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Research paper

Impact of Financial Modelling of Concrete Waste Using Life Cycle Assessment and Damage Cost

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Abstract

Over the last two decades, Dubai has seen remarkable infrastructural growth, resulting in a corresponding increase in concrete debris being dumped in landfills around the United Arab Emirates (UAE). There is a serious environmental problem since the number of building and demolition sites has increased faster than the availability of efficient waste management options. Putting this concrete debris in landfills is dangerous for people, animals, and the environment. To solve this problem, researchers performed a thorough Life Cycle Assessment (LCA) to effectively evaluate the environmental effects of landfilling against those of recycling concrete debris. The purpose of the analysis was to determine the financial impacts of different waste management strategies. By ISO 14040:2006, a systematic LCA procedure was used to conduct the research. We utilized the EcoInvent 3.4 database and the SimaPro 8.5.2.0 program to streamline the LCA steps and provide clearer outcomes. Damage prices linked with different environmental consequences were also calculated using the Handbook of Environmental Prices 2017. Damage cost and Life Cycle Impact Assessment (LCIA) comparisons show that recycling is much more cost-effective than landfilling. The former has been demonstrated to have much greater impacts on the environment than the latter, which involves recycling and transporting concrete debris. The importance of this research lies in its provision of LCA conclusions related to concrete waste management solutions, including landfilling, recycling, transportation, and the advancement of modeling methodologies for calculating damage costs. It draws attention to the critical need for more environmentally friendly methods of waste management and provides helpful insights into those methods' effects on the natural world. This study suggests identifying crucial impact indicators and management methods with significant environmental impacts. In addition, a Life Cycle Cost Analysis (LCCA) might be performed to support the results by calculating the savings from using various concrete waste management techniques. In conclusion, Dubai has a significant difficulty with its growing concrete waste problem due to the city's rapid infrastructure development. Life cycle assessments (LCAs) that compare landfilling versus recycling emphasize the necessity of sustainable waste management. This research not only improves our knowledge of damage cost modeling but also provides a thorough analysis of potential solutions for dealing with concrete waste, which can help guide policymakers toward more effective responses.

Keywords: *Financial; Concrete Waste; Life Cycle; Damage Cost; Infrastructural Growth; Dubai.*

1. Introduction

Eight separate parts cover various aspects of concrete debris. The first part provides some theoretical context, outlining the issue statement and research gap caused by the dearth of LCA studies in recent years (Khudhair, H. Y., Jusoh, A., Mardani, A., Nor, K. M., & Streimikiene, D., 2019). The utilization of construction debris and concrete, as well as their environmental effects and evaluation methodologies, are discussed in parts 2 and 3, respectively. LCA procedures for modeling concrete waste's ecological implications are covered in part 4. The study strategy and technique are presented in Part 5. Results from the LCIA were calculated using ReCipe2016 and explained in Part 6. Knowledge contribution, implications, limits, and suggestions are presented in part eight, after a discussion of the study results presented in part VII. Won and Cheng (2017) highlight the necessity of proper waste management within the construction industry by noting the extensive research done so far to discover effective waste management solutions for handling construction and demolition debris. Reducing waste is the first step in waste management, as part of the 3Rs approach that also includes reusing and recycling (Yas, H., Mardani, A., & Alfarttoosi, A., 2020). While it is preferable to reuse or recycle materials, it is understood that landfilling is still a viable alternative if these strategies prove unsuccessful (Shwedeh, F., Hami, N., & Baker, S. Z. A., 2020). Waste disposal requires careful preparation, including an accurate estimate of time and the assignment of trucks to transfer trash to landfills. Ghosh (2016) stresses the importance of recycling garbage because of the monetary advantages it provides and the role it plays in realizing the project's ultimate sustainability objective (Khudhair, H. Y., Jusoh, A., Mardani, A., & Nor, K. M., 2019). On the other hand, building waste has a significant effect on the environment because of how it is transported and broken down (Khadragy, S., Elshaeer, M., Mouzaek, T., Shammass, D., Shwedeh, F., Aburayya, A., and Aljasmi, S., 2022). The rising price of building supplies makes this an increasingly pressing issue. Ghosh (2016) offers a strategy to reduce these costs by reusing resources such as steel and bricks, which not only saves money but also brings in extra cash for construction companies. To further support his argument against wasteful landfilling, highlights the possibility for cash creation via recycling for commodities including steel, concrete, and masonry block (Khudhair, H. Y., & Mardani, A., 2021).

Kulatunga (2006) argues that using best practices in waste management would lead to more durable and high-quality projects. Poon (2003) agrees, elaborating on the adverse effects of trash dump expansion. Bossink & Brouwers (1996), cited by Yuan (2013), demonstrate the profound efficacy of the 3Rs principle by elucidating how its adoption reduces material procurement costs, transportation expenses, and disposal outlays, and fosters revenue generation through waste sale. In addition, Lu and Yuan (2010) show that the budget, schedule, and environmental integrity of a country are all negatively affected when there is a lack of commitment to sustainable construction waste management. Kulatunga (2006) elaborates on the wider advantages of establishing explicit waste management standards in construction, including the introduction of sustainability, improved economics, and higher quality. Lingard (2000) agrees, arguing that less trash is generated when proper waste management is practiced, which in turn reduces the need for landfills. Lu (2016) estimates that China produced 1.13 billion tons of rubbish in 2014, illustrating the enormous scale of building and demolition waste management in that country. Ulubeyli, Kazaz, and Arslan (2017) agree that recycling should be given top priority in the management of C&D waste since it is the eco-friendliest option. Europe has set an aggressive goal of achieving a 70% reuse, recycle, and recovery rate for non-hazardous building and demolition waste by the year 2020 (Tojo & Fischer, 2011), demonstrating the world's growing focus on waste management strategies. Some nations have already accomplished this goal; for example, the Netherlands, Denmark, Estonia, and Germany have all achieved recycling rates of above 90% (Bohne, Bratteb & Bergsdal, 2008). Recycling rates in the United States are also an excellent example of the practice's feasibility; they sit at 73.5 percent for construction and demolition debris, 35.0 percent for mixed garbage, 85.0 percent for bulk aggregate, and 99.99 percent for asphalt pavement, respectively. Furthermore, depending on the waste stream's characteristics, the recycling potential for building and demolition debris might vary from 50% to 95%, as proposed by Ortiz, Pasqualino, and Castells (2010).

According to Sales and de Souza (2009), the value of waste management strategies varies depending on the context of their use. The building of roads and highways in Brazil often makes use of recycled material (Sales & de Souza, 2009). Public construction projects in Hong Kong also make use of recycled aggregates (Lu & Tam, 2013). Recognizing the necessity for quality assurance, several nations have established systems of certification to control the use of recycled materials across the building industry (Khadragy, S., Elshaeer, M., Mouzaek, T., Shammass, D., Shwedeh, F., Aburayya, A., and Aljasmi, S., 2022). In Germany, for instance, the quality of recycled materials must be evaluated by certified factories before they can be included in new building projects (Weil, Jeske, & Schebek, 2006). Netherlands, Australia, Germany, the United Kingdom, Spain, Belgium, Italy, Ireland, and Sweden all have above-average densities of recycling plants, with 1000, 150, 120, 100, 92, 50, 30, 10, 8, and 6 facilities, respectively (Symonds Group, 1999). The average recycling rate in the European Union is 47% (Torgal, 2013), which is in line with the goal of 70% set by the Waste Framework Directive for non-hazardous waste by 2020. Ismail and Ramli (2013) explored the possibility of recycling leftover building and demolition debris into fresh aggregates and cement as another route for environmentally friendly waste management. Overall, the variety of waste management strategies highlights the difficulty of striking a balance between building practices' impact on the economy, the environment, and long-term sustainability (SHWEDEH, F. F., 2021). By giving these approaches serious thought, we may reduce waste and make better use of our resources, leading the way to greener, more effective building methods (Yas, H., Jusoh, A., Streimikiene, D., Mardani, A., Nor, K. M., Alatawi, A., & Umarlebbe, J. H., 2021).

1.1. Statement of problem

According to many studies (Fischer & Davidsen, 2010; Flower & Sanjayan, 2007), concrete is used more often than any other material on Earth. It has been estimated that 8% of all CO2 emissions come from the manufacturing of cement, which is used extensively in the making of concrete (Pade & Guimaraes, 2007; Huntzinger & Eatmon, 2009). Vieira and Pereira (2015) point out the importance of reusing and recycling construction and demolition (C&D) materials in easing the burden on landfills and conserving natural resources. Demolitions and leftover building supplies are the primary sources of concrete debris (Elchalakani & Elgaali, 2012). Dubai, along with the other Gulf Cooperation Council (GCC) nations, has a serious garbage problem. In 2010, Dubai created 120 million tonnes of rubbish, making it one of the world's top ten waste producers (Dubai Municipality, 2010). About 75% of the garbage thrown away in landfills is construction and demolition debris (Salameh, M., Taamneh, A., Kitana, A., Aburayya, A., Shwedeh, F., Salloum, S., and Varshney, D., 2022). Dubai also has the most significant per capita trash production in the world, at over 76,000 tonnes per day (Elchalakani & Elgaali, 2012). These numbers demonstrate the critical need for developing efficient methods for handling concrete waste (Saeed, M. D., & Khudhair, H. Y., 2024).

Several factors highlight the need for further study into the ecological implications and repair costs associated with concrete waste. Construction and demolition waste management has been the subject of a great deal of study, but there is a paucity of data connecting it to ecological consequences and repair costs (Won & Cheng, 2017). Mah's (2017) LCA research of concrete waste is typical of the existing literature in this area; it focuses primarily on LCA without accounting for damage costs or doing a thorough impact assessment. In particular, there is a lack of studies examining the concrete waste's ecological implications (Bravo, Brito, & Evangelista, 2017). Both the benefits and drawbacks of concrete in terms of the environment have been recognized (Ravikumar, R., Kitana, A., Taamneh, A., Aburayya, A., Shwedeh, F., Salloum, S., & Shaalan, K., 2022). There is still a lack of knowledge on how concrete waste affects our resources, health, and ecosystems (Richardson, 2013). No previous research has predicted LCA and damage cost outcomes for genuine effects, even though concrete consumption is expected to increase from the current level of around 3 billion tonnes per year to about 3.5 billion tonnes by 2020 (Richardson, 2013). Many studies support the financial advantages of recycling concrete debris, such as Europe's 47% waste recycling rate (Torgal, 2013). However, these metrics are exclusively focused on certain waste items and recycling techniques, and they do not include LCA and damage costs. So far, there has not been a thorough benchmarking that considers the effect that emissions have on health, ecosystems, and resources. Still, some studies have suggested CO2 emissions and energy consumption as significant indicators of waste concrete's ecological impact (Kolay & Akentuna, 2014). To better understand the environmental effects and damage cost of concrete debris, from disposal to recycling to transportation, this research is invaluable (Shwedeh, F., Hami, N., & Bakar, S. Z. A., 2021). It makes a substantial contribution to LCA research in this field by offering in-depth data on ecological and damage costs. Construction projects, consultants, contractors, concrete product producers, and public and commercial organizations engaged in waste management as well as environmental control may all profit from the study's findings. Sustainable waste management choices are made easier with the use of LCA and damage cost evaluations, which this study helps to facilitate (Yas, H., Dafri, W., Sarhan, M. I., Albayati, Y., & Shwedeh, F., 2024).

2. Literature review

This area provides a good introduction to Life Cycle Assessment (LCA). It describes several methodologies for quantifying environmental effects, as well as outlining concrete's function in building, exploring waste in its usage, examining ecological damage from concrete waste, and more.

2.1. Concrete as a construction material

Rapid urbanization and rising standards of living necessitate the widespread use of concrete in civil engineering projects. It may be used for everything from constructing buildings to laying down roads to completing drainage projects (Elchalakani, Basarir, & Karrech, 2016). Elchalakani, Basarir, and Karrech (2016) note that the manufacture of concrete, which is made up of sand, aggregates, cement, and water, is crucial. Concrete happens to be the second most utilized material in the world, and its high production rates have been connected to environmental issues (Fischer & Davidsen, 2010; Flower & Sanjayan, 2007). A significant portion of the world's carbon dioxide emissions come from cement production (Pade & Guimaraes, 2007; Huntzinger & Eatmon, 2009). Because of this, continued infrastructure expansion contributes to global warming (Eisa, 2014; Richardson, 2013). Standard Portland cement manufacture releases greenhouse gases (OPC; Sadati et al., 2016; Saravanakumar & Dhinakaran, 2013; Maholtra & Mehta, 2008). OPC production emits 3 billion tonnes of CO2 yearly (Collins & Sanjayan, 2002; Sadati et al., 2016; Maholtra & Mehta, 2008), 5% of the world's greenhouse gas emissions. This shows the importance of green concrete production (Yas, H., Dafri, W., Sarhan, M. I., Albayati, Y., & Shwedeh, F., 2024).

Concrete makes up 20–80% of construction and demolition (C&D) debris in Europe (Fischer & Davidsen, 2010; Klee, 2009), but the numbers vary by nation. Despite today's technology's ability to recycle concrete, recycled concrete mixes are commonly used for backfilling or road construction (Tam, 2008). Concrete hollow blocks are only one example of the many forms of concrete, each with its own set of strengths, building time savings, and practical applications (Elchalakani & Elgaali, 2012). Cement, binders such as slag and fly ash, aggregates, and water all combine to form concrete, a material with many different properties (Akpinar & Khashmanb, 2017). Millions of tons of aggregates and gallons of freshwater are used annually by the building sector, attesting to rapid growth (Elchalakani & Elgaali, 2012). Most of the garbage is from building demolitions or site overflows of concrete. Sustainable, ecologically friendly, and long-lasting concrete is being developed via research that stresses the use of recycled materials and water (Aburayya, A., Salloum, S., Alderbashi, K., Shwedeh, F., Shaalan, Y., Alfaisal, R., Malaka, S., and Shaalan, K., 2023). This tendency is supported by the findings of the EPA (2009), as well as the publications of Dubai Municipality (2010) and Fisher and Werge (2010). This highlights the necessity of continued research and practical solutions in establishing ecologically friendly practices and indicates the need for measures that reroute concrete debris from landfills.

2.2. Waste concrete in the UAE construction industry

Bridges, buildings, traffic barriers, and drainage systems are all built primarily out of concrete in Dubai and the United Arab Emirates (DCL, 2018). It is the most common building material worldwide (DCL, 2018; Elchalakani & Elgaali, 2012). Dubai is no exception, with 15 concrete block manufacturers and 57 ready-mix plants. For example, Elchalakani and Elgaali (2012) note that the widespread usage of concrete for road barriers, blocks, pavement, and drainage projects is a significant factor in the material's popularity. However, environmental issues arise due to their widespread occurrence. Waste production is relatively high in the GCC, with Dubai being a major contributor (Dubai Municipality, 2010). About 75 percent of all trash is made up of C&D debris that is dumped (Salloum, S., Al Marzouqi, A., Alderbashi, K. Y., Shwedeh, F., Aburayya, A., Al Saidat, M. R., & Al-Maroof, R. S., 2023). According to Salloum, S., Al Marzouqi, A., Alderbashi, K. Y., Shwedeh, F., Aburayya, A., Al Saidat, M. R., & Al-Maroof, R. S. (2023), Dubai generated an astounding 76,000 tonnes of garbage every day in 2010. Compared to the United States and the European Union-28, GCC nations, including Dubai, produce 36-40% more C&D trash, with waste output per capita reaching 2.25 compared to 0.42 and 1.170 in the United States and the European Union-28, respectively (Yas, H., Alnazawi, A. A., Alanazi, M. A., Alharbi, S. S., & Alghamdi, A., 2022). GCC nations, with a population of 120 million in 2010, outnumber the USA's 380 million and the EU-28's 2.742 billion (Fisher & Werge, 2009), which may explain the disparity. This highlights the need to design and implement efficient waste management techniques to deal with the growing environmental impact of building activities in fast-expanding countries (Ibrahim, E., Sharif, H., & Aboelazm, K. S., 2025).

Table 1: Three regions' C&D Waste (Fisher & Werge, 2009)

Region	EU-28	USA	GCC
Population in 2010 (million)	501	310	40
Total Waste (million ton/year)	2742	380	120
C&D Waste (million ton/year)	850	130	90
C&D Waste (ton/capita/year)	1.70	0.42	2.25
C&D Waste / Total Waste (%)	31%	35%	75%

Dumping of construction debris, including concrete goods like hollow concrete blocks, is a significant problem. Although hollow blocks might save money by cutting down on trash, they nonetheless account for an estimated 8-10% of building expenditures that are lost to landfills every year. According to forecasts, the Gulf Cooperation Council (GCC) nations would generate 350 million tonnes of trash by 2014. Over 76,000 tonnes of garbage are produced every day in Dubai, making it the city with the largest per capita garbage output in the world (Dubai Municipality, 2010). Reinforced, regular, and hollow concrete blocks, as well as building site trash, make up the bulk of the garbage that ends up in landfills and has a detrimental effect on the environment (Yas, H., Alkaabi, A., Albaloushi, N. A., Al Adeedi, A., & Streimikiene, D., 2023). Efforts to reuse recycled concrete in building are underway, although collection and segregation on construction sites remain obstacles (Dubai Municipality, 2018) despite recycling programs' best efforts. It costs 10 AED per truck entrance to dump concrete trash in Dubai's Al Bayada landfill (Khudhair, H. Y., Mardani, A., Albayati, Y., Lootah, S. E., & Streimikiene, D., 2020). High waste percentages and the lack of an effective treatment procedure contribute to ineffective waste management in the UAE. These problems emphasize the critical nature of resolving specific waste management difficulties to lessen their effect on the environment (Aboelazm, K.S., 2024).

2.3. Financial impact of concrete waste

The manufacture, upkeep, and destruction phases of concrete's lifetime account for the majority of the material's toxic emissions and add to environmental problems (Kim, 2016). Kim stresses the significant CO2 emissions caused by the aggregate and cement manufacturing process when all stages of production are included (including transportation and energy use). According to Roh (2013), 70% of emissions associated with building components like steel are attributable to concrete, demonstrating its central importance (Aboelazm, K.S., Tawakol, F., Ibrahim, E., & Ramadan, S. A., 2025). Emissions from buildings are broken down into three distinct phases: construction, operation, and maintenance; concrete's lifetime is broken down into three distinct phases: raw material, transportation, and production. While acknowledging concrete's benefits and drawbacks, Bravo, Brito, and Evangelista (2017) emphasize the material's environmental imprint as a key issue that calls for sustainable construction sector solutions. Concrete's emissions problem must be addressed if the construction sector is to survive in the long term (Khudhair, H. Y., & Hamid, A. B. A., 2015).

2.4. Methods of assessing these impacts

The environmental impacts of brick waste were measured using Eco-indicator 95 by Yahya and Boussabaine (2010). Goedkoop et al. (2000), however, highlight difficulties in LCA result weighting. The bottom-up nature of many LCIA methods, which is grounded in inventory results, often results in separate, unweighted indicators. Figure 1 displays the steps necessary to get a 99 score on the eco-indicator. To begin, utilize LCA to determine the various sources of emissions, such as those caused by mining and agriculture. Second, calculate the costs to people, ecosystems, and resources. Eco-indicator ratings may then be generated once the damage categories have been weighted.

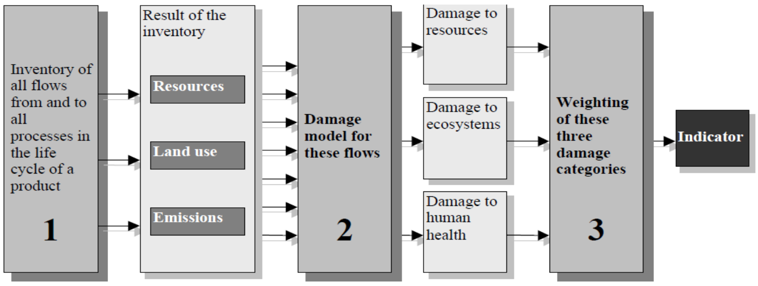

Fig. 1: Phases of Eco-Indicator 99 Scores (Goedkoop et al., 2000, P. 4).

Over ten effect categories, including ecotoxicity and acidification, make up the Eco-indicator methodology's disputed weighting phase (Goedkoop et al., 2000). According to Sharaai, Mahmood, and Sulaiman (2010), LCIA differs from EIA and risk assessment due to its reliance on functional elements. (Sharaai, Mahmood, & Sulaiman, 2010) LCIA incorporates categorization, description, normalization, and weighting (if desired). LCIA incorporates both mid-way (e.g., CML 2001, EDIP 97) and endpoint (e.g., Eco-indicator 95, 99) methods. Goal scope definition, life cycle inventory, life cycle impact assessment, and life cycle assessment and interpretation are the four steps that make up the LCA evaluation (Yas, H., Mardani, A., & Alfarttoosi, A., 2020). Eco-indicator 99 was used to evaluate concrete. An impact route method (Pea et al., 2003) is used to categorize impacts. Figure 2 depicts the weighting mechanism used by Eco-indicator 95 to evaluate items according to their environmental consequences and to identify areas for development. The effects may be detrimental to human health, animal life, and ecosystems (Goedkoop, 2000).

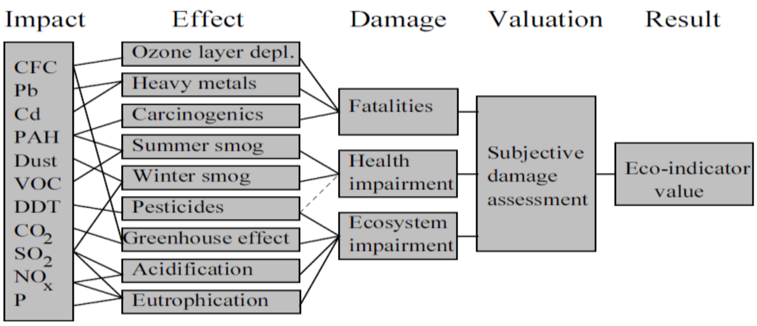

Fig. 2: Eco-Indicator 95 Impact Assessment Method (Goedkoop, 1995, P. 1).

Eco-indicator 99 is divided into three harm categories by Guardigli, Monari, and Bragadin (2011): Human Health, Ecosystem Quality, and Resources. Eco-indicator 99 calculates the carbon footprints of steel and wood. Adding critical impact categories to Eco-indicator 99 has improved its ability to quantify environmental harm, according to Neri (2007). Toxopeus, Lutters, and Houten (2006) questioned the subjective weighting variables used in indicator CML-92, Eco-indicator 95, and Eco-indicator 99. Designers can compare using these indicators (Toxopeus, Lutters, & Houten, 2006). Koroneos and Dompros (2009) note that Eco-indicator 95 aggregates effect categories for cement product and concrete life cycle environmental evaluation. Using SimaPro, LCA, and Eco-indicator 99, Pushkar, Becke, and Katz (2005) optimize building design. Goedkoop et al. (1998) model Eco-indicator 99's cause and effect chain using inventory data, damage categories, and assessment findings (Figure 3).

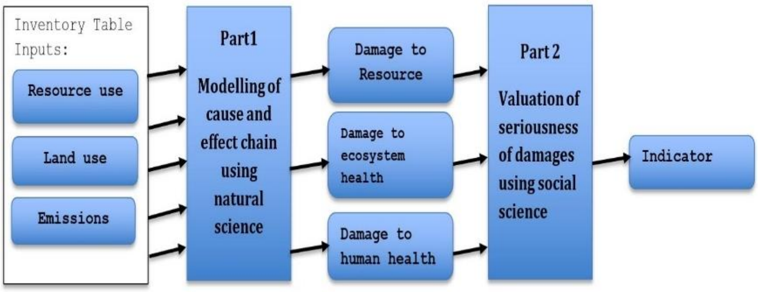

Fig. 3: Inventory and Types of Damage (Goedkoop et al., 1998, P.353).

The environmental implications of goods and materials are often evaluated using Eco-indicator 99 and CML 2 (2000), as noted by Simoes, Xara, and Bernardo (2010). Using Eco-indicator 99, Evangelista and Brito (2006) evaluated the environmental impact of concrete made using recycled aggregates, highlighting its importance in gauging harm to public health and ecosystems. Recycled aggregates, according to their research, are eco-friendly than their native counterparts when used to make concrete (Khudhair, H. Y., Jusoh, A., Nor, K. M., & Mardani, A., 2021). Eco-indicator 95 & CML 2 baseline 2000 are integrated into the SimaPro LCA program and the EcoInvent LCA database for an environmental assessment of the production of brick components, concrete, and plaster (Giama & Papadopoulos, 2015). Emissions and construction materials are measured in kilograms, whereas embodied energy is expressed in megajoules per kilogram (Giama & Papadopoulos, 2015). Since it provides a boundary by ISO14040 and facilitates scenario analysis, direct impact assessment, and weak point analysis, SimaPro is well suited for building assessments (Peuportier et al., 2009), even though it was not designed specifically for building LCAs. Table 2 from Peuportier et al. (2009) provides examples of several approaches to evaluating environmental consequences.

Table 2: Methods of Assessing the Environmental Impacts (ENSLIC -BUILDING- State of the Art Report, p.6)

Method	Characteristics
Impact 2002+	Damage approach; it is similar to Eco-indicator 99, but recalculates toxicity influences
TRACI 2002	Established by the US EPA and is based on the midpoint method
CML 2 baseline 2000	Updated revision of the 1992 method; more developed models and presence of fate analysis
EPS 2000	Damage approach, by conducting monetarisation (willingness to pay) in place of weighting by a panel
Eco-indicator 99	The damage approach uses classification indicators at the endpoint stage. Three types are involved by using different moulds
Ecopoints 97 (UBP)	Distance to objective, which is based on Swiss policy targets, is referred to as the Ecoscarcity method or UBP
EDIP/UMIP 97	Characterisation and normalisation method established for Danish EPA; it also has a 2003 version
Eco-indicator 95	Includes damage approach and distance to objective method based on scientific targets
CML 92	Very commonly conducted for the midpoint method, moderately simple characterisation; it does not include fate or exposure, and has several normalisation sets

Photochemical oxidation, acidification, and eutrophication are all factors in TRACI 2002's midway approach (Aboelazm, K.S., 2023). EPS 2000 considers human health, ecosystem renewal capacity, resource assets, and biodiversity, in addition to economic considerations and environmental damage restoration (Peuportier et al., 2009). Among the most popular are Eco-points 97, EDIP/UMIP 97, Eco-indicator 95, and Eco-indicator 99. Pollutants in the air and water are only two examples of the types of impacts measured by (Eco-Points 97). All these issues and more are accounted for in EDIP/UMIP 97: ozone depletion, warming ecosystems, acidification, toxicity, smog, eutrophication, pollution, radioactive waste, waste, and resources. The revised Eco-indicator 99 is available from three different vantage points: qualitative (E), individualistic (I), and hierarchist (H).

The CML 92 methodology, developed by the Environmental Training Centre (CML) at the University of Leiden in the Netherlands, evaluates impact categories including greenhouse effect, ecotoxicity, ozone layer, power eutrophication, human toxicity, acidification, solid wastes, pollution, and resources. Comparatively, the widely used Eco-indicator 99 is the most prevalent methodology (Goedkoop et al., 2000).

Notably, differences between the Japanese method LIME2 and Eco-Indicator 95 and 99 are observed in terms of inventory, effect categories, and damage effects (Itsubo & Inaba, 2012).

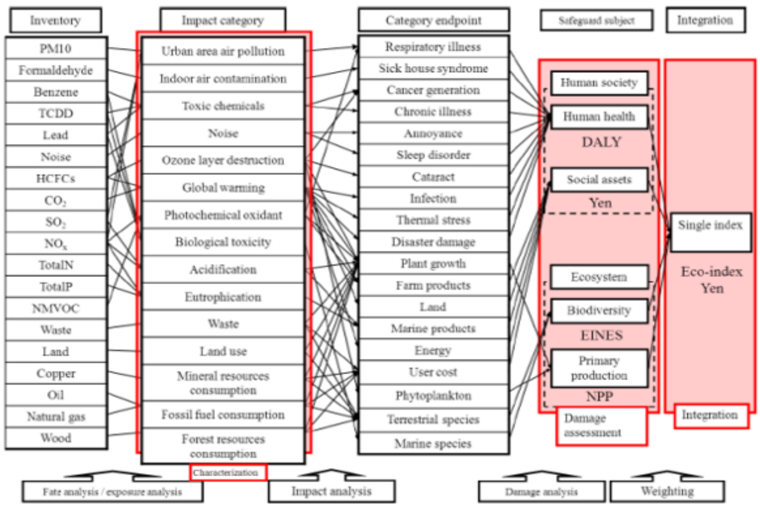

Fig. 4: Assessment Method of the LIME2 Method (Itsubo & Inaba, 2012, P. 2).

Estanqueiro (2011) emphasizes the significance of Life Cycle Assessment (LCA), underscoring that while the construction industry is vital for global economic and social development, it carries substantial environmental burdens through resource consumption and waste generation. A substantial proportion of C&D waste, often disposed of illicitly, poses grave risks to both the environment and human health, necessitating proper waste management. According to Wang and Gangaram (2014), life cycle assessment (LCA) is a systematic strategy for assessing potential environmental consequences over the whole lifecycle of a product, including stages such as raw material extraction, production, use, and disposal. It provides measurable indicators to evaluate progress made in achieving environmental sustainability (Aboelazm, K.S., Ibrahim, E., Sharif, H., & Tawakol, F., 2025). In the realm of European recycling research, Bovea and Powell (2016) underscore the crucial role of LCA-driven analyses in assessing construction materials from an environmental perspective. Similarly, in Japan, Oh et al. (2014) highlight endeavors to employ recycled materials in cement production, aiming to curb emissions of $CO2$. Kolay and Akentuna (2014) suggest using $CO2$ emissions and energy use to assess the environmental impact of waste concrete. Figure 5 shows ISO 14040:2006's formal LCA framework. The framework includes goal and scope formulation, inventory analysis, and effect evaluation. The interpretation of each phase's key results, recommendations, and limitations enhances LCA strategies and decisions for products.

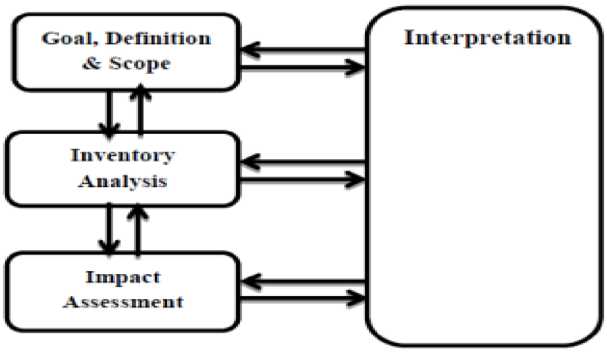

Fig. 5: Framework of LCA by the International Standards Organization (ISO) 14040:2006.

Khasreen (2011) emphasizes that Life Cycle Assessment (LCA) can effectively assess the environmental effects of building materials, particularly considering emissions like $SO2$ and $CO2$, which can have repercussions on the environment. The process of construction, along with operation, demolition, and the depletion of natural resources, can significantly impact the climate. Additionally, Porhinčák and Eštoková (2013) underline the adverse effects of building materials on occupational health and the environment. Bribian, Capilla, and Uson (2011) highlight that approximately 24% of construction activities contribute to the depletion of raw materials. Figure 6, derived from Weiler et al. (2017), depicts the cradle-to-grave concept of the LCA process. This circular approach encompasses the entire life cycle of a product, from creation and usage to disposal. Throughout this cycle, emissions are released, with manufacturing and disposal stages being particularly emission-intensive. Employing the LCA process enables the tracking and monitoring of material or product life cycles, including energy consumption and environmental impact. This aids in developing effective management strategies, optimizing material usage, energy consumption, and minimizing environmental consequences.

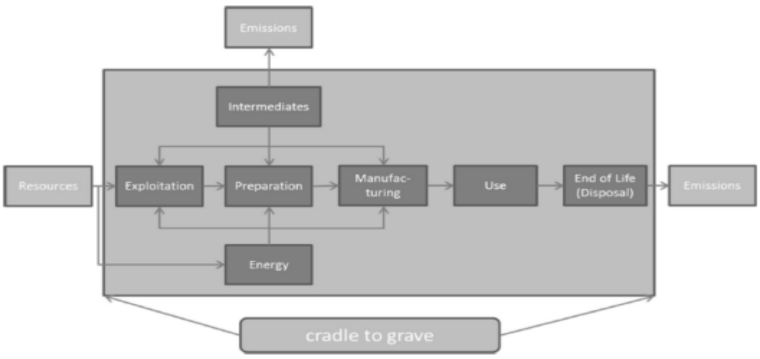

Fig. 6: Cradle to Grave of LCA Process (Weiler et al, 2017, P. 321).

3. Methodology

The study breaks down each step of Life Cycle Assessment (LCA) into its parts, with an emphasis on data gathering and a flowchart of the study's methodology. The evaluation of 18 midpoint effect parts, nine damage pathways, and three endpoint protection zones from the ReCiPe2016 Life Cycle Impact Assessment (LCIA) is outlined, along with the associated calculations and analyses. This part describes how the calculations performed by ReCipe2016 are integrated into SimaPro 8.5.2 to provide the final LCA results. ISO14040 criteria for LCA on concrete waste management were followed in developing the technique used here. The software incorporates the equations and data supplied in this part to calculate concrete waste inventory data and obtain LCA results. In the upcoming sixth part, we will go into the results and talk about how the LCIA data was analyzed.

4. Discussion and analysis

This part delves further into the Life Cycle Impact Assessment (LCIA), the last stage of the Life Cycle Assessment (LCA) as defined by ISO14040:2006. The research uses both interim and final evaluation techniques, including 18 impact categories, nine damage routes, and three protected regions at the interim stage (Aboelazm, K.S., & Afandy, A., 2019). The study evaluates the environmental effects of unreinforced concrete waste by examining several waste management strategies, including disposal, recycling, and transportation. The ReCipe2016 evaluation considers both intermediate and final conditions (Aboelazm, K.S., 2021). The EcoInvent database is used to compile impact inventory information for activities such as waste disposal, recycling, and transportation. The findings of the LCIA evaluation are computed and streamlined with the help of the program SimaPro 8.5.2. Furthermore, the study delves into damage costs and their correlation with LCA outcomes. The assessment monetizes environmental indicators using damage costs, relying on the Handbook of Environmental Prices (2017), which encompasses 15 effect prices relevant to ReCiPe2016. The analysis covers the year 2018, while additional results from 2013 to 2017 can be found in the appendices. This part essentially provides a comprehensive overview of the LCIA phase, methodology, data sources, and results, along with insights into the relationship between damage costs and LCA outcomes for unreinforced concrete waste. The study employed damage costs sourced from the Handbook of Environmental Prices 2017, utilizing 15 prices relevant to the LCIA conducted through ReCiPe2016. The impact category prices are presented in Table 6, expressed in euros per corresponding unit, and cross-referenced with the associated page number in the Handbook Environmental Prices 2017.

Table 6: Environmental Prices (Handbook Environmental Prices, 2017

No.	Impact Category	Unit	Price (€)	Page
1	Climate change	ε/k * g CO_2-eq.	0.057	42
2	Ozone layer depletion	€/kg CFC-eq.	30.4	42
3	Acidification	€/kg SO_2-eq.	5.4	42
4	Freshwater eutrophication	ε/k * g P-eq.	1.9	42
5	Marine eutrophication	€/kg N	3.11	42
6	Land use	€/m²a	0.0261	42
7	Terrestrial ecotoxicity	ε/k * g 1,4 DB-eq.	8.89	42
8	Freshwater ecotoxicity	ε/k * g 1,4 DB-eq.	0.0369	42
9	Marine ecotoxicity	ε/k * g 1,4 DB-eq.	0.00756	42
10	Human toxicity	ε/k * g 1,4 DB-eq.	0.214	42
11	PM2.5	ε/k * g $PM_{2.5}$ eq.	79.5	100
12	Nitrogen oxides (NOx) (Human health)	ε/k * g NOx eq.	18.7	107
13	Nitrogen oxides (NOx) (Terrestrial ecosystems)	ε/k * g NOx eq.	18.7	107
14	Mineral resource scarcity (Atmospheric)	$/kg Cu eq	4.2	165
15	Mineral resource scarcity (Soil)	$/kg Cu eq	0.239	173

The method used in this study to calculate the monetary value of environmental impact is to correlate the results of the LCA with those of the damage cost analysis, using data from Table 4 of the Handbook of Environmental Prices 2017. Life cycle inventory (LCIA) is performed using the ReCipe2016 methodology, and then the EcoInvent database is used to do the life cycle analysis. The SimaPro program was used to carry out the LCIA stage (the third stage of LCA), which enabled the results to be simplified and organized efficiently. The damage costs are calculated in conjunction with the LCIA results in order to evaluate their effect on the environment using the damage prices from Table 4. Table 5 shows how the amount of concrete thrown away in Dubai has increased from 2013 to 2018. The study included LCIA and damage cost midpoint assessments for 2018, with data for 2013–2017 included in Appendices 4 and 5, using the same inventory and Table 7.

Table 7: Quantity of Concrete Waste in Dubai Landfill in Each Year Separately (Public Source, 2019)

Year	Normal Concrete Waste from C&DW going into Landfill	Tonnes
2013	"	3,900,000
2014	"	4,150,000
2015	"	4,400,000
2016	"	4,700,000
2018	"	5,000,000
2017	"	5,400,000

Table 7 depicts the outcomes of the midpoint LCIA, encompassing 15 impacts along with their associated damage costs. The figure indicates that both landfilling and transportation methods yielded higher midpoint damage costs in comparison to the recycling method. Higher damage costs are associated with global warming, the production of delicate particulate matter, the generation of ozone (health), and terrestrial ecotoxicity. The average costs associated with marine eutrophication and ecotoxicity were lower than those of the other factors. Appendices 4 and 5 show LCIA and damage prices at their midpoints from 2013 to 2017. Figure 7 from the LCA shows that fine particles are produced at a higher rate from landfill disposal of waste concrete (52.9%) than through transportation (6.22%) or recycling (40.8%). There were 148,450.38 kilograms of PM2.5 equivalents produced by landfill disposal, compared to 17,440.96 kilograms by transportation, and 114,384.59 kilograms by recycling. The recycling and landfilling operations both produce microscopic dust particles. As the prevalence of respiratory disorders increases, endpoint protection is compromised, hurting the growth of tropical ozone (human health).

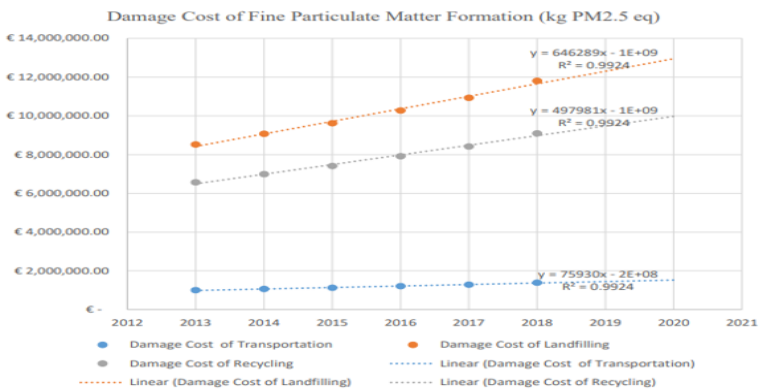

Fig. 7: Damage Cost of Fine Particulate Matter Formation.

5. Recommendation

The study identified several issues requiring further research, including the need to determine the financial benefits associated with various concrete waste treatment solutions through a Life Cycle Cost Assessment (LCCA). The execution of a thorough Life Cycle Assessment (LCA) covering a variety of waste management strategies for concrete, from raw material extraction through processing, final product, and waste treatment. Constructing an LCA cost model that takes various concrete waste treatment techniques into account. Improving the UAE's model for managing concrete waste by integrating multiple recycling scenarios to calculate LCA and damage costs, and extending the range of variables taken into account when calculating the cost of concrete waste damage.

6. Conclusion

The present study employed a monetization approach based on a Life Cycle Assessment (LCA), specifically its Life Cycle Impact Assessment (LCIA), to assess the economic implications associated with three distinct waste management systems. The process of monetizing social and environmental challenges facilitates their comprehension. The concept of natural capital value refers to the evaluation of sustainability return on investment, specifically from a financial standpoint (Pre-sustainability 2018, p. 1). The valuation of ecological impacts in euros per kilogram of pollution was conducted by CE Delft (2018), utilizing the Handbook Environmental Pricing (2017). The study demonstrated the presence of substantial costs associated with environmental harm, as determined using damage costs and life cycle assessment (LCA) calculations. As an example, the expenditure for all three procedures related to Ozone Formation (Human Health) witnessed a significant increase, rising from €200,000 to €900,000 on an annual basis. The phenomenon of global warming has dramatically raised the cost of disposing of concrete trash, which now totals €4,120,242.50, inflicting a substantial financial burden on all disposal options. Costs associated with landfilling were estimated at €11,446,760.69, transportation at €4,711,544.29, and recycling at €4,979,775.78, all based on data from a study on ozone formation in terrestrial ecosystems. For terrestrial ecotoxicity, the costs associated with landfilling were €1,833,140,313.90, whereas those associated with recycling were €1,147,140,619.10 and €77,395,172.74. The impact of terrestrial ecotoxicity on landfilling, transportation, and recycling yielded profits of €1,881,462.17, €753,609.10, and €663,544.93, respectively. Destruction of stratospheric ozone, human carcinogenic toxicity (especially cancer), freshwater eutrophication, freshwater ecotoxicity, land development, marine ecotoxicity, and marine eutrophication all contributed to some negative consequences. However, these were relatively modest in comparison to the positive ones.

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Data availability

The datasets used during the current study are available from the corresponding author on reasonable request.

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