ORIGINAL PAPER

Environmental feasibility of recycling construction and demolition waste

I. Atta[1] · E. S. Bakhoum[2,3]

Abstract
Construction, demolition, and renovation activities generate a significant amount of waste, posing serious environmental risks. The scarcity of recycling facilities makes it difficult to implement the new legislation, which calls for producing recycled aggregates. Moreover, the lack of studies on the environmental feasibility of recycling construction and demolition waste in regions with plentiful natural resources of aggregates is a contributing factor to this scarcity. Therefore, this paper studies the environmental feasibility of establishing a construction and demolition waste (CDW) recycling plant. A case study approach compares the CDW recycling process against the traditional quarrying process for generating aggregates. The lifecycle assessment method is used for evaluating both scenarios. Contribution analysis is performed to infer the factors influencing the viability of the recycling process. Thereafter, a sensitivity analysis is conducted to determine the suitability of the proposed location for the recycling facility. As revealed by the single score, the recycling alternative has a 23% more negative environmental impact than quarrying. Nevertheless, there is a chance that the recycling process could be environmentally advantageous. Findings indicated that a total travel distance of 70 km between the demolition site and the construction site is recommended to guarantee environmental feasibility. The transportation distance is found to be the most critical element influencing the environmental feasibility of recycling CDW. The findings of this study help the decision-makers in environmental affairs to consider the influencing factors when constructing a CDW recycling plant.

Keywords Construction and demolition waste · Natural aggregate · Quarrying · Recycling · Recycled aggregate

Introduction

Background

The need to build new societies has become unavoidable as a result of developing countries' rapid population growth.

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Simultaneously, development work for current societies is necessary to meet the needs of the current generation and maintain social stability. As a result, natural resources such as quarries and mines are threatened with depletion, putting the needs of future generations at risk. Furthermore, large amounts of construction and demolition wastes (CDW) are generated, resulting in significant environmental and social damages that cannot be ignored (Da Paz et al. 2020).

The environmental impact of manufactured products, including construction materials, is directly associated with health concerns. Therefore, measures of human health and toxicity are among the most crucial ones that are used in many environmental assessment tools and models, such as environmental product declaration (EPD), product environmental footprint (PEF), and USE-tox (Munch-Petersen and Lewis 2022). Particulate matter is one of the indications used to assess human health due to the significant disease and mortality it causes. These particles are produced by various operations such as excavation, backfilling, machine operation, and demolition

works. They are usually classified according to their size into particles less than 2.5 μm ($PM_{2.5}$) and particles less than 10 μm (PM_{10}). A study by Gao et al. (2022) indicated that 17.6% of premature mortality due to air pollution in the North China Plain is caused by particulate matter. The authors emphasized the need of controlling these pollutants through legislation and policies to increase worker productivity and protect people's health.

Ionizing radiation is also one of the most serious hazards to human health and living things. A study by Ruth et al. (2020) revealed that some of the quarries where construction stones are mined are radiation sources. Given that each 1 millisievert/year is expected to cause 0.5% of total cancers and genetic illnesses in the general population, the study highlighted the need of checking radiation levels in quarries. Moreover, Kancheva (2022) stated that the demolition of some structures may result in the release of radiation due to the presence of radioactive additives such as fly ash in the concrete or aggregate. The previously-mentioned studies have emphasized the value of managing construction and demolition waste wisely and effectively, whether by reusing it whenever feasible or by properly disposing of it.

In this regard, several governmental institutions are developing CDW management plans, including the creation of platforms to guide and collaborate with persons involved in waste management, as well as the issuance of regulatory legislation and standards. Looking at the experiences of developed countries, reports state that the recovery rate of construction and demolition wastes in the European Union has reached 88% of around 800 million tons in 2018 (Deloitte 2017). Countries like Netherlands, Luxembourg, and Belgium recover and recycle up to 100% of the generated CDW. Reports also show that some of these countries import waste more than they generate. Recycled aggregates in the UK and the Netherlands cover up to 27% and 35% of the market demand respectively, reducing the burden on natural resources drastically (Eurostat 2021). While in the US, recovered CDW accounted for 76% of the total CDW generated which amounted to 600 million tons (US EPA 2020). These high percentages are justified by the presence of dozens of treatment and recycling stations distributed throughout most of the provinces (Andriamasinoro and Monfort-Climent 2021; CDRA 2021), which is severely lacking in Egypt and many developing countries. Another successful example can be seen in Japan, where a CDW recycling rate of 97% has been reached. Legislations of public cleansing, waste disposal, and recycling laws played a major in reaching this state. The basis for the previously mentioned laws is to establish

a material-cycle society that gives the priority to reducing, reusing, and recycling (3Rs), respectively (MLIT 2019).

The 3Rs rule is considered one of the most prominent strategies put forward for construction and demolition waste management (El Haggar 2007). Usually, reduce and reuse strategies are more related to the pre-construction stage as they depend on innovative design concepts such as design-for-deconstruction (DfD). However, the current situation indicates that this concept is still not widespread, especially in developing countries (Olofinnade et al. 2021), which calls for interest in the recycling strategy of traditionally designed buildings that are nearing their end of life. This strategy is reinforced by Desmond (2009) who pointed out that proposing a sustainable strategy must be driven by the fulfillment of legislation, environmental protection, and compatibility with existing facilities.

Previous studies discussed the management of construction and demolition wastes from a variety of perspectives. Several studies have focused on waste management practices that can be carried out at different stages of a project (Al-Ansary et al. 2004; Daoud et al. 2023). In another context, plenty of studies have been conducted to investigate the technical viability of using recycled CDW in the production of construction materials such as concrete (Bandara et al. 2022), high-performance concrete (Aslani et al. 2018), backfill paste (Yılmaz and Ercikdi 2022), and cement bricks (Sharkawi et al. 2018). Also, road construction is considered to be one of the most common applications of recycled CDW. Various parts of the road were investigated such as base/subbase layers (Deshmukh et al. 2019), surface layers (Galan et al. 2019), paving blocks (Özalp et al. 2016), embankments (Zhang et al. 2019), and other uses (Rahman et al. 2014; Suluguru et al. 2019). The preceding investigations were mainly focused on the mechanical properties of the recycled CDW to better understand its applicability.

Furthermore, many studies have been conducted to determine the economic viability of recycling CDW. Marzouk and Azab (2014) found that recycling CDW can provide an economic benefit over disposal. Hoang et al. (2021) expected a promising market for using recycled CDW in road construction activities when compared to natural aggregates. In a related context, several studies have discussed the factors influencing the economic feasibility of recycling CDW, such as the type of the recycling plant (Zhao et al. 2010), their location (Coelho and De Brito 2013a, b), taxation and subsiding policies (Liu et al. 2021), and the demand of the recycled products (Ding et al. 2021).

When looking at research that focused on the environmental aspect, it can be observed that there are two
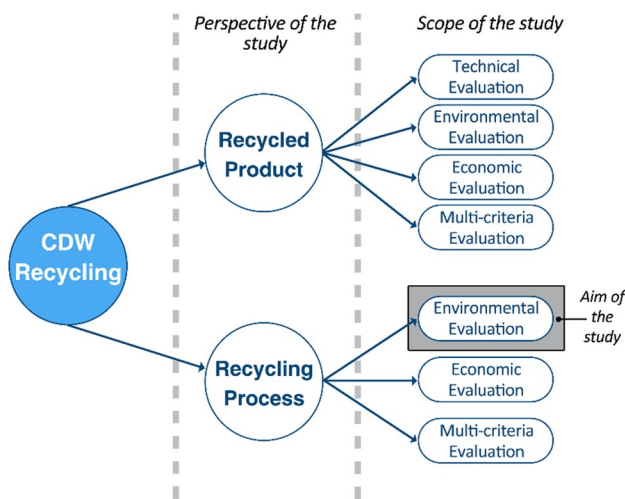
Fig. 1 Perspective and scope of recycling CDW studies

categories of study. The first category was concerned with assessing the final product manufactured from recycled waste. Whereas, the second one was concerned with assessing the recycling process itself (Fig. 1). Wijayasundara et al. (2018) conducted one of the studies that focused on evaluating different recycled products. The cost–benefit analysis approach is utilized to assess 15 recycled concrete aggregate combinations with varying replacement ratios and additives. In the same direction, Silgado et al. (2018) used a multi-criteria decision-making technique to evaluate different combinations of green concrete made from recycled aggregates and recycled gypsum cement. In addition, a variety of construction and demolition wastes were investigated in previous studies to manufacture valuable construction materials such as glass (Ahmad et al. 2021), wooden ash (Ahmad et al. 2022), and plastics (Guðmundsdóttir 2018). Moreover, recent research has dealt with the possibility of exploiting waste from the agrifood industry in the manufacturing of building materials. Silvestri et al. (2021) studied the utilization of wastewater from the olive milling process in the production of fired clay bricks. Reduced global warming potential (GWP) compared to traditional brick manufacture is a clear advantage from an environmental standpoint. It is also found that the transportation distance of the wastewater from the olive mill to the manufacturing site is essential for establishing such viability.

On the other hand, the review of the literature concerned with recycling CDW reveals that the majority of these studies use the life cycle assessment approach. However, the considerations employed in the evaluation vary and have several shortcomings. Rosado et al. (2017) compared between the production of basalt as a natural aggregate and the manufacture of recycled aggregate for use in road base/subbase layers in Brazil. The research considered four burdens that may be avoided by recycling: steel production, timber production, clay extraction from quarries, and inert waste landfilling. The approach of life cycle assessment (LCA) is used along with indicators from the IMPACT2002 + method. For most indicators, the results showed that recycling outperformed natural quarrying. However, the only variable parameter considered in the study was the transportation distance. A comparative study was performed by Jain et al. (2020) to evaluate the environmental implications of both recycling and landfilling CDW for a case in India. Indicators of the ReCipe method are used for evaluation. Recycling had a significant advantage in terms of GWP due to the avoidance of transportation for raw materials. Furthermore, the advantages of the land use indicator were achieved owing to the avoidance of landfill. Despite its significance, the study did not account for the effects of avoiding steel production. Satisfactory results are not always present in all investigations. Freire et al. (2018) utilized the LCA technique to estimate the environmental impact of recycling CDW generated from pavements for use in rehabilitation works in Portugal. Energy consumption and carbon footprint were the indicators used for the evaluation. Results showed that landfilling of wastes has a preference over the recycling option despite the economic benefits that can be gained from the recycling scenario. Ferronato et al. (2022) investigated the environmental viability of CDW recycling in Bolivia. The recycling scenario is compared to waste disposal. The LCA boundary system comprised a simulation of energy use, transportation distances, and recycling capacity. However, the framework fails to take into account the avoided impacts of producing reinforcing steel. Also, all activities other than transportation are not taken into account when determining the avoided impact of producing natural aggregate. A study by Tefa et al. (2022) evaluated the structural and environmental feasibility of recycling CDW for use in semi-rigid and flexible pavement subbase layers. For both unbound and cement-stabilized layers, several mixtures incorporating natural and recycled components were examined. The results showed a closeness in the structural aspect, while many of the recycled mixtures showed more promising results than their natural counterparts. However, the technique employed did not take into account the avoided impact of steel production. Also, variations in parameters such as transportation distances and energy consumption were not considered. The

author emphasized the importance of taking into account geographical differences when applying this type of study.

Research gap and objective

By the recommendation given in the last reference cited, the authors investigated studies that had been conducted within the geographic area of Africa and the Middle East, where many nations have an abundance of construction raw materials. Several studies were found addressing the feasibility of the recycled product whether from a technical (Sharkawi et al. 2018) or an economic (Kamel and Abu-Zeid 2008) aspect. Furthermore, various studies have been conducted to evaluate the economic aspect of the recycling process (Abdelhamid 2014; El-Shaboury et al. 2019). Conversely, the review of the literature showed a significant lack of research addressing the environmental impact of the recycling process, particularly from the lifecycle perspective. This is reinforced by the recent bibliometric analysis conducted by Mesa et al., (2021), who indicated that Africa and the Middle East have minimal studies on CDW recycling. The limitations in the previous-mentioned research can be summarized into three points: (1) the assessment framework lacks considering crucial avoided impacts; (2) the variability of crucial parameters are not addressed; and (3) few studies have examined the feasibility of recycling CDW in regions with abundant raw materials.

This research aims to study the environmental feasibility of recycling construction and demolition waste in Egypt, where building materials quarries are abundant. Egypt is an example that can be generalized to many African and Middle Eastern countries that share the same geographical characteristics (Blatt et al. 1980; Taylor et al. 2005). To fill the gap in the aforementioned studies, this study considered two avoided impacts in the assessment method: waste landfilling and reinforcing steel production. Also, it addresses the variability of parameters involved in the assessment using sensitivity and uncertainty analyses. This is in line with Guo and Murphy (2012) who emphasized the necessity of performing sensitivity and uncertainty analyses on LCA studies for transparency and confidence. Hence, the novelty in this research is the investigation of the environmental feasibility of recycling CDW in regions possessing a plentiful resource of raw materials where recycling viability is debatable. Additionally, the study included factors that increase the reliability and accuracy of the results in the evaluation technique such as avoided impacts and analyses of sensitivity and uncertainty.

To achieve the aim of this research, a comparative study of recycling CDW and quarrying, for the sake of producing construction aggregate, is presented. The following steps were arranged to conduct the study:

(1) Identifying the methodology and the tools used for the environmental assessment.
(2) Introducing the case study and applying the adopted methodology.
(3) Discussing the findings and deducing the influencing factors on the recycling process.
(4) Analyzing the sensitivity of the identified influencing factors on the results.
(5) Analyzing the uncertainty of the data on the results.
(6) Concluding the best conditions for performing the recycling process.

Materials and methods

Considering the aforementioned review of literature, the lifecycle assessment (LCA) technique was determined to be the most appropriate for implementing this study. This technique has proven to be effective due to its simplicity and comprehensiveness. Furthermore, the variety of indicators it includes has played an important role in preferring it over other assessment techniques (Elia et al. 2017). According to ISO14040/14044 standards, the lifecycle assessment process must include four main phases: goal and scope definition, inventory analysis, impact assessment, and interoperation (ISO 2006). Each of these phases is described in the following subsections. To simulate the processes of producing recycled aggregates (RA) and quarrying natural aggregates (NA), OpenLCA 1.9 software is utilized. This software provides options for using and adapting existing lifecycle inventory databases in an efficient way to model the alternatives understudy. It also provides an impact analysis that shows the detailed contribution of each process concerning impact categories (GreenDelta 2021).

Goal and scope definition

The goal of this study is to investigate the environmental feasibility of recycling construction and demolition wastes in Egypt. The research is limited to the Giza region, an Egyptian governorate of Greater Cairo that encompasses the country's most important archaeological and historical monuments. It covers an area of around 13,184 km^2 and has 12 districts under its administrative boundaries

Fig. 2 Giza governorate landmarks, Egypt
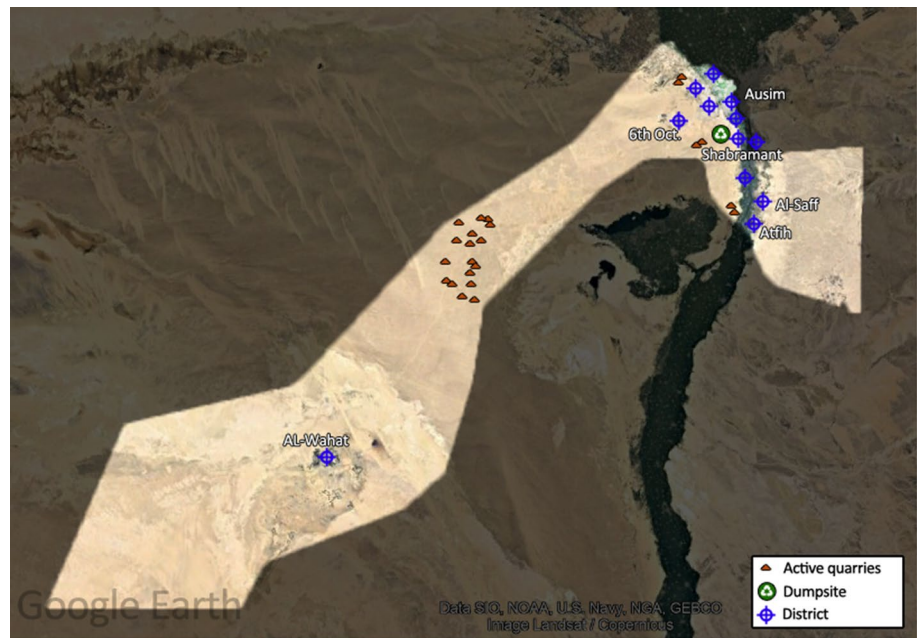
(CAPMAS 2007). One of the governorate's most valuable resources is its quarries. Mining activities are widely used in various raw materials, whether they are used in construction or other sectors. The recently approved waste management law in Egypt addressed some of the prior shortcomings of previous laws. Previously, there was no obligation on the part of the stakeholder to pursue any strategy that promotes reuse or recycling. They were just instructions for landfill procedures and conditions. Also, there was no clear classification or characterization of construction and demolition wastes. Despite reforms in the new legislation, enforcement of the law remains dubious. This prediction is supported by the fact that there are no working recycling facilities in many major governorates (CAPMAS 2021). Given the abundance of quarries in the governorate under study, a competitive comparison between quarrying and CDW recycling is expected. The only active dumpsite is located in Shabramant town. The common geographical nature makes this study generalizable to most countries in the Middle East and North Africa (Blatt et al. 1980). Figure 2 depicts the governorate landmarks considered in the study.

The functional unit of this study is considered to be 1 ton of the product whether it is recycled or natural aggregate. The functional unit indicates the measurable reference amount of a product or a system in which its performance is assessed (De Simone Souza et al. 2021). Using a mass-based functional unit is justified since it is prevalent among building materials stakeholders and has been expressive

in several previous research. The recycling process begins with the demolition and sorting of the built element, followed by the transportation of waste to the recycling plant. Waste is fed into the recycling plant through a hopper and then to a vibrating feeder. The demolished pieces are sent to the crushing equipment through a series of conveyor belts. Crushing and screening are carried out in phases till the desired size is attained. In the meantime, it is passed through a magnetic separator to remove any undesired metallic elements. Finally, the recycled aggregate is transported to the worksite. The quarrying process is nearly similar, except that a magnetic separator is not required. As well, it takes less energy to extract the aggregate from quarries. For an impartial and consistent evaluation, the recycling process is evaluated from gate to gate. While the natural aggregate quarrying is assessed from cradle to gate. This is because the phases of construction and utilization represent an earlier stage of the lifecycle of the demolition waste, as they also represent a later stage after the processing phase in the natural aggregate production. Hence, including these stages in the study is pointless. Figure 3 depicts the lifecycle phases of each of the processes investigated.

Transportation activities were taken into account. Since there are no working CDW recycling plants in the area under study, some assumptions were considered. The distance from the demolition site to the recycling plant is considered as the distance between the recycling plant and the construction site. The location of the recycling plant is assumed to be next to the active dumpsite in the governorate. These
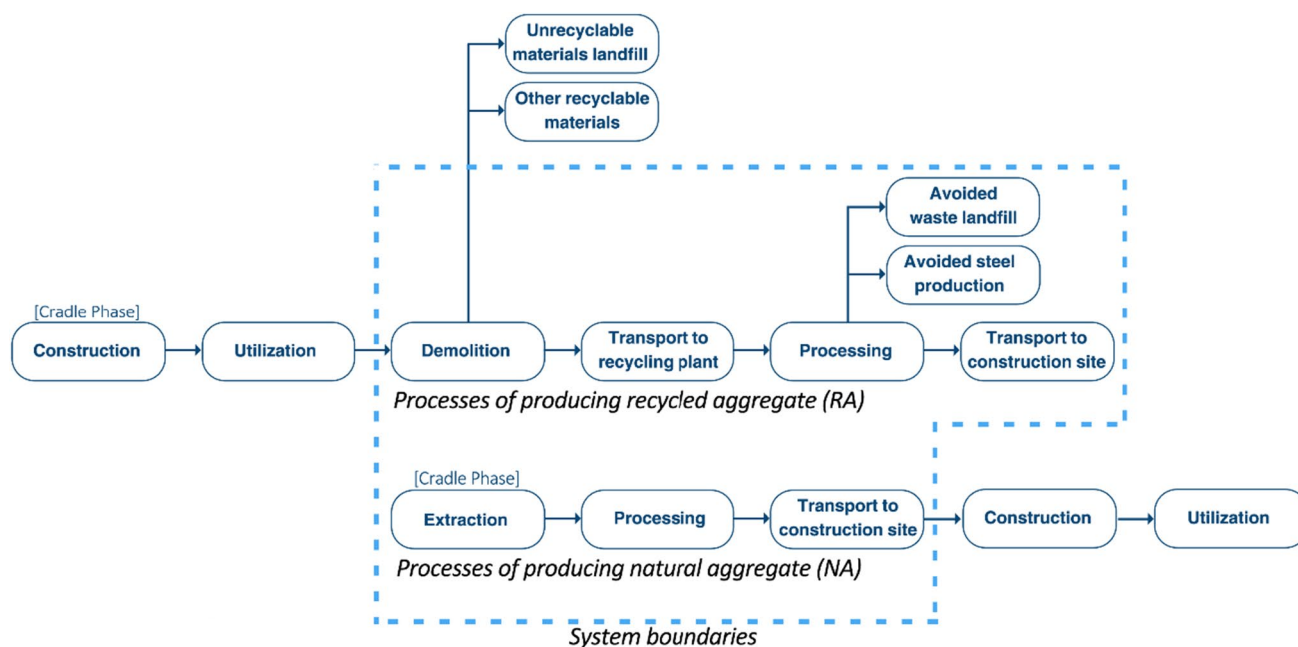
Fig. 3 System boundaries for LCA of producing natural aggregates and recycling CDW

Lifecycle inventory

assumptions are reasonable to avoid additional burdens for disposing of unrecyclable materials. However, these distances were considered preliminary to assess the status quo without making new landfills. A sensitivity analysis is performed for the transportation distances to avoid any biases in the results. The replacement ratio of the natural aggregates with the recycled ones is assumed to be 1:1 as the considered use for the recycled aggregates is for road construction. The recycled aggregate is transported directly to the worksite after being recycled. Manual sorting of CDW occurs at the demolition site before transporting it to the recycling plant. The processing of other recyclable materials is out of the scope. A summary of the system boundaries of this study is illustrated in Fig. 3.

Lifecycle inventory

Ecoinvent 3.5 database is utilized in this study to represent the processes. This database was created by Swiss non-profit organizations. It contains around 18,000 processes gathered from various regions. The cutoff model was chosen for this investigation among many allocation systems. This option is justifiable since it is consistent with the study's aim of comparing the two quarrying and recycling processes individually without bearing the burdens of earlier processes (Ecoinvent 2021). To adapt processes included in the Ecoinvent database, data on quarrying,

Table 1 Summary of inventory data for both scenarios

Flow	Unit	Amount	Reference
Recycling process			
Demolition RC waste	ton	1.0024	
Diesel (demolition)	MJ/ton	61.2	Ecoinvent v3.5
Electricity	kWh/t	3.8	Primary source
Lubricating oil	kg/t	0.00083	Ecoinvent v3.5
Land occupation	m^2	1500	Primary source
Transportation	Km	67.7	Primary source
Avoided burdens			
Steel production	ton	0.0024	Primary source
Landfill	ton	1	
Quarrying process			
Limestone	ton	1	
Diesel (extraction)	MJ/t	40	Primary source
Electricity	kWh/t	2.43	Primary source
Lubricating oil	kg/t	0.00083	Ecoinvent v3.5
Land occupation	m^2	1050	Primary source
Transportation	Km	44.5	Primary source

recycling, and dumping were acquired from primary sources such as specialist experts and governmental bodies. These experts are the direct officials and supervisors of the operations that take place on the ground. Also, they work in quarrying, dumping, and recycling research. The

average transportation distance for the quarrying process is calculated based on the nearest quarry to each district as obtained from the primary sources. Similarly, the average transportation distance for the recycling process is calculated based on the closest distance between each district and the landfill. In order to make the comparison consistent it is assumed that the capacity of both the quarrying and recycling plant are equal. Since the actual quarrying plants in the area under study are in a small capacity, both quarrying and recycling plants were assumed to be small-scale with a 50 TPH capacity (Giza-Governorate 2007). Technical specifications of the recycling and quarrying plants were extracted from well-known suppliers who specialize in manufacturing quarrying and recycling plants and have several projects worldwide. Table 1 summarizes the flow of both the recycling and quarrying processes. Detailed inventory data for each process are attached in online Appendix A.

Lifecycle impact assessment

The IMPACT 2002 + method is used in this study to evaluate both alternatives. This is owing to the large number of midpoint indicators it contains, which provide a holistic view of environmental performance. Also, many studies have used this method for its compatibility with the Egyptian context (Ali et al. 2016; Elkhayat et al. 2020). Indicators in this method are classified into four endpoint damage categories (Jolliet et al. 2003): ecosystem quality (EQ), resources (R), climate change (CC), and human health (HH). Land occupation (LO), aquatic acidification (AA), aquatic ecotoxicity (AEC), aquatic eutrophication (AET), terrestrial acidification/nutrification (TA), and terrestrial ecotoxicity (TE) are indicators used to measure ecosystem quality. Mineral extraction (ME) and non-renewable energy (NRE) are indicators used to measure

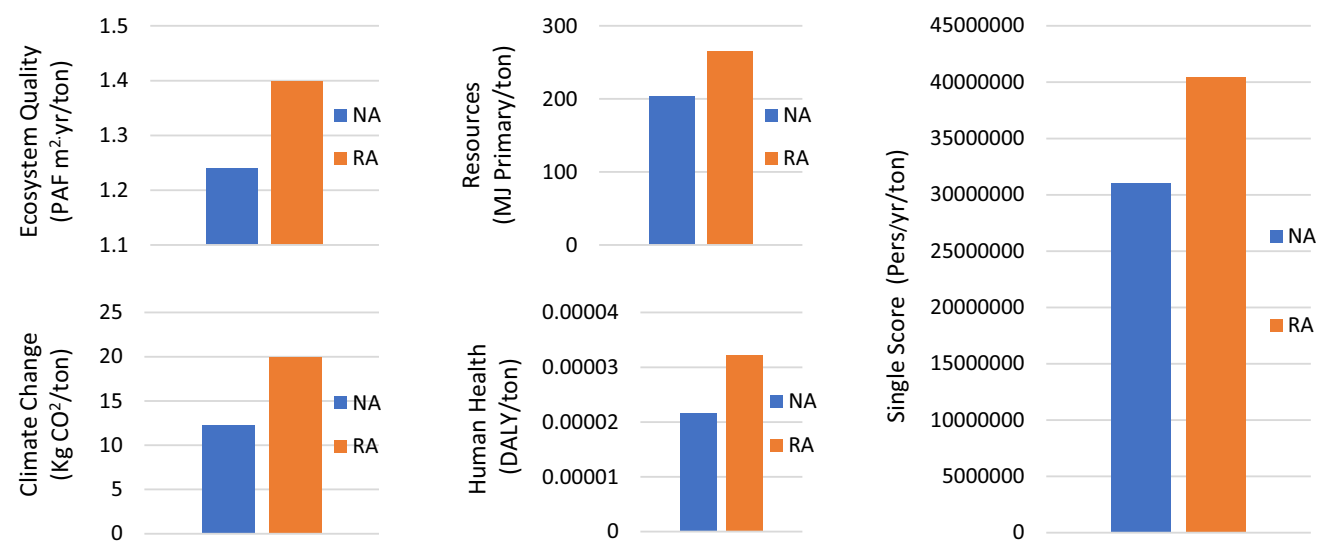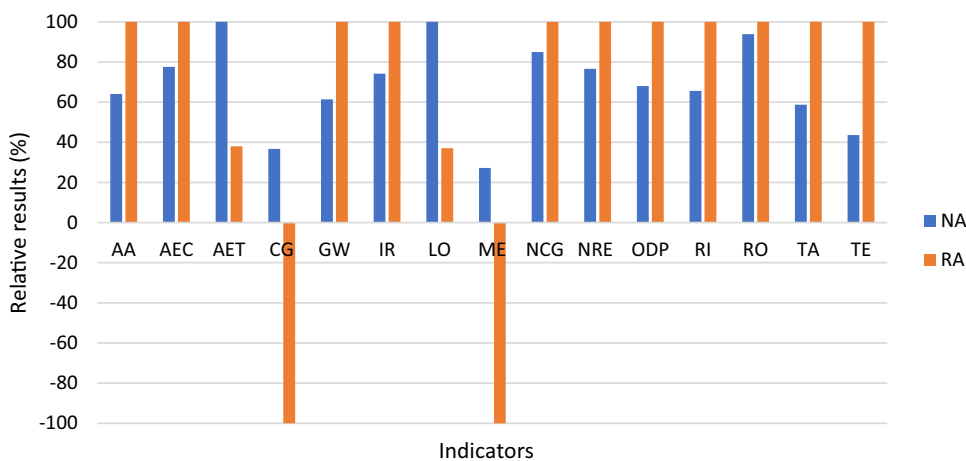Fig. 4 LCA midpoint relative results of NA and RA alternatives

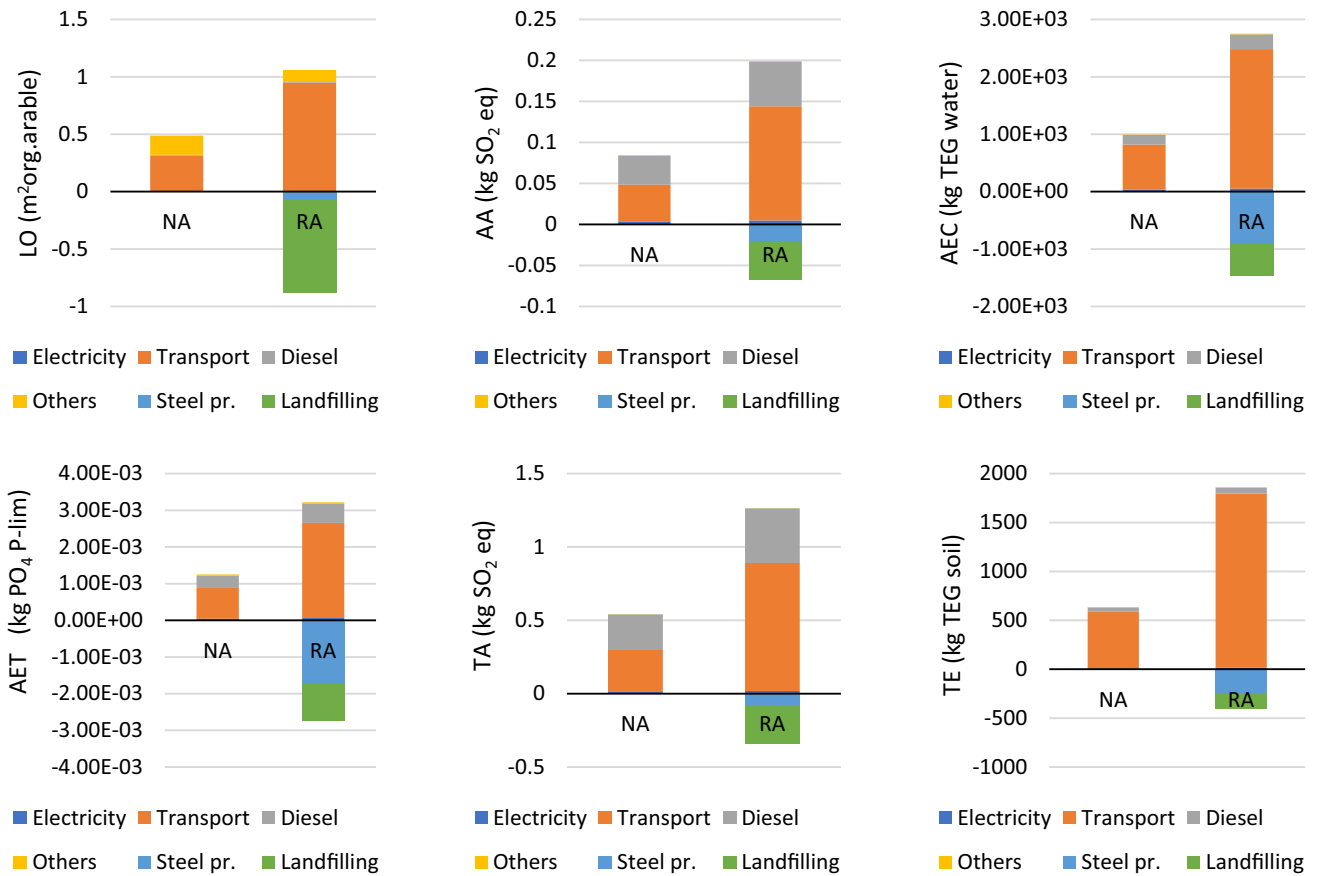Fig. 5 LCA endpoint and single score results of NA and RA alternatives

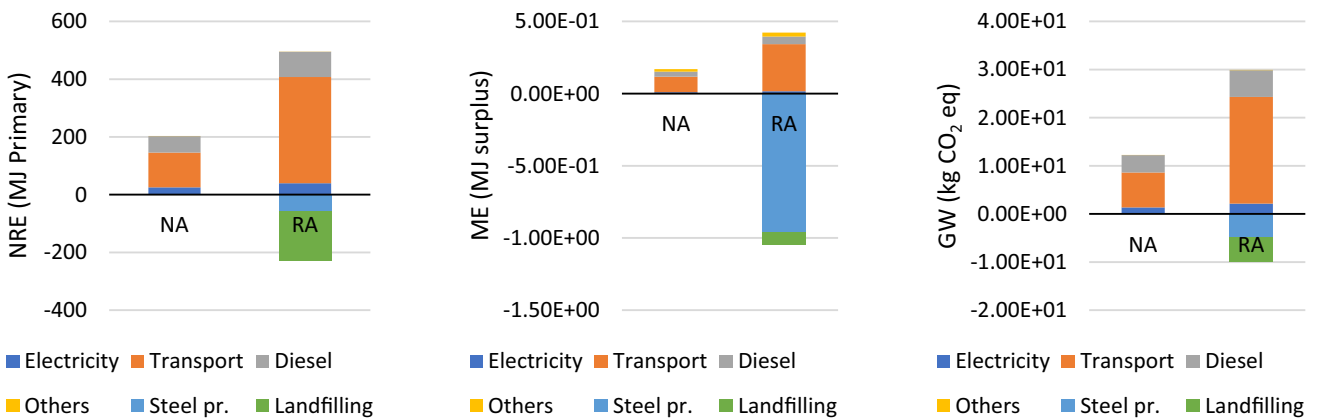**Fig. 6** Contribution analysis of EQ midpoint indicators

Fig. 7 Contribution analysis of R and CC midpoint indicators

resource consumption. Climate change is measured using global warming potential (GW). In addition, carcinogens (CG), non-carcinogens (NCG), respiratory organics (RO), respiratory inorganics (RI), ozone layer depletion (ODP), and ionizing radiation (IR) are used to assess the impact on human health. This study provides an assessment of the competing alternatives using midpoint indicators, endpoint damage categories, and a single score. Characterization factors used by the developers of this method are adopted to normalize the midpoint indicators and the impact categories into a single score that is expressed in the number of persons affected per year (Pers/yr.) (Jolliet
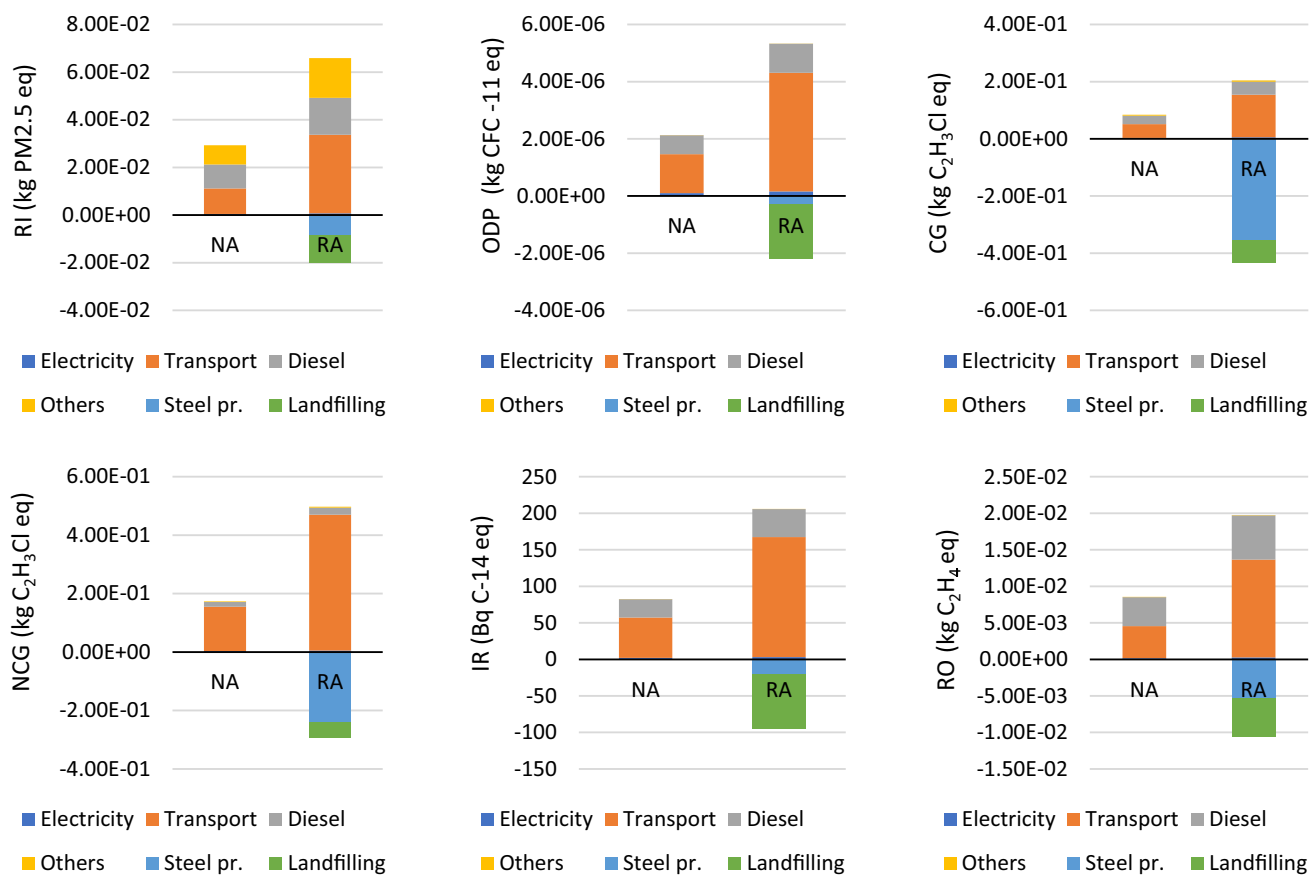
Fig. 8 Contribution analysis of HH midpoint indicators

Results and discussion

Relative results of midpoint indicators are illustrated in Fig. 4, whereas results of the endpoint categories and the single score are shown in Fig. 5. Midpoint indicators show the preference for the quarrying alternative over the recycling one concerning AA, AEC, GW, IR, NCG, NRE, ODP, RI, RO, TA, and TE. Whereas, the recycling alternative takes advantage of AET and LO in addition to achieving an overwhelming superiority over CG and ME compared to the quarrying process. Furthermore, the overall single score reveals that the recycling process has a negative environmental impact of 23% more than the quarrying does. Due to differences in scope, geographies, technologies,

et al. 2003). The upcoming section discusses and interprets the results of each of the aforementioned indicators. It is worth noting that the harmful impacts are referred to as negative, whilst the avoided impacts are referred to as positive.

and assumptions, it is difficult to compare the results of this study with other LCA studies. Nevertheless, some similarities can be observed. The positive impacts of CG and ME associated with the recycling alternative are aligned with the study of Simion et al. (2013). Also, the preference for the quarrying results in most of the indicators is consistent with Estanqueiro et al. (2016). Justifications for these results can be further clarified in the contribution analysis shown in Figs. 6, 7, and 8. In some unclear results, impact analysis is reviewed to find out the detailed justifications. The first impression of the overall contribution analysis results indicates that transportation distance is the most influential parameter in the majority of the impact categories. Furthermore, other parameters like electrical consumption, diesel consumption, and avoided impacts play an essential role in the final results achieved. The following subsections delve in-depth into the contribution analysis for each impact category.

Ecosystem quality impact

The land occupation impact is one of the considered indicators for assessing ecosystem quality. It refers to the damage caused to a land area that is occupied and prevented from returning to its natural state (Goedkoop and Spriensma 2000). The relative results in Fig. 4 demonstrate that the quarrying process causes more land occupation (LO) damage than the recycling process. When looking at the contribution analysis for this impact category, as shown in Fig. 6, this result may be justified. The longer transportation distance required to execute the recycling alternative results in higher LO damage, which is measured to be 0.94 m²org. arable. The LO damage from quarrying aggregates is predicted to be 0.31 m²org.arable. When reviewing the impact analysis for the quarrying alternative, it could be seen that road construction is responsible for 59.9% of LO damage. Then, quarry infrastructure construction accounts for 20.9% of the LO damage. On the other hand, road construction is determined to contribute 84% of the negative LO impact of the recycling option. The construction and operation activities of the recycling plant come in second, accounting for 9.2% of the negative LO impact. Nonetheless, the advantage of recycling versus quarrying is supported by the beneficial impact of the avoided landfilling area.

Furthermore, the acidification impacts mentioned in the relative results refer to the increase in acidity in both aquatic (AA) and terrestrial (TA) environments. They are caused by sulfur oxides, nitrogen oxides, and other emissions from activities such as fuel combustion, power generation, and transportation (Rice and Herman 2012). Machinery used in transportation, excavation, and handling plays a fundamental role in influencing the values of these impacts. Thus, it seems to reason that a scenario with a higher transportation distance would have a greater influence on the aforementioned impact categories. This is evident in the results given in Fig. 6, where transportation activities account for almost 70% of the negative effect of the AA impact category. Other diesel consumption processes account for about 27.4% of the influence of the AA impact category on the recycling scenario. These contribution results are nearly identical for the TA impact category.

Similarly, toxicity in the ecosystem is described in aquatic (AEC) and terrestrial (TE) environments. Emissions to air, water, and soil are measured, characterized, and expressed in equivalent kilograms of triethylene glycol (TEG) into water and soil, respectively (Humbert et al. 2012). Transportation activity contributes 88% to the negative AEC impact, while it contributes 96% to the negative impact of TE for the recycling alternative. Whereas, avoiding steel production and waste landfilling for the recycling alternative has a noteworthy contribution to the positive impact of AEC estimated at 63% and 37%, respectively.

Another impact category that indicates ecosystem quality is aquatic eutrophication (AET). It is the excessive biological growth of living organisms caused by nitrogen and phosphorus substances emitted mostly from waste and fuel combustion (Ngatia et al. 2019). The contribution analysis shown in Fig. 6 shows that transportation and diesel consumption are the most influencing processes for both scenarios. However, the avoided consequences from waste landfilling and steel production offset the negative effects of AET on the recycling scenario, providing it an advantage over the quarrying option.

As shown in Fig. 5, the overall damage to ecosystem quality caused by the recycling process is 12% worse than the effect of the quarrying process. For the recycling alternative, both the terrestrial acidification and land occupation impacts are considered to be the most contributory factors to this damage category with proportions of up to 68% and 14%, respectively. Whereas they contribute 45% and 43%, respectively, to the quarrying alternative. This finding confirms the impact of transportation and machinery operations. It also implies that the impact of land occupation should not be overlooked. In this context, further considerations should be paid to mobile stations that do not require land occupancy.

Resources impact

Non-renewable energy consumption is considered one of the most crucial characteristics in assessing industrial alternatives. Two types of energy were considered for the case study: electricity for operating quarrying and recycling plants and diesel for demolition, excavation, and transportation activities. According to the relative results, the recycling process consumes the most non-renewable energy, exceeding the quarrying process by 23.4%. This can be attributed to the significant energy consumption associated with transportation, which accounts for 367.8 and 120.5 MJ primary for recycling and quarrying, respectively (see Fig. 7). The energy consumed by demolition and excavation activities came in second, accounting for 87.3 and 56.9 MJ primary, respectively. The electrical power energy consumed to operate equipment is shown to be 39.7 MJ primary for the recycling plant. Whereas, the quarrying plant consumes about 25.39 MJ Primary. This variation can be ascribed to the additional screening operations required by the recycling plant to separate unwanted materials from crushed concrete wastes.

Mineral extraction is another indicator that measures damage to resources. This damage is measured in terms of the increasing energy used to extract resources (Goedkoop and Spriensma 2000). Relative results show a superior

preference for the recycling scenario over the quarrying one. Despite the highest impact caused by the transportation process, the elimination of reliance on raw materials extraction helps to alleviate the burdens on natural resources. The avoided steel production contributes heavily to promote the environmental benefits of the recycling alternative. Where nearly 0.96 MJ surplus/ton for steel production has been saved by recycling as depicted in Fig. 7.

Regarding the endpoint indicator, the overall resource consumption shown in Fig. 5 depicts that the energy consumed in the recycling process is 23% greater than that of the quarrying one. For both the recycling and the quarrying options, non-renewable energy is overwhelmingly dominant in this damage category.

Climate change impact

Global warming potential (GW) is a widely used indicator to evaluate the climate change impact. It refers to the rise in the earth's surface temperature caused by increasing concentrations of greenhouse gases. Emitted greenhouse gases are characterized and expressed in equivalent carbon dioxide (Gohar and Shine 2007). In addition to the expected effect of the transportation distance in both alternatives, the contribution analysis of GW shows that the emissions released from the diesel used to power the excavator and the loader in the natural aggregate extraction process were about 3.632 kg CO_2-eq, which contributes to 29.61% of the GW impact of the quarrying process (see Fig. 7). The quarrying plant's electrical consumption follows, producing 1.364 kg CO_2-eq and accounting for 11.12% of the GW impact. On the other hand, machines employed in the demolition of reinforced concrete require greater power. As a result, it emits approximately 5.57 kg CO_2-eq from diesel burning, accounting for 18.6% of the GW negative impact of the recycling alternative. Furthermore, emissions resulting from the electricity used to operate the recycling plant contribute to 2.13 kg CO_2-eq, amounting to 7.14% of the negative GW impact for this choice. The results also show that the recycling process can avoid roughly 10 kg

CO_2-eq that would otherwise be emitted by landfilling and iron production.

Human health impact

The respiratory effect is a midpoint indicator used to assess damage to human health. The damage is classified according to the type of substances emitted into two types: respiratory inorganics (RI) and respiratory organics (RO). Respiratory inorganics are assessed by characterizing various air emissions and expressing them in equivalent kilograms of particulate matter less than 2.5 μm in size ($PM_{2.5}$). Whereas, respiratory organics are expressed in equivalent emitted Ethylene into the air (kg of C_2H_4-eq) (Jolliet et al. 2003).

According to the midpoint relative results shown in Fig. 4, the recycling scenario has a greater respiratory inorganics impact than the quarrying scenario does, as the impact of the quarrying scenario is around 35% lower than that of the recycling scenario. Figure 8 depicts the contribution analysis of these particles on the RI result. A thorough estimation of particulate matter in terms of $PM_{2.5}$ and PM_{10} is discussed due to its detrimental effect on human health. Figure 9 depicts that $PM_{2.5}$ emitted during the recycling process is approximately 0.0238 kg, compared to 0.0168 kg from the quarrying process. This means that the recycling process yields $PM_{2.5}$ 42% more than quarrying. According to the impact analysis, this increase is attributed to demolition operations. It reveals that these particulates contribute by 0.0166 kg $PM_{2.5}$-eq to the negative RI impact of the recycling option while contributing by 0.008 kg $PM_{2.5}$-eq to the negative RI impact of the quarrying option. On the other hand, results shown in Fig. 9 reveal that the releases of PM_{10} during the recycling process were about 32% lower than those during the quarrying process. The impact analysis reveals that the processing phase is the main contributor to PM_{10} in both the recycling and quarrying operations.

With regard to the respiratory organics, the convergence of relative results for both alternatives can be noted with a slight preference for the quarrying option. Diesel burning activities resulting from operating machines used in

Fig. 9 Particulate matter of NA and RA processes

extraction and demolition contribute by 46.3% and 30.7% to the negative RO impacts for quarrying and recycling alternatives, respectively. This is followed by road construction activities and their non-methane volatile organic compounds (NMVOCs) emissions that contribute by 18.7% and 24.7% to the negative RO impact of quarrying and recycling alternatives respectively, as provided by the impact analysis. In opposition, the avoided impacts of steel production and landfill obviously contribute to reducing the overall RO impact of the recycling alternative.

In another aspect, emissions to the air are regarded as the only contributing factor to ozone layer depletion (ODP) impact that represents human health damage. Different emissions are characterized and expressed in the equivalent mass of Chlorofluorocarbons 11 (CFC-11). Fuel combustion is a significant contributor to the anthropogenic emissions that cause ozone layer depletion (Ravishankara et al. 2009). Therefore, fuel consumed by transportation and extraction processes is the most influencing ODP, either for quarrying or recycling alternatives. Since the difference between the fuel consumption required for extracting natural aggregate and that required for demolishing reinforced concrete is not too much, the fuel required for the transportation process controls the preference of the quarrying scenario over recycling. The diesel used in the transportation process shares about 63.8% of the ODP damage in the quarrying scenario, whereas the diesel used in the drilling process contributes around 31.2%. On the other hand, diesel used in the transportation process for the recycling scenario accounts for 77.8% of the ODP effect, while diesel used in the demolition process accounts for 19.1% of the negative ODP impact. Thus, the overall ODP impact of the recycling process is greater than that of the quarrying process by 32% as illustrated in the relative results.

Human toxicity is another midpoint indicator that is used to assess the toxicological effect of chemical substances on human health. It comprises two indicators: carcinogenic (CG) and non-carcinogenic (NCG) impacts. Emitted chemicals were characterized and expressed in equivalent chloroethylene mass (kg of C_2H_3Cl-eq) (Farjana et al. 2019). Even though the recycling process had a higher CG impact than the quarrying process due to diesel combustion activities, the recycling alternative achieved excellence over the quarrying alternative. Thanks to the avoided steel production, about 0.43 kg of C_2H_3Cl-eq emissions were avoided by producing 1 ton of recycled aggregate, representing about 82% of the positive CG impact (see Fig. 7). In terms of NCG, contribution analysis reveals that the impact is tightly influenced by tire wear and brake wear emissions associated with transportation activities. However, it is also reduced by

the avoided steel production and landfilling. As a result, the quarrying option has gained a slight advantage.

Furthermore, ionizing radiation (IR) is another impact that causes damage to human health. Radiations of different substances are measured and expressed in equivalent Carbon 14 becquerels (Bq C-14 eq) (Goedkoop and Spriensma 2000). The results reveal that transportation, excavation, and demolition processes are the most contributing processes to the IR impact. Transportation activity generates 164.3 Bq C-14 eq, accounting for about 80% of the negative IR impact of the recycling option. In the quarrying scenario, it generates 55.4 Bq C-14 eq, which accounts for about 67% of the negative IR impact. Furthermore, diesel used in demolition and excavation operations provides 38.4 Bq C-14 eq and 25 Bq C-14 eq for each of the recycling and quarrying scenarios, accounting for 20% and 30% of the negative IR impact, respectively.

The overall human health (HH) endpoint indicator is concerned with determining the extent of harm caused by toxicological effects, ionizing radiation, respiratory impacts, and ozone layer depletion. These indications are characterized based on their relative importance to get an overall value. This value is described as disability adjusted life years (DALY) (Jolliet et al. 2003). According to the HH impact analysis depicted in Fig. 5, the recycling process has a 33% greater impact than the quarrying process. The majority of this impact is caused by the respiratory inorganics either in the recycling or the quarrying process.

Sensitivity analysis

Sensitivity analysis is performed in this section for two reasons. The first reason is to determine the optimal distance at which a recycling facility becomes environmentally feasible. The second one is to identify the most influential parameters on the results. Thus, three parameters were taken into consideration: transportation distances, diesel consumption, and electricity consumption.

Since transportation distances are varied from one district to another, a sensitivity analysis is performed to determine the preferred distance between the recycling facility and the construction or demolition sites. The average distance to the quarries is considered fixed as it is in practice. It is calculated based on the nearest quarry from each district as provided by the quarrying authority. On the contrary, the transportation distance of the demolition waste to the recycling facility has not yet been determined. Thus, it is under consideration in the sensitivity analysis to determine the appropriate distance. It is constrained to a range of
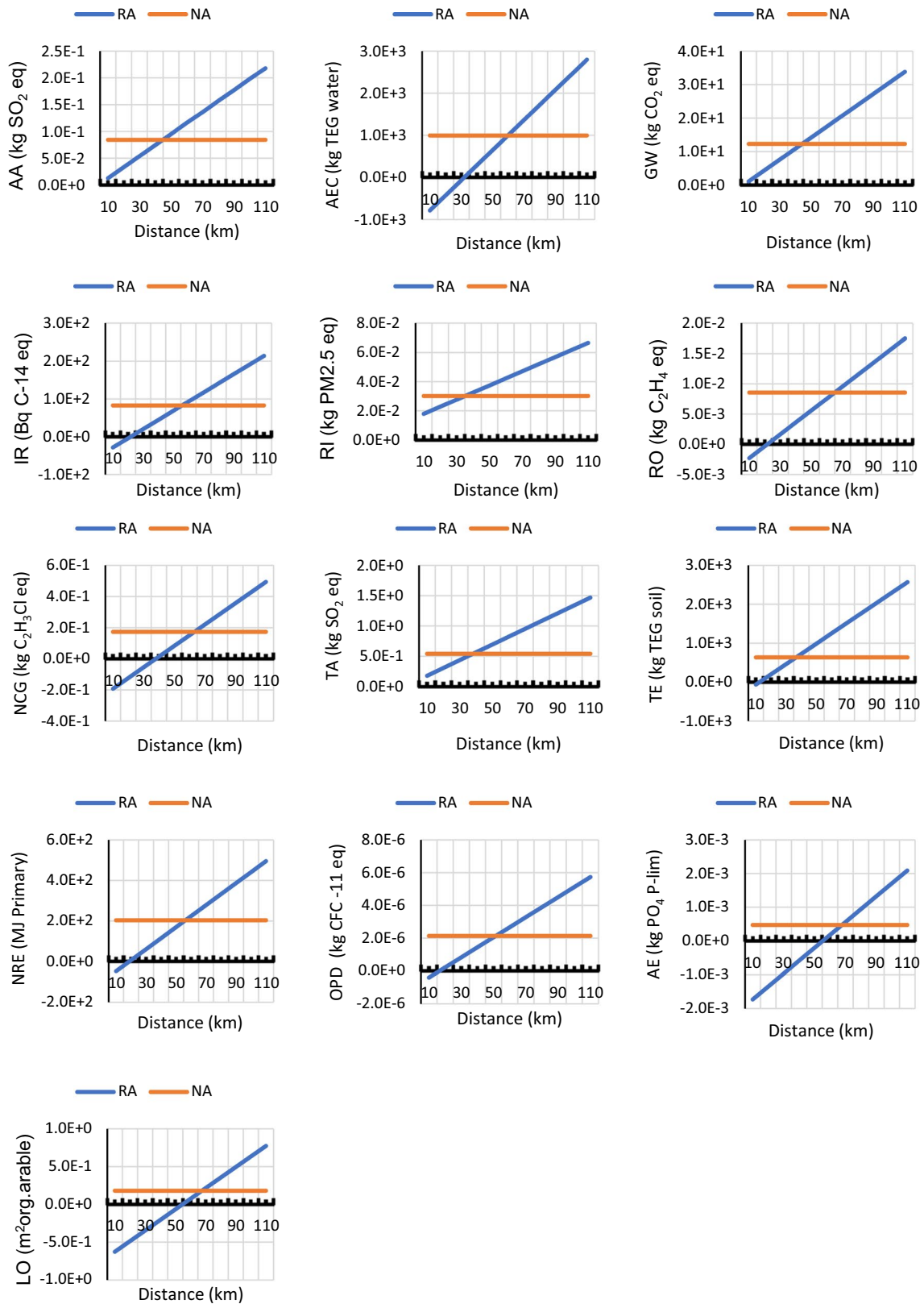
Fig. 10 Sensitivity analysis of transportation distances for the recycling plant

10–110 km depending on the shortest and greatest distance between each district and the proposed recycling facility. The sensitivity of the transportation distance for natural aggregates was also studied to fulfill the comparison. It is considered to be between 10 and 100 km, as is the case on the ground. All impact categories were subjected to the sensitivity analysis except those that achieved an overwhelming superiority for the recycling alternative. OpenLCA is used to recalculate the impact categories for the recycling and quarrying alternatives.

The first scenario in the sensitivity analysis assumes that the average NA transportation distance is constant to analyze the sensitivity of the environmental performance to variations in the RA transportation distance. Results shown in Fig. 10 reveal that the recycling scenario performs better in terms of AA and GW as long as the transportation distance does not exceed 45 km. Furthermore, when the distance is less than 55 km, the recycling scenario performs well in terms of IR and NRE indicators, respectively. Whereas, if the transportation distance is less than 65 km, both the RO, NCG, AE, and LO indicators produce superior outcomes for the recycling scenario. In addition, both the RI and TE indicators achieve better results when the transportation distance is less than 35 km. Finally, if the transportation distance is less than 40, 50, and 60 km, the recycling scenario performs adequately in terms of TA, ODP, and AEC, respectively. On the other hand, the second scenario of the sensitivity analysis assumes that the average transportation distance of the RA is constant to measure the sensitivity of the environmental impact to variations in the distance of NA transportation. Figure 11 shows that the quarrying alternative performs better for AA and GW as long as the transportation distance does not exceed 90 km. Moreover, the quarrying option performs better in terms of RI and TE so long as the transportation distance is less than 105 km. Whereas, the AEC and IR indicators show better results when the distance is less than 60 km. Furthermore, the quarrying option outperforms the recycling one in terms of RO, NCG, NRE, and TA indicators when the transportation distance is less than 50, 55, 65, and 100 km, respectively. Finally, the results of the AE and LO reveal that the recycling option outperforms the quarrying one even with the shortest distances assumed. The aforementioned results indicate that 35 km is considered the accepted transportation distance from the recycling plant to the demolition site or the construction site concerning all impact categories. In other words, a total traveling distance of 70 km from the demolition site to the construction site is acceptable. Whereas, the quarrying option appears as the best option based on the majority of indicators as long as the transportation distance of the natural aggregate from the quarry to the worksite is less than 50 km.

The recycling condition is environmentally viable for 11 out of 12 districts of the governorate. Whereas, it is not viable for the Al-Wahat district due to the large distance that separates it from the rest of the districts. In this regard, several options might be put up to cope with the far-off districts. The recycled waste does not necessarily have to be used in the same area from which it is generated. It can even be moved to the nearest place needed. This could reduce the transportation distance and thus reduce the adverse environmental impacts. Another option is to link this distant district to another governorate, such as Minya, and to establish another recycling facility that serves this area.

In order to achieve the second objective of the sensitivity analysis, the spider plot technique was used to analyze the sensitivity of the input parameters. It is a simple technique for studying the output changes when the model inputs are changed in specific ranges (Borgonovo 2017). The parameters addressed in the sensitivity analysis are diesel consumption, electrical consumption, and transportation distances.

The abovementioned inputs were specifically used to determine the sensitivity of the results, as they are the key parameters that can be controlled. For instance, the lubricating oil has not been subjected to sensitivity analysis since exceeding the amount specified by the manufacturer is pointless and has no impact on productivity. A similar case applies to the land occupation, which is difficult for the operator to manage since it is tied to the manufacturing of the plant. Therefore, these factors were considered in the environmental assessment while they were excluded from the sensitivity analysis. On the contrary, energy efficiency can be controlled and influenced by the operator. Numerous studies have indicated that the skill of the equipment operator and the way the task is performed (e.g., traditional demolition vs. selective one) have a considerable impact on energy consumption (Hassan and Beshara 2019; Pantini and Rigamonti 2020). Subsequently, the possible variation of these factors is considered in the sensitivity analysis.

The variation range of the parameters in the sensitivity analysis is set within 10% less and more than the base value. Several studies used varied energy values while analyzing their environmental impact, including an increased value of 10% or more (Pantini and Rigamonti 2020) and a decreased value of about 10% compared to the current study (Coelho and De Brito 2013a, b). The possibility of this variation is confirmed by Ram et al. (2020) who reviewed many studies and indicated the different values of energy consumption, whether for diesel or electricity. However, it is worth noting that this variation has no effect on the sensitivity analysis since the relationship between these parameters and the environmental impact is linear (Ferronato et al. 2022; Pantini and Rigamonti 2020). Therefore,
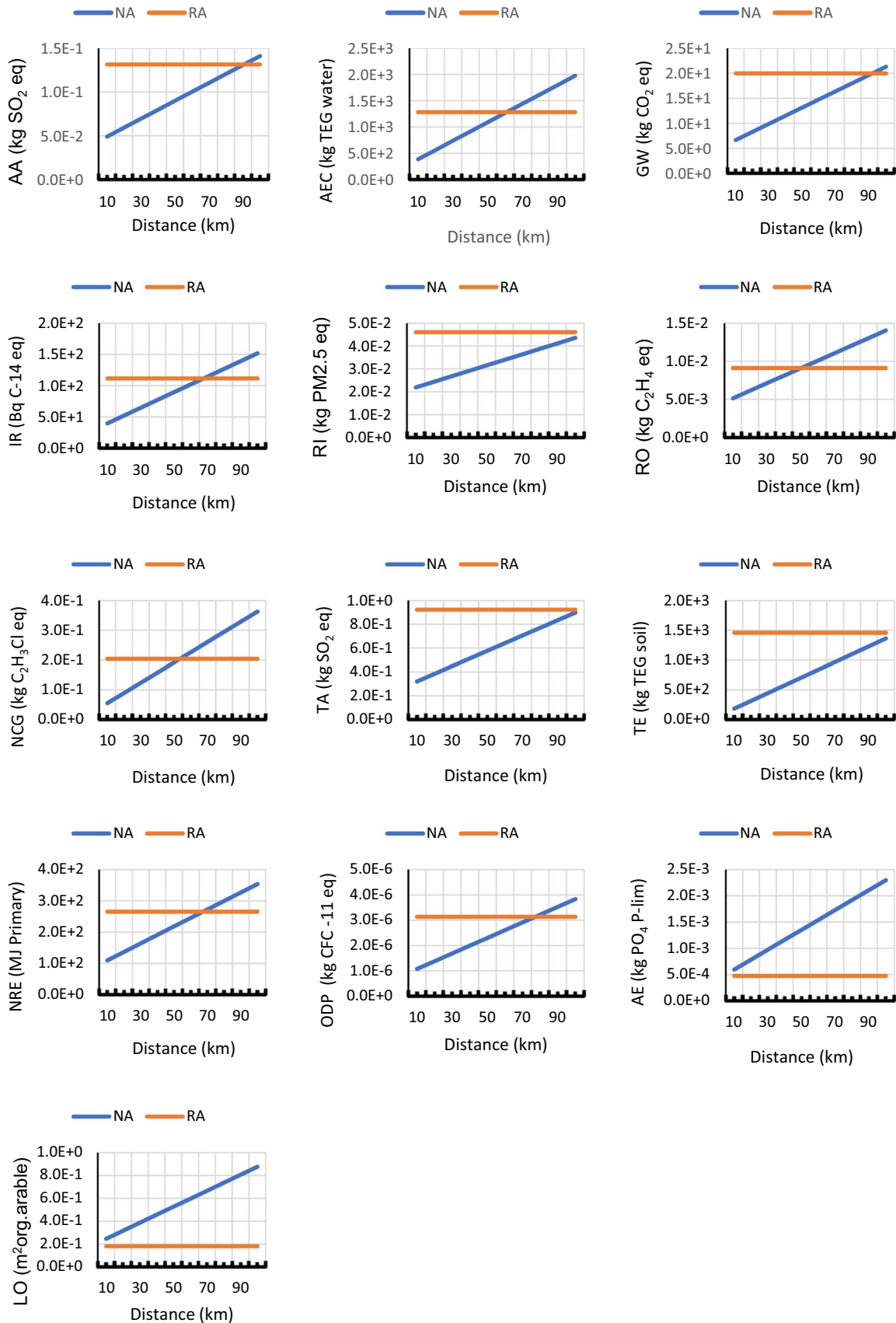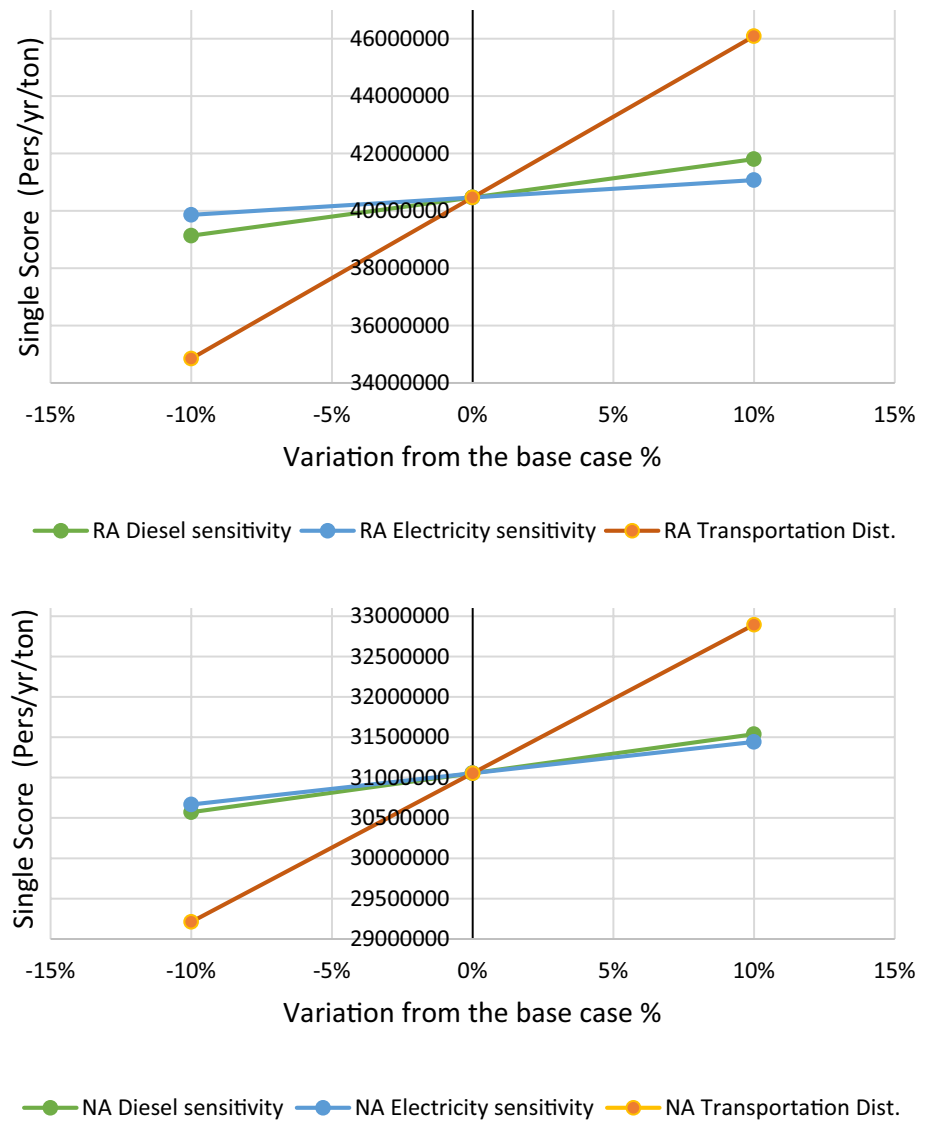
Fig. 11 Sensitivity analysis of transportation distances for the quarrying plant

Fig. 12 Sensitivity analysis of varying parameters on RA and NA

the assumption of the range used for the sensitivity analysis yields the same conclusion (Ram et al. 2020).

Results in Fig. 12 shows that the single score is more sensitive to the changes in the transportation distances in both alternatives. Increasing the transportation distance by 10% leads to an increase in the single score by up to 14% and 6% for both recycling and quarrying alternatives, respectively. While a 10% rise in diesel consumption results in a 3.3% increase in the single score for recycling and a 1.5% increase in the single score for quarrying. This variance can be attributed to the greater energy required for demolition than quarrying. Regarding the electrical consumption, it can be observed that there is a closeness in the results as a 10% increase in electricity consumption

increases the single score by about 1.5% and 1.25% for both recycling and quarrying alternatives, respectively. This is due to the similarities in the machinery used to process both demolished wastes and extracted stones. Generally, results indicate that technical advancements in machinery can have a favorable impact on the environment.

Uncertainty analysis

Monte Carlo simulation has been used to address the uncertainty of the input parameters. This technique allows propagating uncertainty into parameters through a probability distribution. To align with the default values given by

Ecoinvent in their database, uncertainties were expressed in geometric standard deviations. A pedigree matrix is provided by the software to facilitate editing and inserting uncertainty values. It enables the user to calculate the geometric standard deviation of the input parameters using a data quality system that takes into account reliability, completeness, temporal correlation, geographic correlation, and further technological correlation. The results of the simulation after 1000 iterations are included in the supplementary data (online Appendix B). Since the distribution shapes are not the same for the compared indicators, the mean values were compared (Whitley & Ball 2002). The relative results of the mean values were fairly similar to the deterministic values that were calculated in the section of the results.

Conclusion

This paper presented an environmental feasibility study for implementing a CDW recycling process in the Giza governorate to produce recycled aggregate. The case is taken as an example that can be generalized to countries with an abundance of natural aggregates. The recycling process was compared to the process of producing natural aggregates to analyze the influencing factors and the appropriate conditions for establishing a recycling plant. The evaluation was carried out utilizing the life cycle assessment (LCA) approach and indicators from the IMPACT2002 + method. The applied methodology considered avoided impacts that were ignored in most recent studies reviewed in the literature. Avoided burdens of landfilling and steel production have proven their influence on the results. Furthermore, the variability of several input parameters, such as transportation distances, diesel consumption, and electricity consumption, were addressed through a sensitivity analysis. While most of the recent research assesses the transportation distance only.

The single score showed a preference for the quarrying process over the recycling one by about 23%. The midpoint indicators showed the advantage of the recycling process with regard to some indicators such as mineral extraction, land occupation, and carcinogens. However, most other indicators give preference to the quarrying process. Transportation distance was found to have the greatest influence on the practicality of the recycling process. This is corroborated by a sensitivity study that revealed a 10% increase in transportation distance results in a 14% rise in

the recycling process's overall single score. The recycling alternative is viable in most of the districts as long as the total distance for transporting CDW does not exceed 70 km. One of the districts revealed that recycling is impractical due to its remote location from the rest of the districts in the studied area. Nevertheless, the environmental impact of the long transportation distance can be avoided by directing the recycled aggregate to the nearest required location where it is required. The fuel consumption associated with demolitions came in second in terms of sensitivity; a 10% increase in fuel use results in a 3.3% rise in the single score for recycling.

The findings of this study contributed to demonstrating that recycling is not always feasible in countries with abundant natural alternatives until certain conditions are met. The findings help specialists in environmental affairs who are seeking ways to manage solid waste, notably construction and demolition debris, to analyze and identify the environmental feasibility and the acceptable circumstances for recycling construction and demolition waste. The approach used in this study is a real-world application for evaluating alternatives throughout their lifecycle, providing an opportunity for environmental product declaration (EPD) service providers seeking ways to analyze project environmental impacts to recognize and apply this approach to their projects.

Despite these contributions, there are a few limitations and challenges to consider. The study is based on a small-scale capacity of 50 TPH recycling plants as it is the most prevalent capacity of natural aggregate production facilities in the area under study. The larger capacity of the recycling plants should be evaluated in future studies. However, official statistics on the amount of construction and demolition waste are very few. Therefore, a careful investigation of the amount of construction and demolition wastes in the area under study is required before evaluating the large-scale capacities of recycling plants. Also, information about quarries available in some places may be confidential, which may hinder the conduct of this study in some other governorates. The development of a comprehensive geographic information system can mitigate the consequences of a lack of information about accessible quarries and waste quantities in future research.

Data availability All data generated or analyzed during this study are included in this published article (and its Supplementary Information files).

Declarations

Conflict of interest The authors declare no competing interests. The authors have no relevant financial or non-financial interests to disclose.

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