Life Cycle Assessment and Costing of Concrete Waste: A Case Study

Mohamed Saeed[1], Harith Yas[2], Kong Fah Tee[3]

[1]Manager of Pavement and Materials Quality, Roads and Transport Authority, Dubai Municipality, Dubai, United Arab Emirates, mohamed.emirati@gmail.com
[2]Azman Hashim International Business School, Universiti Teknologi Malaysia, Johor 81310, Malaysia.
[3]Department of Civil and Environmental Engineering, King Fahd University of Petroleum and Minerals, Dhahran 31261, Saudi Arabia.

The city of Dubai and the United Arab Emirates (UAE) are grappling with an escalating issue: a colossal volume of concrete waste within their landfills. This predicament stems from the rapid surge in infrastructure expansion over the past twenty years, which has led to a surge in construction and demolition activities. Regrettably, there is currently no effective sustainable strategy to curtail the influx of concrete waste into these landfills. The implications of such landfill accumulation extend beyond just environmental concerns, encompassing human health, resource depletion, and harm to ecosystems. In response, this study embarked on a comprehensive Life Cycle Assessment (LCA) to contrast the existing landfilling and transportation practices for concrete waste with a proposed recycling approach. Conducted within the framework of ISO 14040:2006, the LCA was meticulously structured, with the EcoInvent 3.4 database and SimaPro 8.5.2.0 software employed to streamline its various phases and outcomes. The research did not stop at the environmental realm; it delved into the financial aspect, utilizing the Handbook Environmental Prices 2017 to determine the damage costs associated with each impact. The comparison, rooted in the Life Cycle Impact Assessment (LCIA), demonstrated a stark contrast between the environmental ramifications of landfilling versus recycling and transportation. The findings underscored the profound environmental toll of concrete waste deposition in landfills compared to the recycling method and transport process. By unearthing the disparities in impact indicators and management techniques for concrete waste, this study paves the way for future investigations to pinpoint influential factors. It also suggests the potential for a forthcoming Life Cycle Cost Assessment (LCCA) to supplement this analysis, unraveling the financial benefits of various concrete waste management strategies, and transcending mere damage costs. In essence, this study significantly enriches the comprehension of damage cost modeling and offers LCA insights into concrete waste management, encompassing divergent approaches like landfilling, recycling, and transportation.

Keywords: Life Cycle Assessment, Concrete Waste, Life Cycle Cost, Recycling, Sustainability, Waste Management.

1. INTRODUCTION

Concrete is the second most consumed material globally, following water [1,2]. Cement in concrete production contributes to 8% of global CO_2 emissions [3,4]. Reusing and recycling construction and demolition (C&D) materials, advocated by Vieira fand Pereira [5], offers benefits including landfill reduction and resource preservation. Elchalakani and Elgaali [6] highlight that concrete waste mainly stems from old structure demolition and surplus concrete on construction sites. In the Gulf Cooperation Council (GCC) nations, Dubai produced 120 million tons of waste in 2010, with 75% being C&D waste [6,7]. Dubai generates a staggering 76,000 tons of waste daily, the highest per capita globally [6].

In the context of the 21st century's rapid urbanization and industrialization, meeting the demands of infrastructure and building activities emerges as a pivotal challenge. Concrete plays a vital role as a primary material in various civil engineering construction industries. It is employed extensively in constructing diverse building elements such as foundations, walls, roofs, slabs, columns, and beams. Furthermore, its applications extend to road construction, serving as rigid pavements, and crafting airport runways. The versatility of concrete is demonstrated in drainage projects, production of paving blocks, and solid blocks due to its varying weight characteristics. Constituted by compounds including sand, fine and coarse aggregates, cement, and water, concrete undergoes precise mixing ratios to yield the desired product [8,9]

Global consumption patterns underscore concrete's significance, with it ranking as the second most consumed material worldwide [1]. Cement production, a key component of concrete, contributes significantly to global CO_2 emissions, accounting for about 8% of emissions [3]. This raises concerns about the environmental impact, particularly in light of the increasing demand for concrete driven by booming construction activities [10]. Manufacturing Ordinary Portland Cement (OPC), a major constituent of concrete requires high energy input and releases greenhouse gas emissions [11 -13]. The accumulation of construction and demolition (C&D) waste, containing substantial concrete debris, presents environmental challenges, including landfill space shortage and CO_2 emissions from waste decomposition [1,14]. Recycling technologies offer potential solutions to mitigate these issues [6]. In summary, concrete's pivotal role in construction, coupled with its environmental impacts and growing demand, underscores the need for sustainable practices, including recycling, to manage the ecological consequences of its production and usage.

Effective waste management in the construction industry is crucial, as emphasized by Salameh [15], who highlight the exploration of various waste management options. Waste reduction, the initial step in the 3Rs principle (reduce, reuse, recycle), aims to minimize waste generation, with recycling and landfill disposal as subsequent options when necessary [15]. Proper waste planning and management, as advocated by Ghosh [16], can yield economic benefits and enhance project sustainability. Nevertheless, construction waste poses environmental concerns due to transportation and demolition [16]. Materials such as steel and bricks offer recycling potential, reducing costs and environmental impact [16].

Best practice waste management, suggested by Nokiti [17], ensures project quality and sustainability. Alkashami [18] and Onyema [19] affirm the 3Rs' potential to curtail material costs, transportation expenses, and generate revenue from waste sales. China's construction and demolition waste reached 1.13 billion tons in 2014 [20]. Recycling is a favored eco-friendly treatment, as indicated by Yas [21]. Europe, aiming to recycle 70% of non-hazardous construction waste by 2020, has achieved success in several countries [22, 23].

Waste management's importance varies based on usage nature [24]. Recycled aggregate finds use in pavement construction in Brazil and public projects in Hong Kong [24, 25]. Certification schemes in certain countries ensure recycled material quality [26]. Economically, Europe's average waste recycling rate is 47%, with a 70% target for non-hazardous waste by 2020 [27]. The potential to recycle surplus construction waste into new aggregate and cement is promising [28].

The research gap concerning the ecological impacts and damage cost of concrete waste reveals several significant aspects. Despite extensive research on construction and demolition waste management for suitable strategies [29], there remains a dearth of reliable evidence linking these findings. Existing studies, like [30] LCA study on concrete waste, focus solely on LCA without considering damage costs and comprehensive midpoint and endpoint impacts. Though concrete possesses pros and cons, such as its environmental footprint [31], research on the ecological impacts of concrete waste itself remains insufficient. Uncertainty surrounds the effects of concrete waste on resources, human health, and ecosystems [10], with no prior investigation into forecasting LCA and damage cost results for real impacts. While some studies emphasize the economic aspects of recycling concrete waste [27], these assessments often neglect LCA and damage cost considerations. The ecological impact of waste concrete has been evaluated using limited benchmarks, like CO_2 emissions and energy consumption [32], yet a comprehensive benchmark encompassing all impact dimensions on human health, ecosystems, and resources is absent.

This research aims to assess the environmental impact and associated damage cost of concrete waste in the United Arab Emirates. This goal is achieved through these objectives: determine the eco-impact and footprint using LCA for landfilling, recycling, and transportation, calculate the environmental damage cost for these methods, and establish the mathematical correlation between LCA outcomes and damage cost results.

This study presents a valuable opportunity to advance our understanding of the environmental impact and damage cost assessment for concrete waste via landfilling, recycling, and transportation. Through significant contributions to LCA research, it reveals ecological and cost-related findings associated with landfilling and recycling of concrete waste. The insights benefit construction projects, consultants, contractors, and concrete manufacturers, along with government and private entities focused on waste management and environmental control. By leveraging LCA and damage cost results, this study aids in identifying optimal waste management options for construction sustainability and minimizing environmental impact, and costs.

2. WASTE IN THE CONSTRUCTION INDUSTRY

In the realm of construction, concrete, the most prevalent building material, necessitates substantial aggregate consumption [33]. Urbanization's surge spurs escalating construction waste, comprising steel, concrete, soil, and masonry materials [33]. This chapter delves into waste's environmental implications, commencing with its definition and subsequently addressing construction and demolition waste intricacies. It encompasses pertinent issues, encompassing waste management policies, disposal methods, costs, and environmental impact [33]. This section emphasizes the significance of concrete waste within the construction and outlines waste policies globally. The composition of C&D waste is explored, alongside various waste disposal methods aimed at minimizing concrete waste. Ultimately, the environmental impact of concrete waste is significant due to its contribution to greenhouse gases and harmful substances.

2.1. Definition and Concept of Waste

The categorization of general waste, inert and non-inert, from public landfills and resources is described by [34] and further detailed by[35]. This waste issue has financial and climate implications [35], while Tafesse [36] points to resource depletion due to increased usage. Efficient waste minimization challenges the construction field [37]. Countries employ recycling to curb waste generation and environmental damage [37]. Waste sorting for recycling, emphasized by [38], aids in reducing waste by identifying and segregating types. Construction industry-generated waste, associated with raw material depletion, impacts the environment negatively [39]. Fabrice Berroir [40] introduces a waste hierarchy promoting reduction, reuse, recycling, and landfill disposal in that order. Reduction and reuse prevent landfill accumulation, while recycling is environmentally favorable, curbing greenhouse gas emissions [40]. Recycling minimizes landfill waste, offers energy recovery, and mitigates environmental impact [40].

The UAE's rapid construction growth in the past two decades has led to significant waste accumulation in landfills [41]. To address this, cities like Abu Dhabi, Dubai, and Sharjah have adopted waste management strategies, aiming to convert waste to energy and reduce landfill waste and greenhouse gases [41]. Dubai's integrated master plan for waste management, established in 2012, aims to eliminate landfill waste through a recycling-focused approach [42]. Abu Dhabi's Tadweer Center and Sharjah's Beeah company play vital roles in waste management [41]. Construction waste, primarily concrete waste, holds the largest landfill share and adverse environmental impact, underscoring the necessity for efficient treatment [41]. Essam [42] further categorizes waste types, highlighting varying sources and debris types in domestic waste categories.

Dubai's construction and demolition (C&D) waste, emerges from diverse building and road activities, comprising materials like concrete, glass, wood, gypsum board, asphalt paving, plastics, and soil. Beyond this, various waste categories encompass tire, horticultural, hazardous, medical, and sewage waste, as depicted in the same table[42].

In summary, construction waste presents a global concern, with varied waste types contributing to landfills and escalating environmental impact. Construction and demolition (C&D) waste, being predominant, significantly contributes to landfill volume. Certain countries employ strategies to mitigate waste generation and its environmental repercussions. Following the construction waste hierarchy, emphasis should be on preferred stages like reduction, reuse, and recycling over disposal. The heightened landfilling of waste corresponds to heightened environmental consequences.

2.2. Waste Management Policy

The European Union's Waste Framework Directive (WFD) legislation encompasses a comprehensive hierarchy of waste management steps, including prevention, reuse, recycling, recovery, and landfill. Van Ewijk emphasizes the more established waste hierarchy in Europe compared to the USA. Cultural and economic factors contribute to varying waste amounts across countries, as noted by Kourmpanis. Concrete recycling practices commenced in the 1970s in the USA and Europe, reflecting critical rules and policies in construction waste management. Jia reported China generated 1.5 billion tons of construction waste, with a mere 5% of materials reused. Alkashami [18] and Ponnada and Kameswari emphasize the importance of waste management plans, but implementation challenges persist. Despite these insights, effective waste management plan implementation remains elusive [18]

Abu Dhabi's waste management policy, overseen by the Environment Agency, targets diverting 60-80% of C&D waste by 2020 [40] Laws like No. 16 of 2005 and No. 21 of 2005 grant the Environment Agency authority in waste management. Two recycling plants in Abu Dhabi treat C&D waste. Dubai Municipality's circulars and guidelines, including fines for accumulated construction waste, aim to manage waste. However, there is no set landfill waste limit or concrete waste reuse/recycling regulation]. UAE government sectors provide landfills for waste disposal.

2.3. Construction and Demolition (C&D) Waste

There is a significant amount of global construction and demolition (C&D) waste, with much of it ending up in landfills. Reusing and recycling C&D materials can save resources and avoid landfill disposal [5,51]. The management of C&D waste is crucial worldwide, yet inadequately handled in many countries [52-54]. Life cycle assessment aids in evaluating the environmental impact and making informed decisions. Much C&D waste consists of inert materials, offering recycling potential. In Europe, the C&D industry generated over 2.5 billion tons of waste in 2012. Reclaimed aggregate can be used in asphalt pavement, but requires testing. C&D waste management offers significant technical, environmental, and economic opportunities for improvement.

Construction waste is a major industry issue, impacting both the environment and construction. She define it as diverse materials from various construction activities. Developed countries produce massive construction waste: USA - 136 million tons, UK - 70 million tons, and Australia - 14 million tons yearly. Efficient waste management is vital for environmental protection. Natural resource depletion from extensive construction results in substantial C&D waste. Das highlights waste sources like construction, demolition, and renovation, including reusable items like timber and metals. Concrete is a predominant waste type across excavation, roadwork, demolition, and complex waste. Aggregate recovery from waste concrete is feasible. C&D waste grouping by waste types, resources, and components is outlined.

C&D waste encompasses uncontrolled materials from construction, renovation, and demolition activities. Efficient management can decrease its generation [37]. Proper treatment can turn C&D waste into useful resources [37]. Global construction projects have led to increased waste disposal, mainly in landfills [37]. Australia faces a considerable C&D waste share (42%), with 81% of this being concrete waste . In the USA, concrete waste comprises 30 million tons annually, accounting for 29% of solid waste [66,67]. Ponnada and Kameswari report on India's C&D waste quantities: 4.20 to 5.14 million tons of soil, sand, and gravel, 4.40 million tons of brick and masonry waste, and 2.40 to 3.67 million tons of concrete waste.

Construction waste constitutes a significant portion of overall waste, particularly concrete and masonry, which together contribute more than 50%. Recycling these waste materials into aggregates can effectively mitigate landfill accumulation and decrease the reliance on virgin construction materials.

Tam et al provide significant statistical insights into China's waste management practices. In Hong Kong, 38% (14 million tons) of C&D waste is generated annually, with 11 million tons being reused for construction and repair while the remaining 3 million tons are sent to landfills. China demonstrates a stronger focus on waste reduction, generating only 16% (750,000 tons) of C&D waste. This showcases China's proactive approach to mitigating C&D waste's environmental impact. Demolition waste accounts for a substantial portion of global construction and demolition waste, constituting 70% due to the proliferation of infrastructure projects. Consequently, the C&D sector is a major contributor to overall waste production.

In the UAE, a significant amount of construction and demolition (C&D) waste is sent to landfills without effective treatment methods. The UAE landfill contains various types of C&D waste, including reinforced and un-reinforced concrete, precast concrete, ready-mix plant waste concrete, and concrete blocks. The substantial generation of C&D waste in the UAE can be attributed to rapid infrastructure growth. Factors contributing to increased C&D waste include excessive production, poor handling, improper storage, design changes, etc. In the USA, each project can lose 1 to 1.2 million dollars due to debris-related issues Concrete is the predominant material in UAE construction, contributing to its prominence in the C&D waste stream. Excessive material ordering is one cause of waste. For instance, in Dubai, C&D waste reached 6.6 million tons in 2011, outweighing general, horticultural, and liquid waste . Dubai Municipality's 2011 waste generation data highlights C&D waste as the largest contributor, occupying significant landfill space.

Based on data from the Statistics Centre in Abu Dhabi, it encompasses various waste types including industrial, commercial, agricultural, and municipal waste. Significantly, C&D waste predominates over other types. The data demonstrates an initial rise in C&D waste until 2013, followed by a slight decline from 2014 to 2016. The C&D waste is categorized into normal and mixed types. The waste quantity escalated from 7.6 million tons in 2011 to 9.6 million tons in 2012, decreased slightly to 7.7 million tons in 2013 and further dwindled to 2.9 million tons in 2015. In a notable contrast, there was a sudden spike in C&D waste in 2016, reaching 4,532,379 tons.

In summary, the proportion of construction and demolition (C&D) waste is consistently rising annually, driven by increased construction activities. This type f waste significantly populates landfills. Nonetheless, certain countries are adopting positive practices to address C&D waste, exemplified by the establishment of recycling plants to reduce landfill accumulation and repurpose recycled materials. This surge in waste poses challenges, with large quantities necessitating extensive landfill sites and detrimental environmental consequences. In the UAE, select cities engage in waste management, including C&D waste recycling, yet effective implementation remains lacking. Furthermore, the optimal utilization of recycled C&D waste remains a challenge not only in the UAE but also in other countries like India.

2.4. Current Method of C&D Waste Disposal

In summary, construction and demolition (C&D) waste management practices vary globally. Kabir highlights waste disposal issues in GCC countries, often relying on fly-tipping and landfilling. Mauras reports that 25-45% of waste is discharged from building and demolition activities, while Kuwait and Hong Kong heavily rely on landfilling. Arulrajah defines C&D waste materials, and Lima notes Brazil's substantial C&D waste generation. Coelho and de Brito classify C&D waste into inert and non-inert types, excluding excavation materials. Construction waste includes diverse materials. The 3Rs concept (reduce, reuse, recycle) is advocated for waste management, with examples of waste management practices in the Netherlands, Germany, and Japan. Yong's study outlines C&D waste management in Shenzhen, China, involving sorting, recycling, and proper disposal of inert, non-inert, and mixed waste.

In the GCC countries, landfilling is the predominant method for C&D waste disposal, and recycling is practiced for both general waste and some C&D waste, indicating regional waste management efforts . In conclusion, C&D waste comprises inert and non-inert materials, with substantial quantities being sent to landfills. Effective waste management strategies are essential to mitigate the negative environmental impact of accumulated landfill waste.

2.5. Impact of C&D Waste on the Environment

C&D waste from the construction industry poses environmental threats, resource depletion, and increased pollution . Environmental impacts span all construction phases. Waste disposal fills dumps, hindering future use, while de Magalhães [39] state that industry waste escalates with development. Buildings contribute 30% to global carbon footprints, stressing the importance of sustainable materials. LCA and carbon footprint tools reduce environmental harm, favoring materials like bricks, cement, steel, and concrete. Aggregates, vital in construction, deplete natural resources. Recycling C&D waste curtails landfill use conserves resources, and minimizes environmental impact . Although waste generation can't be zero, better practices can minimize it. Delivery waste accounts for 10-20% of building weight [35]. Cement contributes 8.6% to global CO_2 emissions

Dubai experiences a rising yearly generation of C&D waste due to extensive infrastructure projects, necessitating increased concrete production and impacting the environment through heightened carbon dioxide emissions. The use of primary aggregates extracted from mountains for concrete further depletes natural resources.

3. METHODOLOGY

This section delves into the diverse LCA modeling methods employed in various studies, emphasizing the significance of Life Cycle Assessment (LCA) and its recommended phases by ISO14040:2006. Originating around 1970 at the Midwest Research Institute in the USA, LCA emerged as a pivotal tool for environmental analysis and energy conservation. Roberts defines LCA as a comprehensive framework linking ecological products or services across their life cycle, encompassing raw material extraction to waste disposal. Employed globally, LCA evaluates the environmental impact of building materials, aiding in identifying areas for improvement. LCA serves as an environmental management tool, as described by Caldas, facilitating the assessment of specific company services. Particularly relevant in C&D waste management, LCA assesses both recovery and reuse potential, exemplified by studies such as

Dahlbo who employed LCA to evaluate Finland's C&D waste performance towards EU recycling targets. Multiple Life Cycle Impact Assessment methods are outlined and elaborated upon. Furthermore, this study encompasses an exploration of environmental impact monetization, illustrating various methods that can complement Life Cycle Assessment (LCA) to gauge environmental harm.

4. RESULTS AND DISCUSSION

This section focuses on the Life Cycle Impact Assessment (LCIA) phase of LCA in accordance with ISO14040:2006. It outlines data analysis utilizing midpoint and endpoint assessment methods, spanning 18 midpoint impact categories, nine damage pathways, and three endpoint areas of protection. The study assesses unreinforced concrete waste's environmental impact through ReCipe, aligning with research objectives regarding waste management options (disposal and recycling) and transportation methods. EcoInvent database contributes inventory data for landfilling, recycling, and transportation impacts, while SimaPro 8.5.2 software aids in result calculations. Furthermore, the chapter addresses the relationship between damage costs and LCA outcomes, employing environmental prices from Handbook Environmental Science and Ecotechnology and applying them to the ReCiPe2016 LCIA. The analysis encompasses 2018, while appendices offer data for 2013-2017.

Damage costs were determined using the prices provided in the Handbook, encompassing 15 prices pertinent to LCIA with ReCiPe2016. Table 1 displays the impact category prices in euros per relevant unit, cross-referenced with page numbers from the Handbook.

Table 1: Environmental Prices

Handbook Environmental Prices 2017				
No.	**Impact category**	**Unit**	**Price in Euros (€)**	**Page**
1	Climate change	€/kg CO2-eq.	0.057	42
2	Ozone layer depletion	€/kg CFC-eq.	30.4	42
3	Acidification	€/kg SO2-eq.	5.4	42
4	Freshwater eutrophication	€/kg P-eq.	1.9	42
5	Marine eutrophication	€/kg N	3.11	42
6	Land use	€/m2a	0.0261	42
7	Terrestrial ecotoxicity	€/kg 1,4 DB-eq.	8.89	42
8	Freshwater ecotoxicity	€/kg 1,4 DB-eq.	0.0369	42
9	Marine ecotoxicity	€/kg 1,4 DB-eq.	0.00756	42
10	Human toxicity	€/kg 1,4 DB-eq.	0.214	42
11	PM2.5	€/kg PM2.5 eq.	79.5	100
12	Nitrogen oxides (Nox) (Human health)	€/kg NOx eq.	18.7	107
13	Nitrogen oxides (Nox) (Terrestrial ecosystems)	€/kg 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 integration of LCA results with damage cost outcomes is achieved through reference to the Handbook (as detailed in Table 1). The LCA assessment initiates with the LCIA phase employing the ReCipe method, while the EcoInvent database is employed for the life cycle inventory phase. SimaPro software is utilized in the third LCA phase, LCIA, to simplify and categorize the results. Damage costs, delineated in Table 1, are incorporated annually to assess the environmental impact alongside LCIA results. The amount of concrete waste in Dubai landfill is consistently escalating, as illustrated in Table 2 for 2013 to 2018.

Table 2: Quantity of concrete waste in Dubai landfill each year separately

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
2017	"	5,000,000
2018	"	5,400,000

The midpoint method, positioned at an intermediate level between environmental mechanism and impact pathway, displays robustness in relation to ecological flows and reduced uncertainty. The results of the ReCipe-based LCA's third phase, depicted in Figure 1, employ the midpoint assessment. This figure illustrates the percentage results of each midpoint impact for three inventories: landfill disposal of concrete waste, recycling of concrete waste, and transportation. Landfilling demonstrates higher environmental damage compared to recycling and transportation for several midpoint impacts, including Global Warming, Ionising Radiation, and Terrestrial Acidification, among others. In contrast, transportation's highest influence emerges in impacts like Human Carcinogenic Toxicity. Recycling method impacts, such as Ozone Formation (Human Health), surpass transportation alone. Overall, landfilling concrete waste bears the highest midpoint assessment impacts relative to recycling and transportation methods.

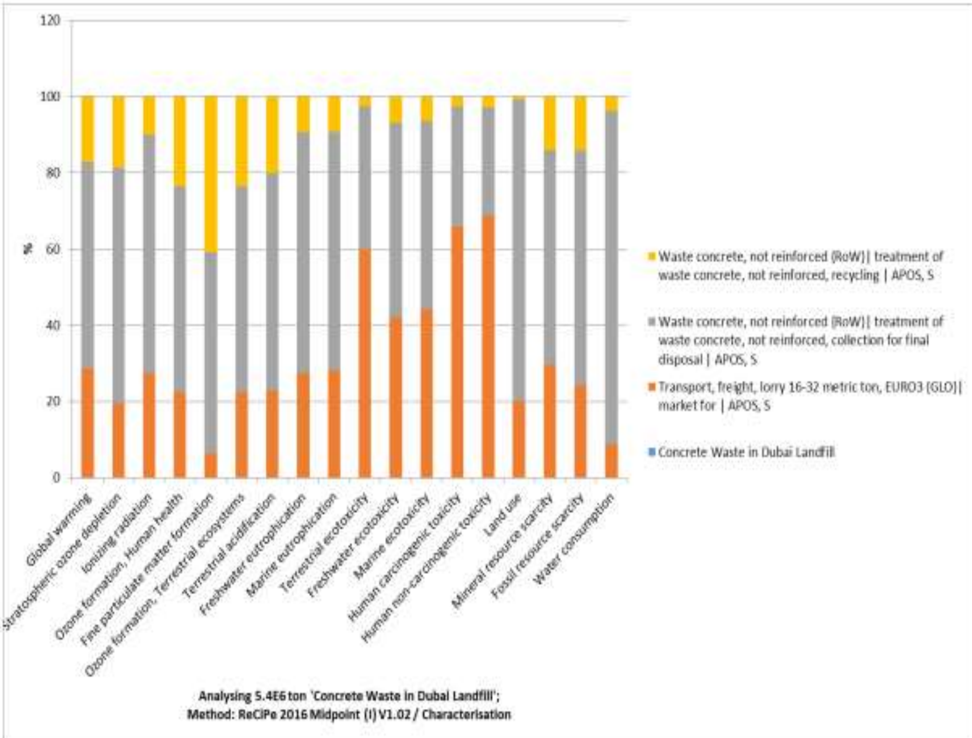

Figure 1: Results of each midpoint impact in percentage

Figure 1 presents the midpoint LCIA results and associated damage costs for 15 impacts. In a broader context, the landfilling method and transportation process exhibit higher midpoint damage costs compared to recycling, particularly evident in impacts like Terrestrial Ecotoxicity, Ozone Formation (Human Health), Fine Particulate Matter Formation, and Global Warming. Lower damage costs are observed for Marine Eutrophication and Marine Ecotoxicity, indicating their lesser impact. Midpoint LCIA outcomes along with related damage costs are accessible for 2013 to 2017.

Airborne Particulate Matter (PM) is a mix of varying-sized liquid and solid particles, that impact human health, structures, and visibility through haze. Fine Particulate Matter, laden with toxic substances, poses health risks by entering the lungs, with smaller particles causing deeper damage. LCA results (Figure 1) reveal landfilling concrete waste has a 52.9% Fine Particulate Matter Formation impact, surpassing transportation (6.22%) and recycling (40.8%). Landfilling and recycling contribute to dust generation. Tropical Ozone Formation (Human Health) damage pathway accentuates respiratory disease, culminating in health impairment.

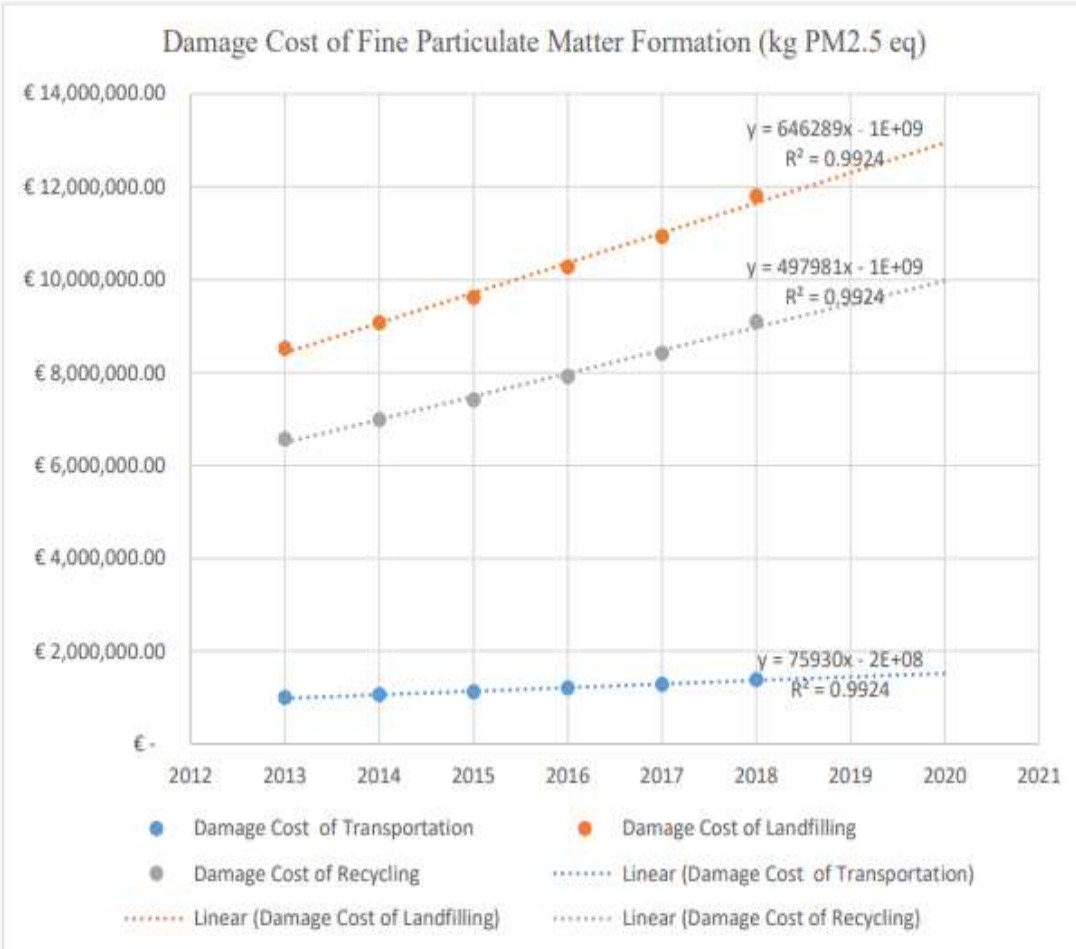

Figure 2: Damage cost of fine particulate matter formation

Figure 2 displays damage cost results for three methods (2013-2018) with $R^2 = 0.9924$. Projections suggest a continuous increase, reaching €13,500,000 in 2020, especially in landfilling. Fine Particulate Matter Formation damage cost grows yearly by €60,000 to €100,000 in concrete waste transportation by lorry. For both landfilling and recycling methods, the damage cost rises by €50,000 to €100,000 annually.

Ozone Depleting Substances (ODSs) heighten UVB radiation, causing harm to human health. Rising atmospheric ozone concentration, paradoxically, increases UVB radiation reaching Earth, negatively affecting health, and leading to heightened skin cancer and cataract risk. LCA findings in Figure 1 reveal landfilling's 54.1% impact on Ozone Formation (Human Health), surpassing transportation (22.3%) and recycling (23.6%). Landfilling yielded 601,163.86 kg NOx eq, whereas transportation and recycling had 248,111.96 and 262,075.62 respectively. Tropical Ozone Formation (Human Health) in ReCipe demonstrates increased respiratory disease, culminating in human health damage.

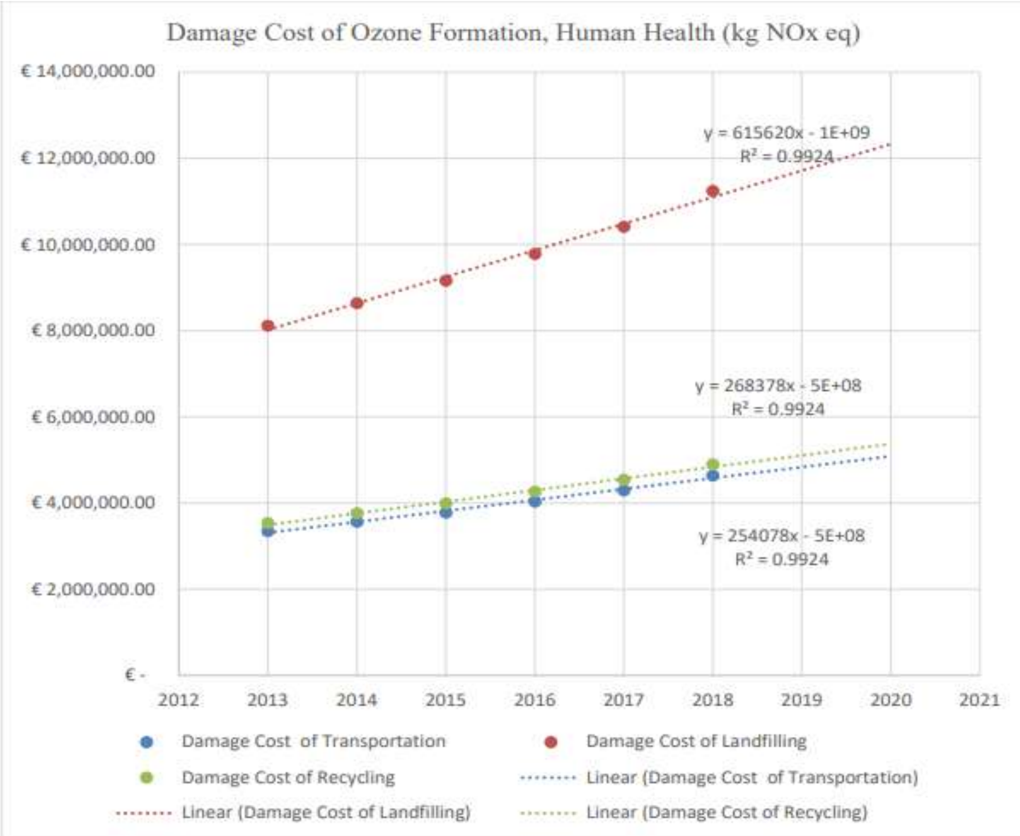

Figure 3: Damage cost of Ozone formation

In Figure 3, the damage cost outcomes for the three methods regarding Ozone Formation (Human Health) impact from 2013 to 2018 demonstrate an annual rise averaging €200,000 to €900,000 across all three methods. The projected trend maintains an increasing trajectory in the future, with landfilling showing the most substantial accumulation.

The emissions of radionuclides, both from the fuel cycle and other human activities, contribute to environmental impact. Dispersion modeling and exposure assessment are followed by analyzing radiation-related health effects such as DNA damage, cancer incidence, and hereditary impacts. Damage to human health is quantified in disability-adjusted life years (DALY). However, quantifying ecosystem damage from ionizing radiation remains challenging due to a lack of assessment methodologies. LCA results in Figure 1 highlight that landfilling waste concrete significantly influences Ionising Radiation impact, at 62.5%, compared to transportation and recycling methods. The latter two methods exhibit lower impacts, at 27.5% and 9.97%, respectively. Although the damaged pathway is linked to various cancers and health issues, the damage cost for Ionising Radiation is unavailable in existing resources, precluding its calculation

Ozone Depleting Substances (ODSs) cause increased UVB radiation, damaging human health through higher rates of skin cancer and cataracts due to atmospheric ozone depletion. Midpoint

LCA results in Figure 1 depict that waste concrete's impact on Stratospheric Ozone Depletion is 61.7% for landfilling, while transportation and recycling methods yield results of 19.5% and 18.8%, respectively. The unit impact for waste concrete in landfills is 29.765 (kg CFC11 eq), whereas transportation and recycling methods exhibit 9.407 and 9.0504113. Stratospheric Ozone Depletion leads to increased cancer instances and other diseases, affecting human health as an endpoint area of protection

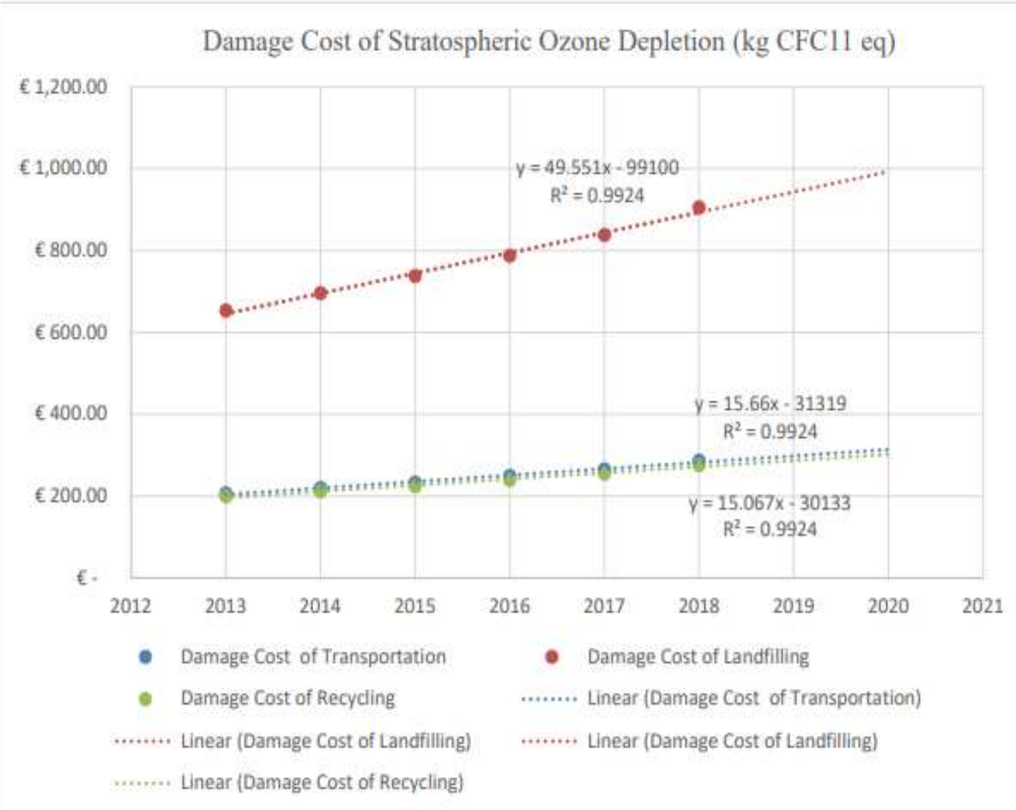

Figure 4: Damage cost of Stratospheric Ozone Depletion

Figure 4 displays damage cost outcomes from 2013 to 2018 for the three methods, with a predictive R2 value of 0.992. The trend suggests escalating damage costs in the future, predominantly within landfilling. Stratospheric Ozone Depletion's damage cost demonstrates an annual rise averaging €20 to €80, predominantly associated with the landfilling method.

The International Agency for Research on Cancer (IARC) assesses the carcinogenic risk of substances to humans, assigning a carcinogenicity class to each based on evidence from studies on humans and animals (IARC, 2004). Classes reflect the strength of evidence. LCA outcomes in Figure 1 reveal that landfilling has a 31.5% impact on Human Carcinogenic Toxicity compared to transportation and recycling methods at 66% and 2.47% respectively. In terms of units, landfilling's impact was 21,587.083 (kg 1,4-DCB), while transportation and recycling methods were 45,149 and 1,692.438 respectively. Human Carcinogenic Toxicity's impact is growing in various cancer categories, contributing to health damage.

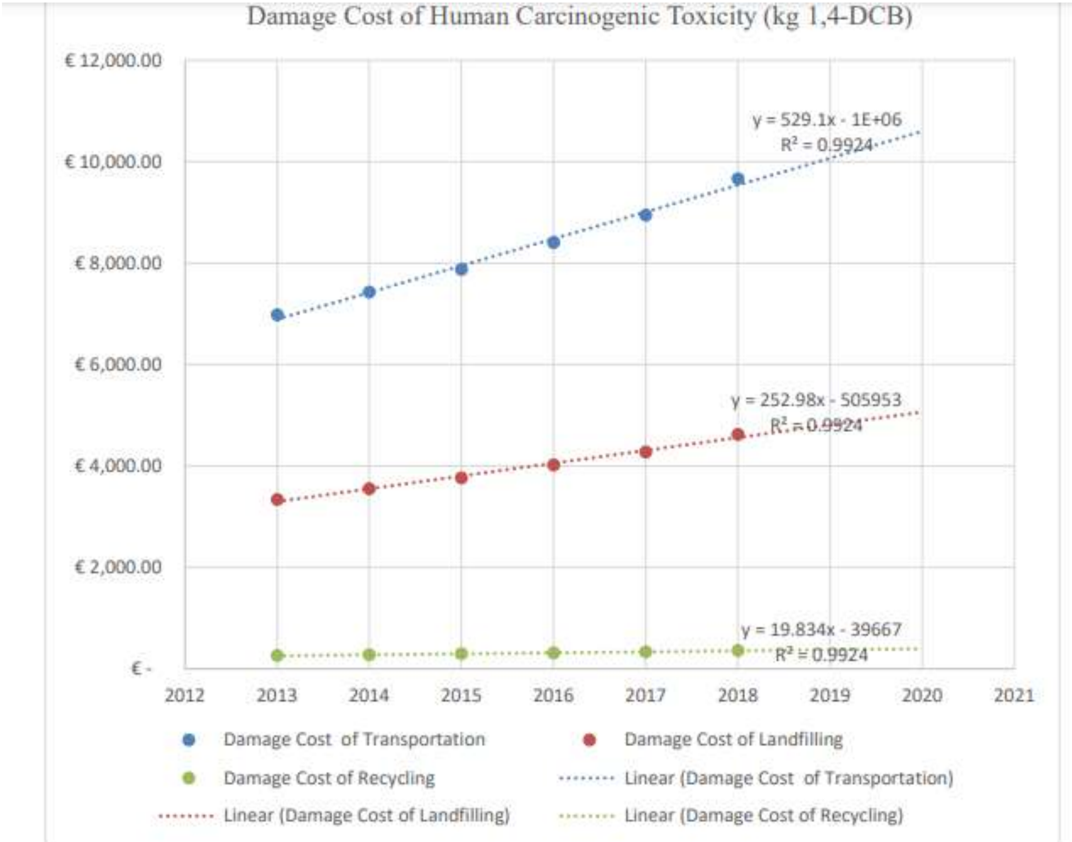

Figure 5: Damage Cost of Human Carcinogenic Toxicity

Figure 5 depicts the damage cost of Human Carcinogenic Toxicity for the three methods from 2013 to 2018, with R2 = 0.992. The forecast for future damage costs of Human Carcinogenic Toxicity indicates an upward trend. Results reveal a greater cost impact in the transportation process, while both landfilling and recycling methods show relatively lower cost impacts.

In Figure 1, the LCA results reveal that the landfilling method contributes to a 28.6% impact on Human Non-Carcinogenic Toxicity, compared to 68.7% for the transportation process and 2.76% for recycling. Unit-wise, the landfilling method's impact is at 746,082.49 (kg 1,4-DCB), while transportation is at 1,792,538.1 and recycling is at 72,150.367. However, the damage price of Human Non-Carcinogenic Toxicity (Non-Cancer) was not computed due to its unavailability in the Handbook Environmental Prices 2017 or other sources.

The damage assessment of the climate change impact category involves multiple steps, including greenhouse gas emissions resulting in increased atmospheric concentration and radiative forcing capacity, leading to a rise in global mean temperature. This rise ultimately affects human health and ecosystems. LCA results depicted in Figure 1 highlight that waste concrete in landfills contributes to a 54.4% impact on Global Warming, in comparison to transportation (28.6%) and recycling (17%) methods. In terms of units, landfilling results in 7,228,4957 kg CO2 eq, while transportation and recycling methods account for 3,793,4796 and 2,2640,946 respectively. Global Warming's effects include malnutrition, and damage to freshwater and terrestrial species, resulting in impacts on human health and ecosystems.

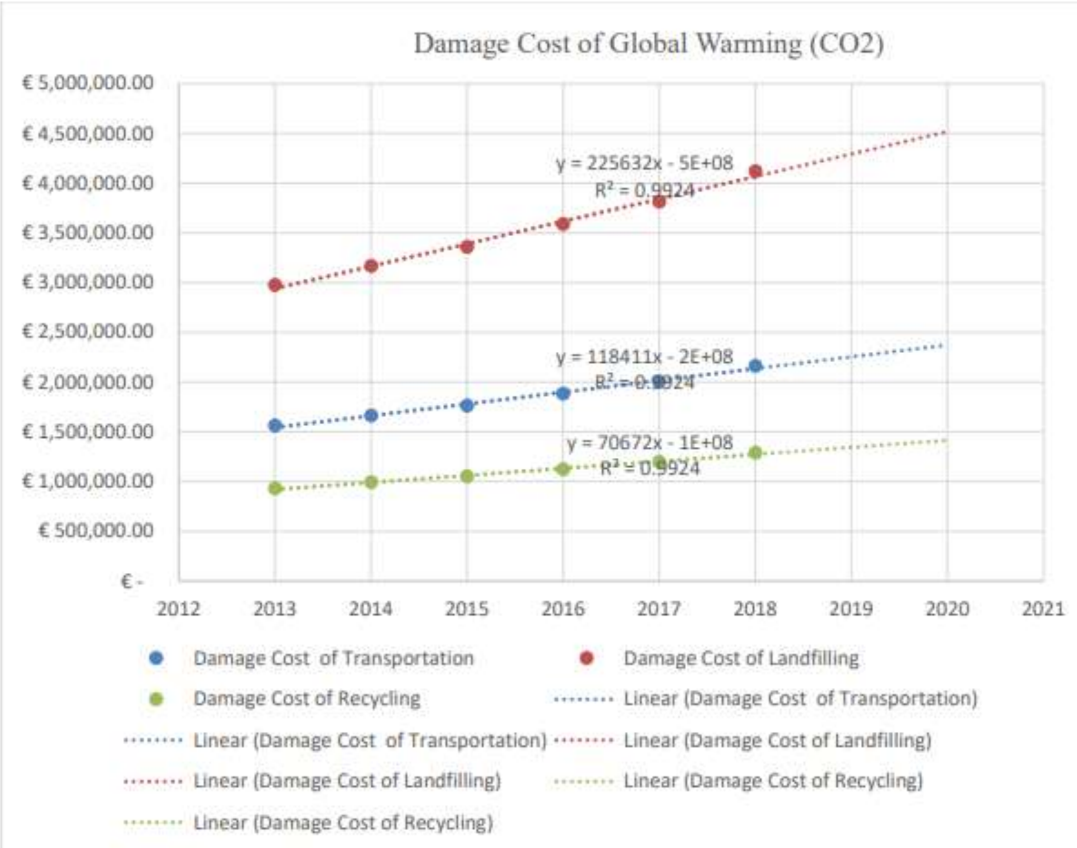

Figure 6: Damage Cost of Global Warming

Figure 6 presents the damage cost analysis for Global Warming spanning 2013 to 2018, revealing a consistent increase in the projection. The damage cost trends for all three methods are evident. Notably, the impact cost of Global Warming is substantial across all methods, with landfilling concrete waste incurring the highest cost, amounting to €4,120,242.50 in 2018.

The scarcity of freshwater poses challenges for diverse water needs, impacting irrigation and leading to malnutrition. Vulnerability to malnutrition increases in regions with lower Human Development Index (HDI), highlighting the link between malnutrition, food availability, and human development. The impact on terrestrial ecosystems is evident through declining vegetation and plant diversity due to decreased water availability. Figure 1 showcases LCA results indicating that landfilling incurs an 87.5% Water Use/Consumption impact, with transportation at 8.76% and recycling at 3.75%. These impacts affect malnutrition and freshwater-dependent species, contributing to damage to human health and ecosystems. However, the damage cost for Water Use/Consumption isn't available in resources like the Handbook Environmental Prices 2017.

The potential marine impact relates to additional essential metal inputs, causing toxicity.

Egalitarian and hierarchic scenarios calculate marine ecotoxicological impacts, while the individualistic scenario considers essential metals like cobalt, copper, manganese, molybdenum, and zinc. Reduced blue water availability affects green water and plant diversity. Freshwater fish evaporate due to water consumption, impacting river-associated species. In Figure 1, landfilling causes 51.1% of Freshwater Ecotoxicity, transportation 42.1%, and recycling 6.81%. Landfill waste concrete leads to 630,299.48 (kg 1,4-DCB), while transportation and recycling are 519,406.790 and 83,955.099, respectively. Freshwater Ecotoxicity relates to damage to freshwater species and ecosystems.

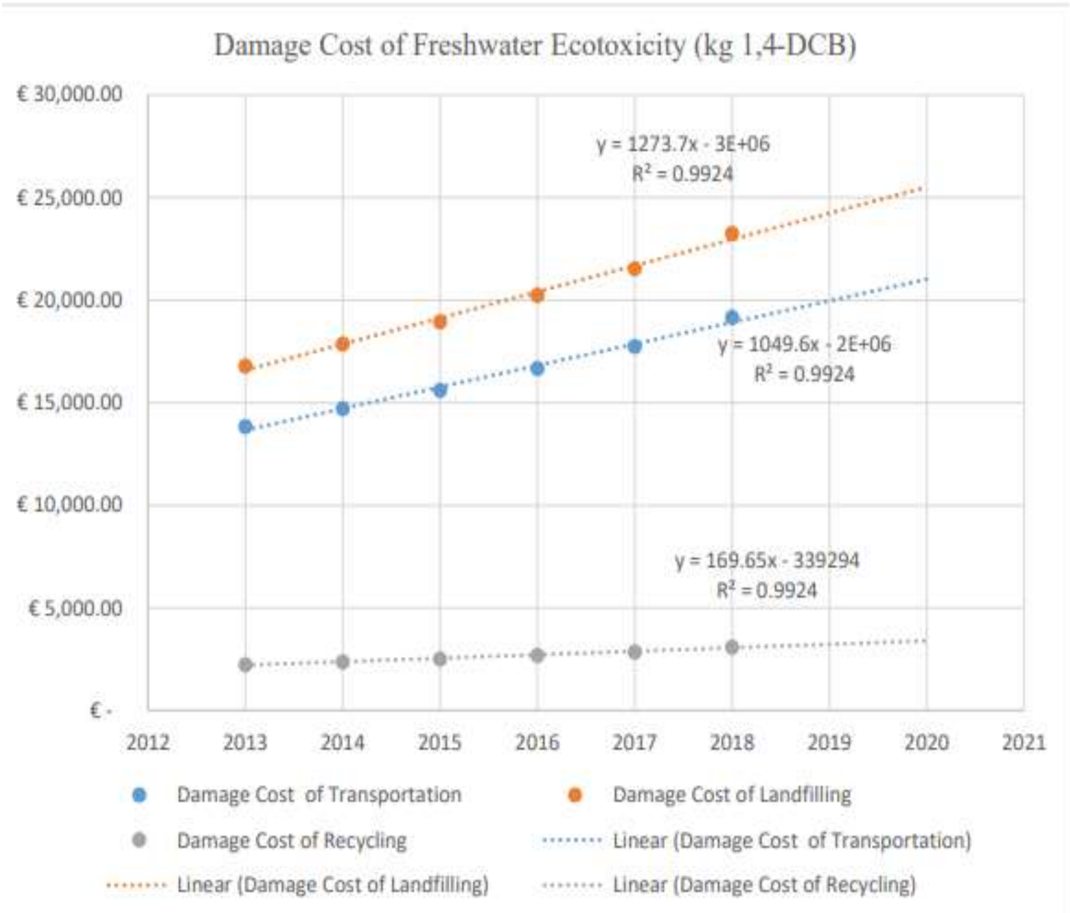

Figure 7: Damage Cost of Freshwater Ecotoxicity

Figure 7 depicts Freshwater Ecotoxicity damage costs for the three methods with an R2 of 0.992. The forecast indicates increasing cumulative yearly costs. Notably, landfilling has high damage costs, whereas the recycling method shows lower costs for Freshwater Ecotoxicity.

The release of nutrients like phosphorus and nitrogen into freshwater bodies leads to freshwater eutrophication, causing ecological imbalances. The impact involves nutrient emissions raising nutrient levels, benefiting autotrophic and heterotrophic organisms. This results in species loss and ecological disruption. LCA findings, as shown in Figure 1, indicate the landfilling method's 63.1% impact on Freshwater Eutrophication, compared to transportation (27.5%) and recycling (9.39%). The unit-based impact shows higher phosphorus levels for landfilling (6365.8561 kg P eq) than for transportation and recycling methods. Freshwater Eutrophication adversely affects freshwater species and ecosystems.

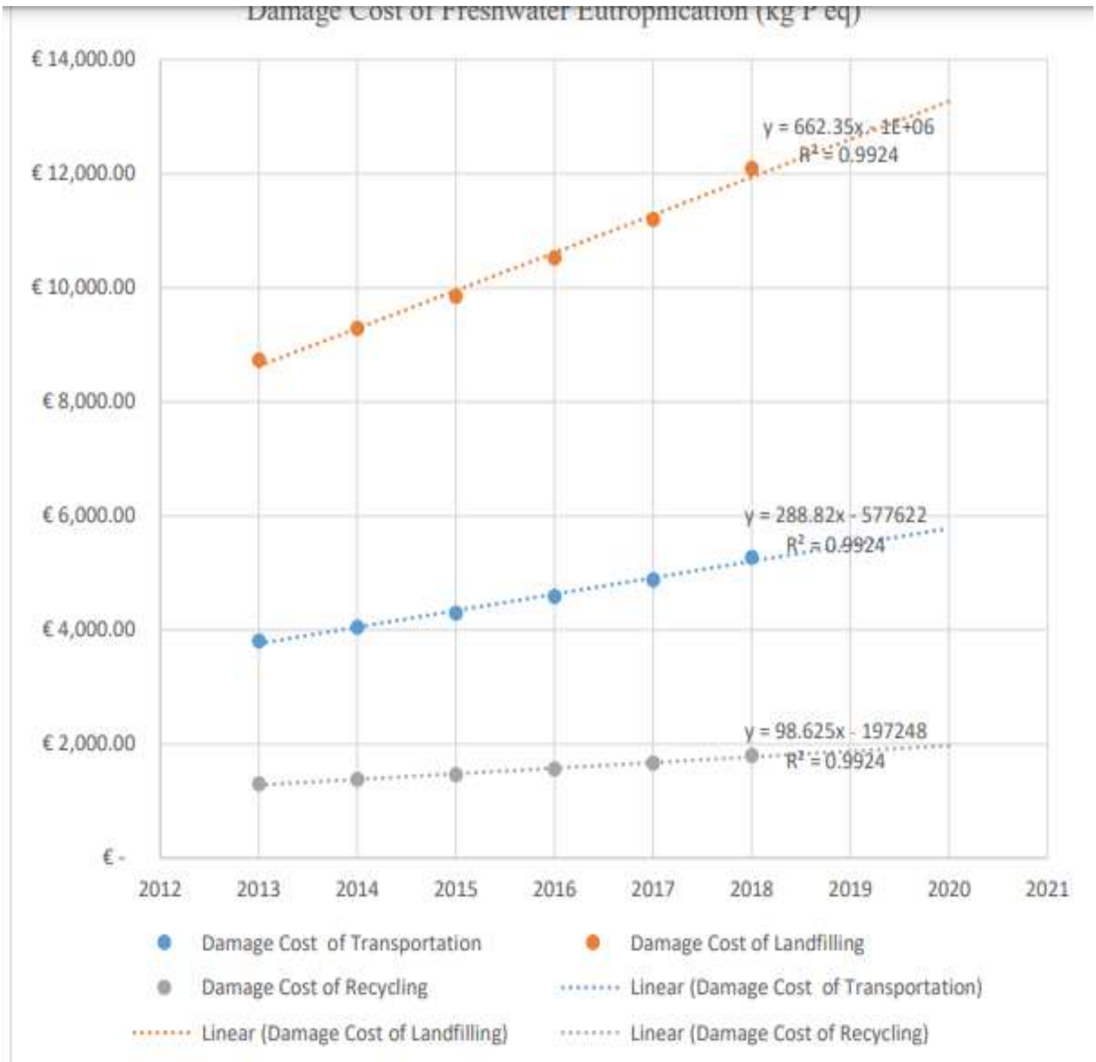

Figure 8: Damage Cost of Freshwater Eutrophication

Figure 8 displays the damage cost trends of Freshwater Eutrophication from 2013 to 2018, with an R2 value of 0.992. The forecast suggests an annual increase, particularly pronounced in the landfilling method. The damage cost associated with Freshwater Eutrophication is notably higher in the landfilling approach, reaching €12,095.13 in 2018, surpassing the costs in other methods.

Ozone Depleting Substances (ODSs) contribute to increased UVB radiation, impacting human health. Higher atmospheric ozone concentration, resulting from ozone depletion, exposes

Earth to more UVB radiation, leading to adverse effects like skin cancer and cataracts. Figure 1 presents LCA findings, indicating that waste concrete in landfills as final disposal contributes to a 54.2% impact on Tropical Ozone Formation (Ecosystems), surpassing the impacts of transportation (22.3%) and recycling (23.6%) methods. On a unit basis, landfilling contributed 612,126.24 (kg NOx eq), while transportation and recycling were 251,954.24 and 266,298.17 respectively. The damaging impact of Tropical Ozone Formation (Ecosystems) affects terrestrial species and ecosystems.

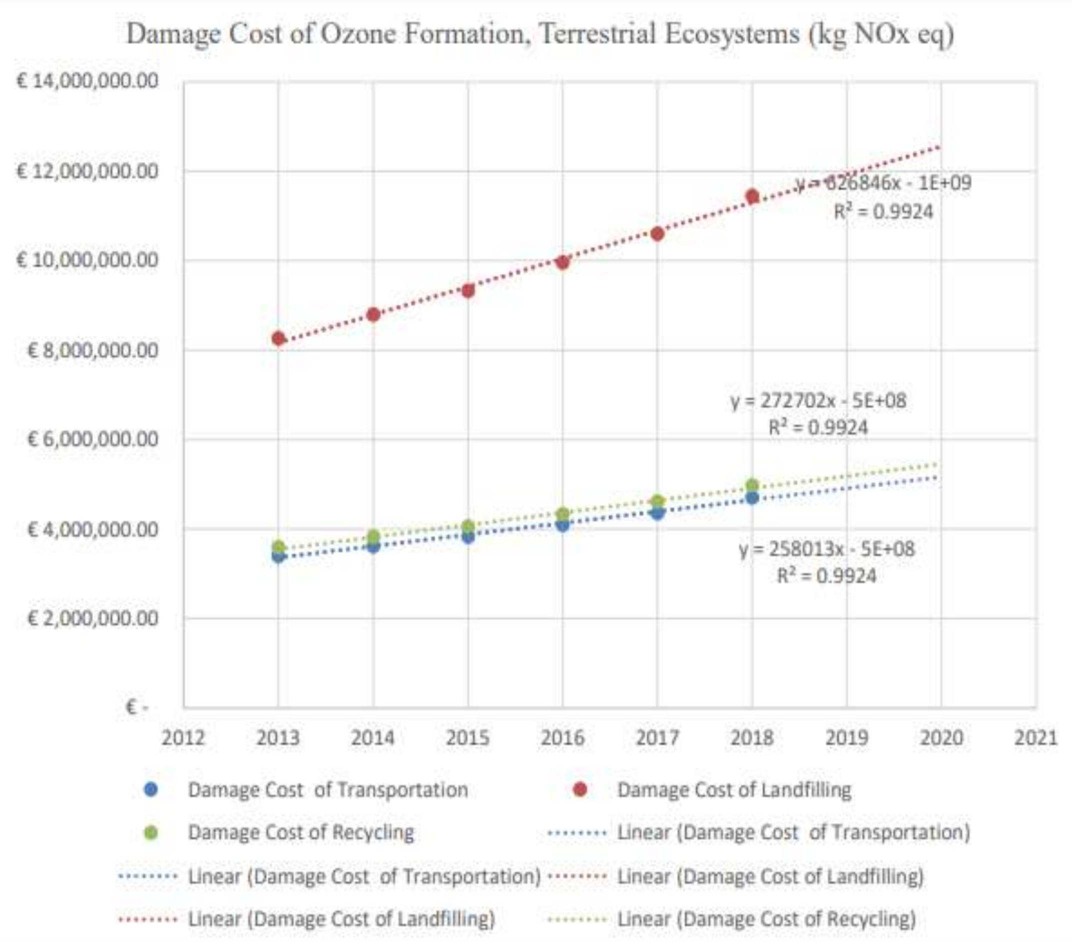

Figure 9: Damage Cost of Ozone Formation, Terrestrial Ecosystems

Figure 9 displays the damage cost of Ozone Formation (Terrestrial Ecosystems) for the three methods from 2013 to 2018, with R2 = 0.992. The projection indicates an annual increase, especially pronounced for the landfilling method. The damage cost for the landfilling method was €11,446,760.69, surpassing the transportation process and recycling method at €4,711,544.29 and €4,979,775.78 respectively.

The LCA findings, as depicted in Figure 1, reveal that waste concrete disposed of in landfills contributes to a 37.5% impact on Terrestrial Ecotoxicity, contrasting with the transportation and recycling methods. The landfilling method's impact accounts for 60%, while the recycling method is at 2.53%. From a unit perspective, waste concrete in landfills leads to an impact of 129,037,190 (kg 1,4-DCB), whereas the transportation and recycling methods are 20,620,2510 and 8,705,868.7 respectively. The damage pathway for Terrestrial Ecotoxicity relates to damage inflicted on terrestrial species, resulting in harm to ecosystems.

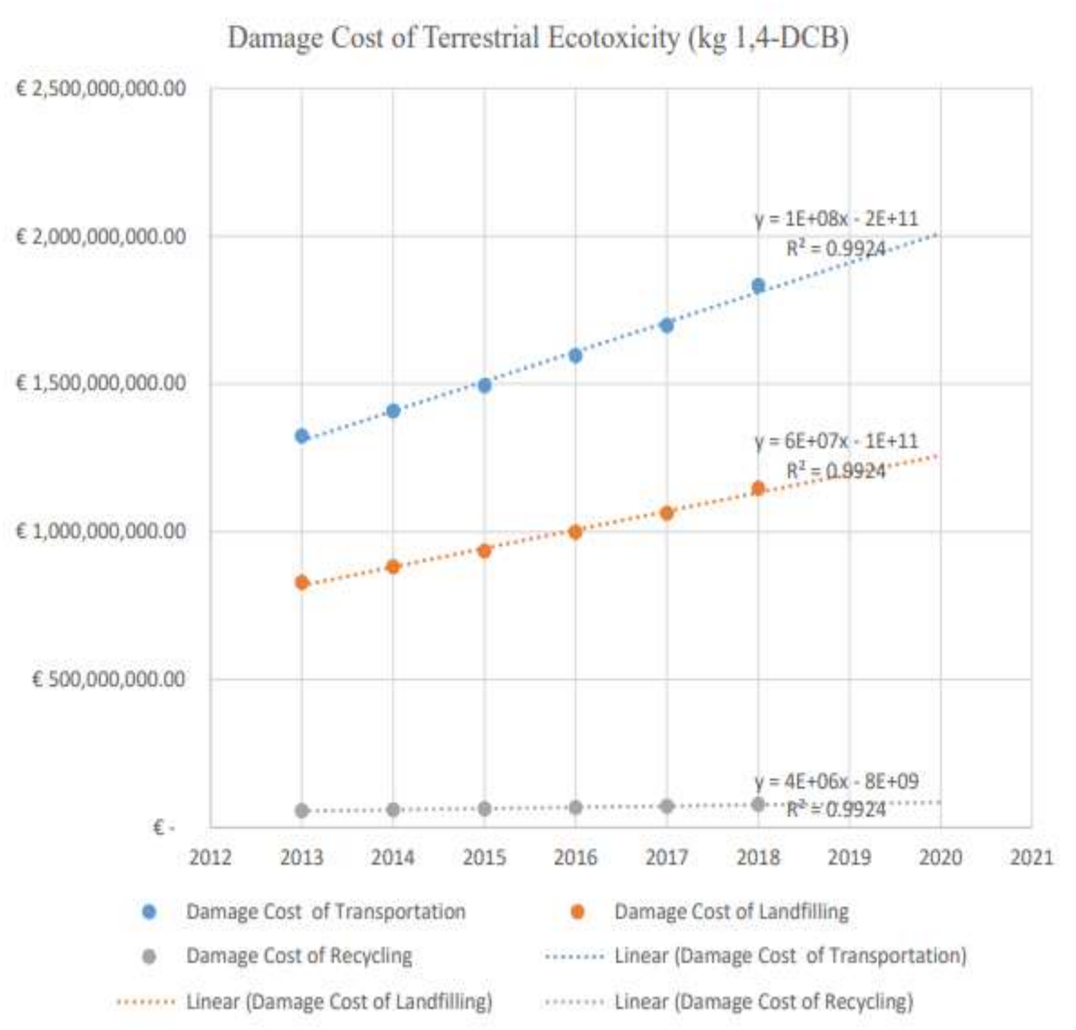

Figure 10: Damage Cost of Terrestrial Ecotoxicity

Figure 10 provides insight into the Terrestrial Ecotoxicity damage costs across the three methods from 2013 to 2018, demonstrating an R2 of 0.992. The projected damage costs for Terrestrial Ecotoxicity are on an upward trajectory each year, with a pronounced rise in the transportation process. The landfilling method exerts a substantial impact, amounting to €1,833,140,313.90, significantly outweighing the costs associated with transportation (€1,147,140,619.10) and recycling (€77,395,172.74) methods.

Certain substances, like sulphates, nitrates, and phosphates, released through atmospheric deposition, can alter soil acidity, potentially affecting plant species. Optimal acidity levels differ among plants, with acidity exceeding these levels causing acidification and harming specific species. Acidification is primarily driven by emissions such as NO_x, NH_3, or SO_2. Wattier et al.an d Hayashi et al. highlight the connection between acidity variations and species presence. Characterization factors for acidification in global biomes are calculated, accounting for substance persistence through atmospheric deposition and geochemical soil acidification models [95]. Effect factors gauge ecosystem damage due to acidification, linked to potential plant species occurrences using logistic regression functions [96]. Figure 1 presents LCA outcomes, indicating that waste concrete in landfills as final disposal holds a 57% impact on Terrestrial Acidification, surpassing transportation (22.8%) and recycling (20.1%). Landfilling accounted for 348,418.92 kg SO2 eq, compared to transportation (139,557.24) and recycling (122,878.69). Terrestrial Acidification correlates with harm to terrestrial species and ecosystem damage.

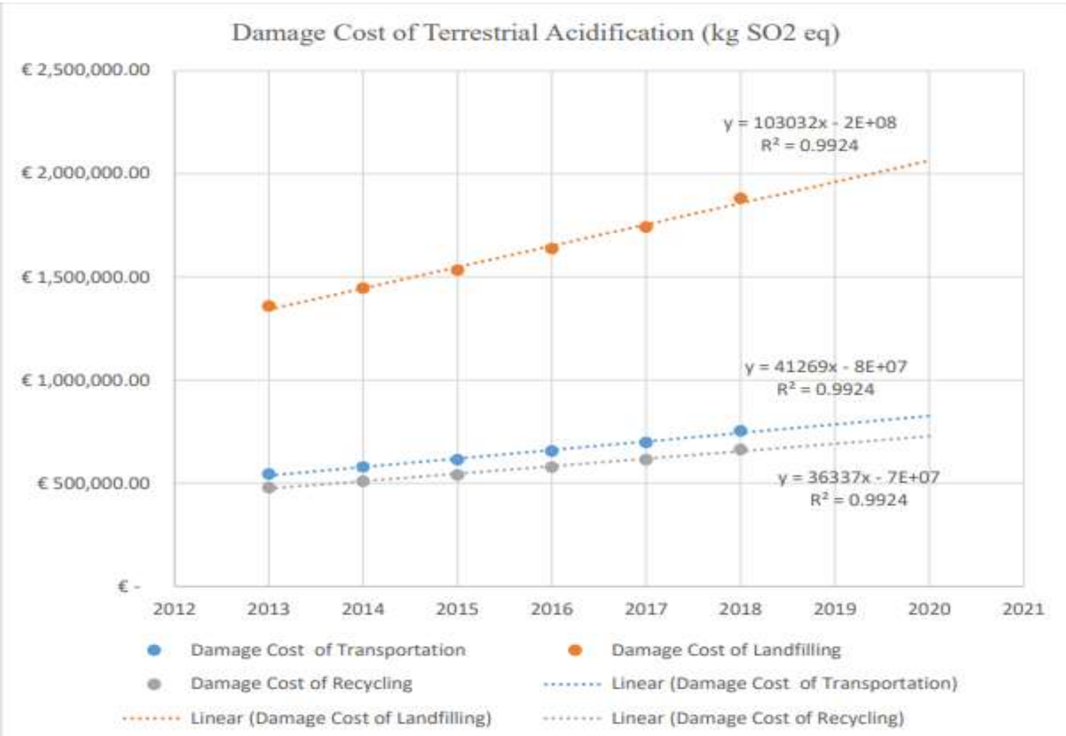

Figure 11: Damage Cost of Terrestrial Acidification

Figure 11 displays the damage cost of Terrestrial Acidification for the three methods across multiple years, with R2 = 0.992. The anticipated damage cost for Terrestrial Acidification is on the rise annually, notably in the landfilling method, which amounts to €1,881,462.17. This is in contrast to transportation at €753,609.10 and recycling at €663,544.93.

Figure 1 presents the LCA results indicating that waste concrete disposed of in landfills has a 79.3% impact on Land Use compared to transportation and recycling methods, with impacts of 20% and 0.693% respectively. The landfilling method had an impact of 6,073,915 (m2a crop eq), while transportation and recycling methods were 1,534,466.5 and 53,116.578 respectively. The damage pathway associated with Land Use/Transformation involves the loss of terrestrial species, resulting in damage to ecosystems.

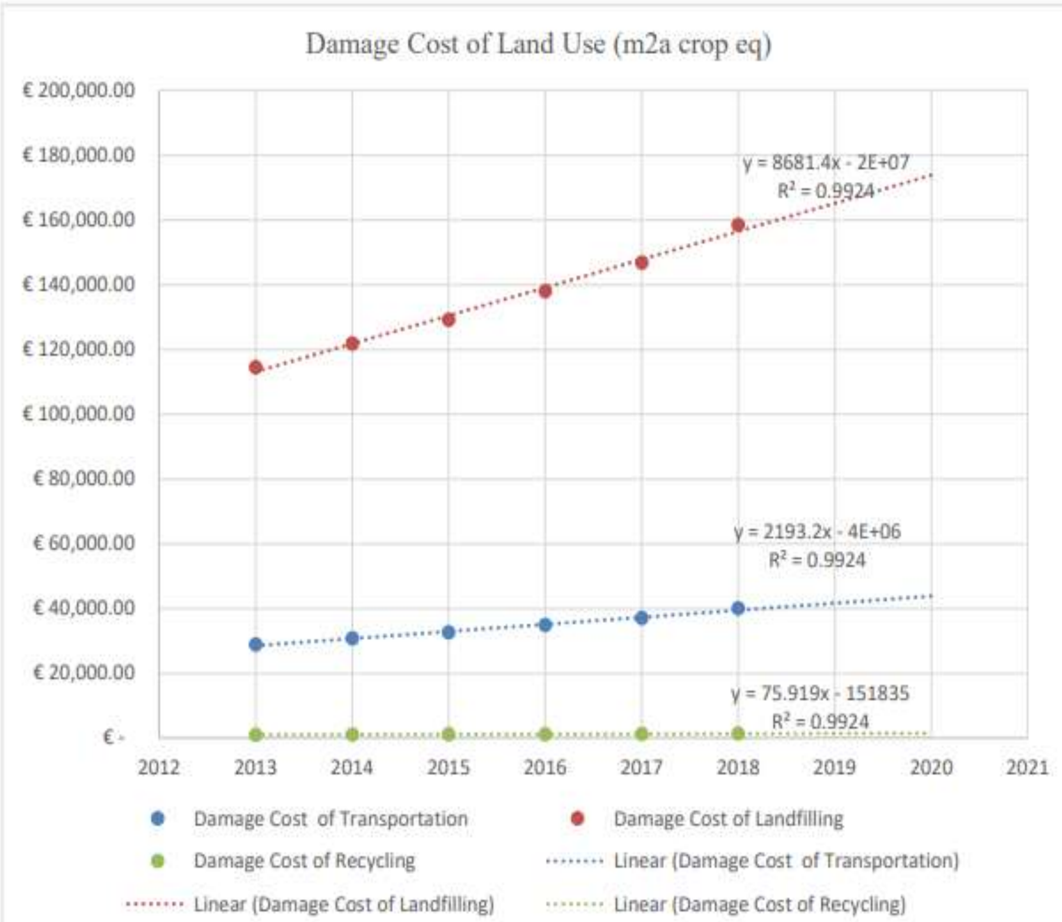

Figure 12: Damage Cost of Land Use

Figure 12 illustrates the damage cost of Land Use over several years, with an R2 of 0.992. The projected damage cost for Land Use shows a yearly increase, particularly in the landfilling method, reaching €158,529.18 compared to recycling and transportation methods.

The introduction of additional essential metals into oceans can lead to toxic effects, impacting the marine environment. The study considers different scenarios for marine ecotoxicological impacts, including the impact of essential metals like cobalt, copper, manganese, molybdenum, and zinc. In the LCA results depicted in Figure 1, waste concrete disposed of in landfills has a 49.4% impact on Marine Ecotoxicity, compared to transportation and recycling methods with impacts of 44.1% and 6.5% respectively. The damage pathway of Marine Eco-toxicity is linked to damage to marine species, resulting in damage to ecosystems as the endpoint area of protection.

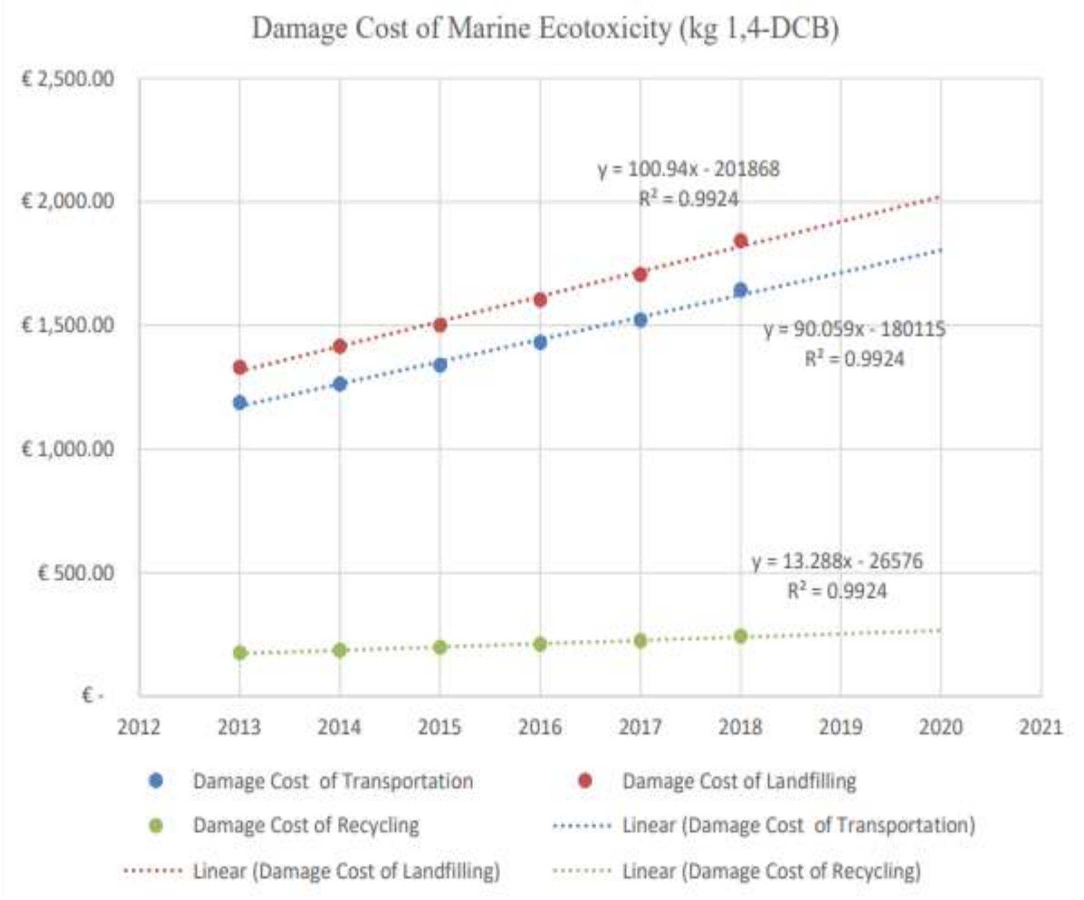

Figure 13: Damage Cost of Marine Ecotoxicity

Figure 13 presents the Marine Ecotoxicity damage cost for the years 2013 to 2018, with an R^2 value of 0.992. The projected damage cost for Marine Ecotoxicity increases slightly each year across all methods, particularly in landfilling, where it is forecasted to rise by an average of €200 annually.

The section concludes the life cycle impact assessment (LCIA) using the ReCiPe method, considering 18 midpoint impacts, 22 endpoint impacts, and three endpoint areas of protection. The assessment is conducted across three methods: final disposal of concrete waste without treatment, recycling, and transportation to landfill. Results consistently indicate that the final disposal method has the most negative impact across all nine damage pathways and three endpoint areas, followed by the transportation process, and finally, the recycling method with the least impact. The damage cost analysis reveals that putting concrete waste into a landfill incurs the highest damage cost across all midpoint impacts compared to recycling and transportation. Certain impacts, such as Ozone Formation in Human Health, Fine Particulate Matter Formation, and Ozone Formation in Terrestrial Ecosystems, have higher damage costs for recycling and landfilling methods compared to transportation. Conversely, Terrestrial Ecotoxicity and Human Carcinogenic Toxicity show higher damage costs for transportation compared to landfilling and recycling. Descriptive analysis for 2018 highlights that transportation has a higher Mean, Standard Deviation, Kurtosis, and Skewness in damage costs compared to landfilling and recycling methods. The mathematical relationships between LCA and damage cost show a positive correlation between impact and cost, with the recycling method displaying a stronger correlation. Overall, the recycling method emerges as the preferable option in terms of both LCA results and damage costs among the concrete waste management choices.

5. CONCLUSION

The research methodology successfully achieved its aim and objectives by employing concrete waste modeling through LCA and damage cost analysis. Government sources provided data on concrete waste quantities in Dubai city landfills, while SimaPro software and the EcoInvent database were utilized. A comprehensive literature review demonstrated significant ecological impacts of concrete waste construction and demolition. LCA based on ReCiPe LCIA was performed to analyze impacts on human health, ecosystems, and resources across various concrete waste management methods. The study identified the importance of LCA results in measuring environmental damage, suggesting optimal waste management practices, and calculating damage costs to safeguard the environment, human health, and ecosystems. Early-stage waste reduction through Best Disposal Option Practice (BDOP) selection was highlighted, favoring eco-friendly methods like recycling over landfilling. The research comprised two phases: LCA using SimaPro and EcoInvent, and monetization of environmental indicators from the Handbook Environmental Prices 2017. Results underscored the considerable ecological impacts and damage costs associated with waste concrete, emphasizing the detrimental effects of landfilling. Recycling displayed fewer impacts and lower damage costs. While recycling is widely recommended for its sustainability benefits, this study offered a detailed assessment of its impacts using 18 midpoint and endpoint methods and damage costs for 15 impacts. The research deepened our understanding of the intricate interplay between concrete waste, various management methods, and environmental consequences.

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