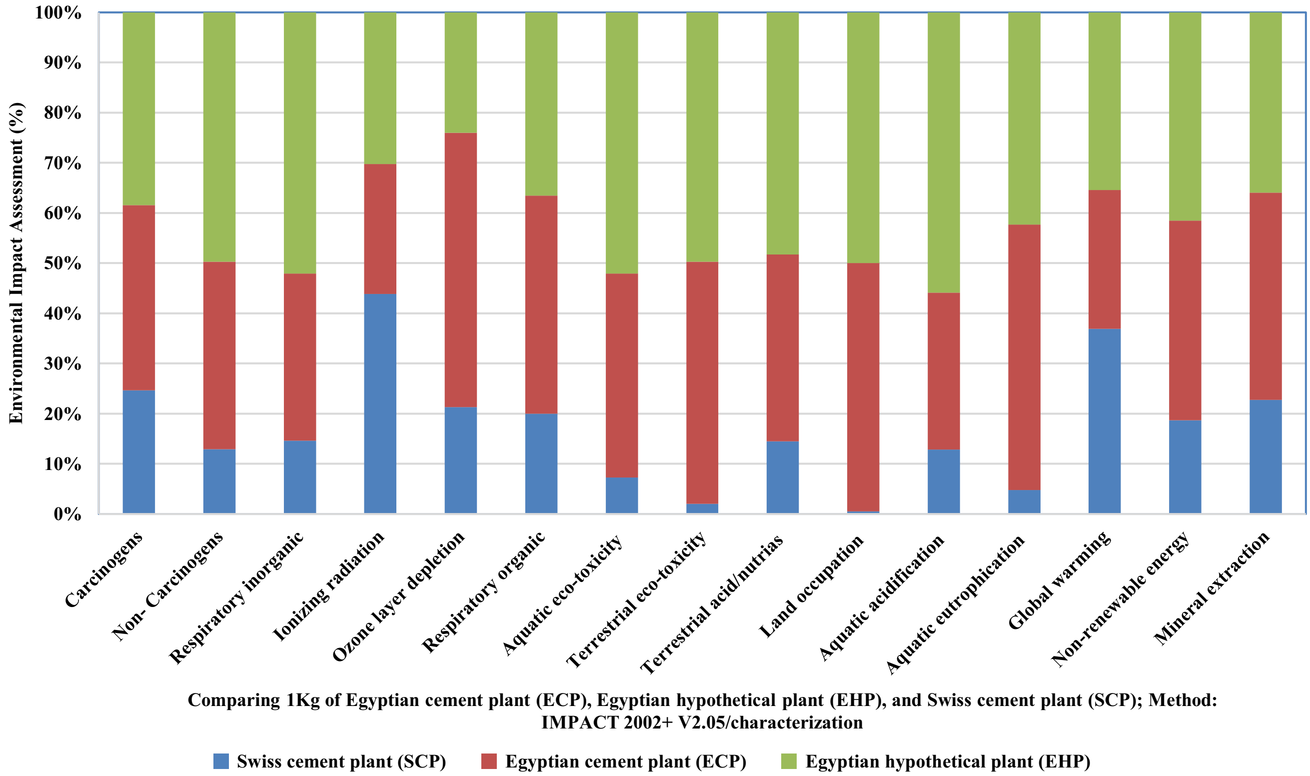


Fig. 7 Comparison of environmental impact categories for the three cases studies

Regarding the main environmental impacts in the combustion stage, it is observed that about 35% has been shared from the respiratory organics, global warming as well as non-renewable energy individually. This was not the case of the aquatic acidification that achieved the highest and prominent impacts of 60% compared to the conventional processes. (Reddy and Venkataraman 2002).

Regarding the ionization, radiation, and global warming potentials, the SCP reflected higher environmental impacts than the other two Egyptian plants. This is mainly because of the devices in the technology used in the SCP for eliminating the excess emissions, such as the scrubbers that remove the emissions from the exhaust of the coal-fired kiln (Lu et al. 2011) and (Senior et al. 2015). Accordingly, the comparison of the life-cycle environmental impact (LCEI) among the three case studies is presented in Fig. 7, identifying which of the three plants imposes the highest adverse impacts. Comparatively, the depicted results are in accordance with (Li et al. 2014) observations, where the coal, oil, and natural gas have the highest environmental impacts pertaining to all categories of IMPACT 2002+.

Midpoint method results

According to the results shown in Fig. 8, despite the fact that SCP uses coal in the cement manufacturing process, the environmental impact is lower than the ECPs in total. Quantitatively, the difference between the SCP and ECP is 162 Eco-points, an approximation of 46 % reduction of the total environmental impact categories. This is consistent with the reduction percentages (54 and 61 %) achieved respectively in China and United States regarding to CO_2 emissions (Ma et al. 2011) and (Senior et al. 2015). Concerning global warming (climate change) and respiratory inorganics, these are the highly affected categories within the entire LCA of the cement industry (Benhelal et al. 2013). Another impact category is the respiratory inorganics; the ECP that uses coal as a fuel type in the combustion unit, recorded higher impacts than the other plants, due to the difference in technology used and kiln age (Ma et al. 2011).

Endpoint method results

As the sequel to the former analysis, the result of the damage assessment (Endpoint method) shows that using coal as a substitution feed energy in the combustion unit is, on average, worse than the ordinary case which is consonant with (Wang et al. 2015) results; (Fig. 9). The SCP records 5 % increase in climate change compared to EHP; this may be due to the difference in the chemical compositions of the used fuels in the oven process (Zhang et al. 2010). Lastly, however, the European cement industry uses coal in the oven kiln stage, although there are limitations

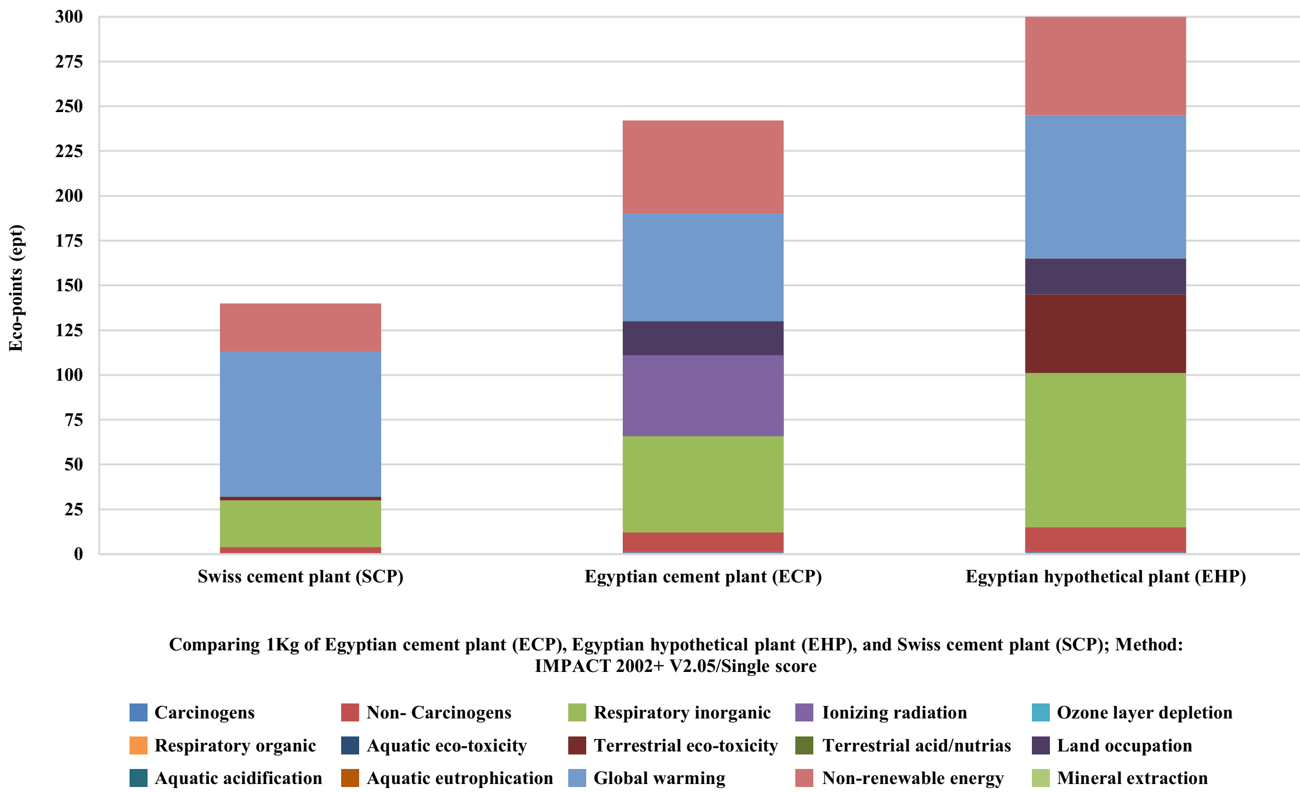


Fig. 8 Comparison of the total environmental impact categories for the three cases studies (Midpoint Method)

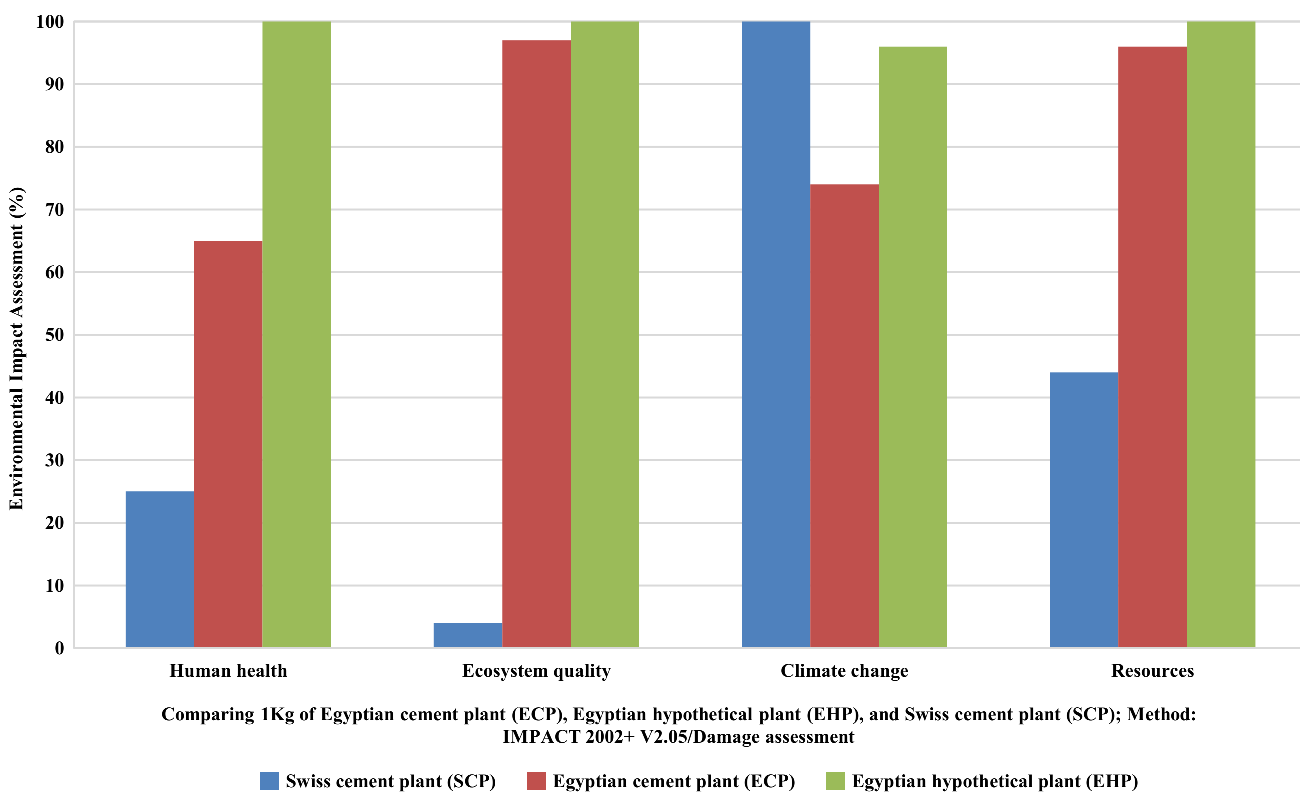


Fig. 9 The damage assessments of the three cement plants (Endpoint Method)

and constraints from the Environmental Agencies on how to control the output emissions from the factory chimney and the technology that is used to omit excess emissions over and above the allowable limits (UNEP 2011).

Therefore, the consideration of international technologies is highly recommended to mitigate the adverse impacts on the environment in case of using coal as an alternative feed energy.

Conclusions

Life-cycle assessment could be a realistic and powerful tool to elucidate the real sustainability of critical industries such as; the cement industry in terms of its entire life, which is getting more and more widespread throughout the world. Although a handful of publications have studied many cases about the cement industry in the world using the LCA perspective, there are no such studies relating to the Egyptian cement industry. This problem is attributed to the failure to adopt the Environmental Affairs Agency for the LCA as an environmental impact tool, as well as the shortage of the dataset and monitoring tools in the Egyptian firms. Therefore, this study aims at shedding light on this to fill this gap, simulating three scenarios of cement plants: An Egyptian cement plant (ECP), an Egyptian hypothetical plant (EHP) and a Swiss cement plant (SCP). To conclude the results obtained during this study, the following information should be pointed out:

1. The respiratory inorganics, aquatic acidification, global warming (climate change) 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 SO_2 emissions from the plant chimneys during the combustion stage of coal in accordance with the provisions of the Environmental Protection Agency (EPA).
2. Based on the difference in the chemical compositions of the fuels used in the oven process, for the SCP, global warming (climate change) and respiratory inorganics (midpoint method) recorded 5 % higher adverse impacts than the EHP.
3. 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).
4. 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.
5. A coal-based plant has higher adverse environmental impacts compared to others.
6. The mitigation of the environmental impact of coal burning using scrubbers must have an important role in the future design of ECPs.

Future outlook

Ultimately, the costing and management together with LCA studies would provide a precise solution to the Environmental Affairs Agency, since a cost-based approach for environmental deterioration mitigation in industry sectors often proves effective. This, however, should lead the cement industries' stakeholders and decision makers to collaborate to achieve cleaner production and a sustainable environment by taking the international experiences in emission reduction into consideration and activating the environmental laws through the EEAA. In addition, the EEAA should encourage the cement industry to utilize new technologies through a set of incentive-based policies.

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