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Advancing Circular Economy Through Optimized Construction and Demolition Waste Management Under Life Cycle Approach

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Abstract: The construction industry significantly impacts the environment, consuming 50% of natural resources and generating 20% of global greenhouse gas (GHG) emissions. In developing countries, managing construction and demolition (C&D) waste is a growing challenge due to rapid urbanization and inadequate waste management practices. This study employs life cycle assessment and life cycle costing to compare landfill and recycling scenarios for C&D waste using ISO 14040 (Environmental Management—Life Cycle Assessment—Principles and Framework) and ISO 14044 (Environmental Management—Life Cycle Assessment—Requirements and Guidelines). The study's system boundary encompasses the entire life cycle of C&D waste management, with one ton of C&D waste as the functional unit. The results demonstrated that landfilling C&D waste is harmful due to negative impacts from transportation and landfill emissions. Recycling shows promising potential by significantly reducing environmental impacts and lowering the demand for new raw materials. The recycling scenario substantially decreased GHG emissions, saving 37 kg of CO_2 equivalents per ton of waste. Economically, recycling C&D waste proved more viable, with favorable indicators. Implementing a recycling plant in Lahore could save USD 2.53 per ton in resource costs and mitigate significant environmental impacts. This study recommends that policymakers in developing countries prioritize C&D waste recycling to enhance sustainability and support the transition to a circular economy. The findings provide valuable insights for developing effective waste management strategies, contributing to environmental conservation and economic efficiency. These recommendations guide future initiatives for sustainable C&D waste management, promoting a greener and more resilient urban environment. Furthermore, this study underlines the potential of C&D waste recycling to contribute significantly to achieving Sustainable Development Goals (SDGs), particularly sustainable cities (SDG 11), responsible consumption and production (SDG 12), and climate action (SDG 13).

Keywords: C&D waste; circular economy; sustainability; resource recovery; waste management

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1. Introduction

Construction is one of the major sectors worldwide that contributes greatly to the economy. The global construction industry was valued at USD 9.7 trillion in 2022 and will grow to USD 4.5 trillion in 15 years [1]. Simultaneously, the utilization of natural resources significantly contributes to global climate change and global warming [2]. The construction sector consumes 50% of the world's natural resources and causes 20% of global greenhouse gas (GHG) emissions [3]. In addition, the rapid increase in the population resulted in the massive expansion of the construction sector, putting pressure on the environment and human health. Construction activities also generate 30% to 40% of the total solid waste worldwide [4]. Construction and demolition (C&D) waste refers to the debris generated during construction, renovation, and demolition activities, primarily consisting of concrete, bricks, and wood [5]. The building-making process directly produces construction waste, while the degrading process of the building produces demolition waste. Anthropogenic activities or natural processes like floods, hurricanes, and earthquakes completely or partially remove existing structures, producing C&D waste [6].

The global C&D waste generation rate is 3 billion tons annually, and it is continuously increasing. China is leading in C&D waste generation, with 1.1 billion tons annually due to rapid urbanization and a large population [7]. Urbanization due to population movement from rural areas to urban centers is the main reason for high C&D waste worldwide. According to the United Nations' projection, the world's population will rise from 8.2 billion in 2024 to 10.2 billion by mid-2080s, which will have immense environmental impacts [8]. Major cities require more infrastructure and buildings to accommodate the growing population. This necessitates the extraction of more natural raw materials from the earth, which in turn disrupts the global carbon cycle. C&D waste is increasingly becoming a significant issue for developing countries, primarily due to the mismanagement of unskilled labor and improper handling of solid waste [9]. Rather than just contributing to C&D waste, urbanization also plays a significant role in climate change, primarily due to industrialization, transportation, and energy consumption [10].

In developed countries, C&D waste contributes only 25% of total solid waste [11]. Developed countries have implemented various strategies, primarily the 3Rs (Reduce, Reuse, and Recycle), to reduce the volume of C&D waste. The next step after achieving the 3Rs is the circular economic concept. A circular economy is an alternative to the linear economy, which degrades the environment by intensively extracting natural resources [2]. In Europe, much C&D waste goes into recycling facilities, reducing environmental burden and contributing to the circular economy. Some European countries are close to achieving zero landfilling, like the United Kingdom, Germany, and the Netherlands [12]. The developed world implements sustainable approaches in C&D waste management to achieve the circular economy concept. Developing countries like Pakistan have limited understanding of the circular economy concept during their transition from pre-industrial to industrial economies [13]. There are multiple statistics regarding solid waste, but the main problem is handling it efficiently.

Pakistan generates around 49.6 million tons of solid waste annually, with an annual growth rate of 2.4%. Only Karachi produces 16,500 tons of solid waste daily [14]. The second waste statistic indicates that Pakistan generates 30 million tons of solid waste annually. The Government of Pakistan (GoP) stated that Pakistan generates 20 million tons of solid waste annually. Karachi has 9000 tons, and Lahore has 6000 tons of solid waste daily [15]. Lahore, the most populous city in Punjab, generates around 400 tons of C&D waste daily due to rapid urbanization [16]. Despite having a comprehensive MSW management system through LWMC, the city lacks a C&D waste recycling facility. These dumping sites release different GHGs, contributing to the city's smog formation [17].

A comprehensive evaluation of the impacts, utilizing advanced techniques such as life cycle assessment (LCA), from these dump sites will aid in determining the most effective method for managing C&D waste in Lahore city. The study selected the ReUrban D5100 recycling plant from India as the baseline scenario for Lahore city, as there is no recycling plant for C&D waste in the city. This recycling plant generates three products: recycled aggregate, recycled sand, and recycled soil. The plant's capacity is 500–600 tons daily, which aligns with the city's daily C&D waste generation. The plant was selected due to its location and capacity relevance, and Pakistan shares the same geographical features and waste characteristics as India. The ReUrban D5100 plant is a European company CDE Group product, and is already operating in India.

LCA is an innovative tool that is used to measure the environmental impacts of any product or service at any stage [18]. This tool can predict the most suitable plan for any environmental damage or benefit. It helps decision-makers or administration [19]. This study applied LCA to evaluate the environmental impacts of C&D waste management in Lahore, Pakistan. It mainly focused on comparing recycling and landfill scenarios to provide actionable insights for improving waste management practices in the region, specifically Pakistan. It also aids in the decision-making process for waste management plans. Over the last ten years, LCA has grown from energy analysis to a complete environmental impact assessment tool [20]. The International Organization for Standardization (ISO) described the framework and principles of LCA [21]. The construction industry uses natural resources and produces GHG and particulate matter. C&D waste from this industry is a problem in rapidly urbanizing developing countries like Pakistan. Particulate matter and other pollutants from the construction sector contribute to smog in Lahore, yet limited studies have addressed C&D waste management within the city's specific socio-economic and waste management context. Like developed countries with established recycling systems, Lahore has no separate facility for C&D waste recycling.

This study presents a novel integrated framework combining LCA and Life Cycle Costing (LCC) tailored explicitly for developing urban contexts like Lahore, Pakistan. Unlike previous studies that typically consider generic recycling scenarios, this research uniquely incorporates local energy mix scenarios (including solar energy integration), localized waste composition, and economic indicators relevant to developing urban environments. This study goes beyond existing frameworks to offer concrete insights tailored to complex challenges faced by urban centers in developing countries. It highlights how C&D waste recycling can help mitigate environmental, smog, and urbanization problems in Lahore. This study can be a replicable model for other similar developing cities transitioning towards sustainable waste management and a circular economy.

2. Materials and Methods

This study involved two types of analyses: environmental and economic. The environmental analysis evaluated the Life Cycle Impact Assessment (LCIA) categories to determine the overall environmental impacts, while the economic analysis focused on calculating the capital cost of the recycling plant and its associated benefits. The sustainability assessment of recycling practices is expected to aid in managing C&D waste in Lahore city. The ReUrban D5100 recycling plant (a product of CDE Group, Ireland), currently operational in Delhi, India, was selected as a baseline scenario for Lahore due to geographical proximity and similar waste management challenges.

The selection of an Indian-based recycling plant was due to the unavailability of a plant in Pakistan. For the validity and relevance of this comparison, localized adjustments were made to the model for differences between the two countries. Waste composition data were collected by direct sampling and reported by LWMC and were adjusted into the

model. Energy mix parameters were updated as per the Pakistan Energy Outlook Report 2021–2030 [22] to reflect actual grid composition and renewable energy potential in Lahore. All these adjustments were made in the scenario to ensure a realistic representation of local conditions, improving both accuracy and applicability of the comparative analysis. This recycling plant generates three products: recycled aggregate, recycled sand, and recycled soil. The plant's capacity is 500–600 tons daily, which aligns with the city's daily C&D waste generation.

2.1. Study Area

This study focuses on C&D waste management in Lahore, the largest city in Punjab, Pakistan. Lahore is in the North-East of Pakistan, at 74.3587° N longitude and 31.5204° E latitude. The city has a total area of 1772 km^2 and a population of 11.12 million, with a population density of 6275 per km^2 [23]. Unfortunately, there is no recycling plant in Lahore for C&D waste management, and all waste goes to landfills. LWMC divides the city into eleven towns, and the total waste generation is 6000 tons daily. C&D waste constitutes 7.63% of the total MSW, with approximately 400 tons generated in the eleven towns of Lahore.

2.2. Life Cycle Assessment (LCA)

The GaBi software (version 9.2.1) was used for the analysis and integration into the local context, including the composition of C&D waste and the region's energy mix. Surveys and interviews with LWMC workers gathered primary data on waste generation rates, transportation distances, and operational practices. Secondary data, such as emission factors and energy consumption, were sourced from the GaBi database and relevant literature. The ISO has provided two standards (ISO-14040 and ISO-14044) to complete LCA study [21]. The ISO standards have four main parts (shown in Figure 1): (i) goal and scope, (ii) life cycle inventory analysis, (iii) life cycle impacts assessment, and (iv) interpretation. The following subsections describe each step.

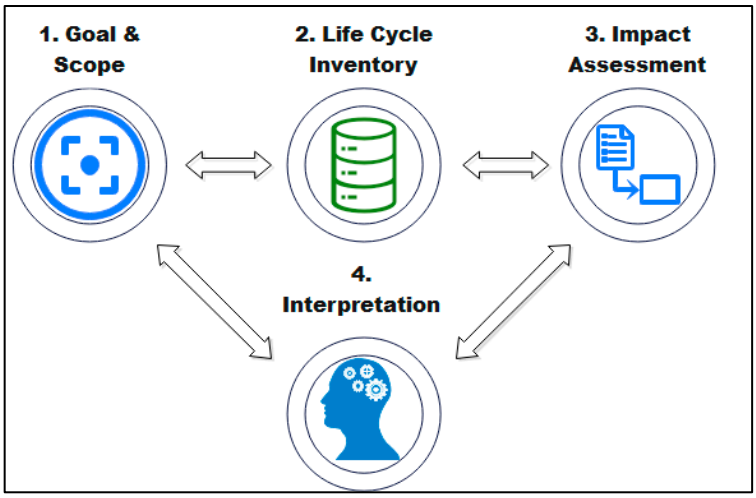


Figure 1. Life cycle assessment framework (ISO-14040).

2.3. Goal and Scope

The first step in conducting an LCA study is to define the objective and scope of the study, including the system boundary. This step briefly describes the product's life cycle and the purpose of the LCA study. The study's goal and scope also dictate the inclusion of certain processes [24–26]. This comparative LCA study aimed to identify the best solution for C&D waste management in Lahore, with a gate-to-grave approach focusing on energy

consumption, resource use, emissions, and overall environmental impact. The functional unit (Clause 4.2.3.2 of ISO 14044:2006) is a crucial step in LCA, providing a unified basis for comparison throughout the study [27]. The functional unit of this study was selected as 1 ton of C&D waste, including concrete, bricks, and demolition debris, based on the primary data from LWMC for both recycling and landfill scenarios.

2.3.1. System Boundary

The system boundary adopted in this study follows a gate-to-grave approach, encompassing the transportation of C&D waste from designated collection points to the recycling plant and the recycling processes within the plant (Figure 2). Inputs include diesel and electricity for transportation and plant operation, while outputs include marketable recycled materials (recycled aggregate, recycled sand, and recycled soil) and emissions to air, water, and soil. Furthermore, the concept of 'avoided burden' was quantified by assuming a 100% substitution rate of recycled aggregates for virgin aggregates, based on market practices and existing recycling standards. The calculations included emission factors and resource use for virgin material extraction from established databases (e.g., Ecoinvent), thus reflecting realistic environmental savings. This system boundary ensures that all relevant life cycle stages are covered in the environmental and economic assessments, as stated by ISO 14040 and ISO 14044. Clause 4.2.3.3 (ISO 14044:2006) clearly describes the outline for system boundary selection. C&D waste recycling is also credited with a huge advantage of avoiding the burden of virgin raw material. Avoided burden is the environmental benefit achieved by substituting recycled C&D materials for virgin resources, reducing emissions and resource depletion.

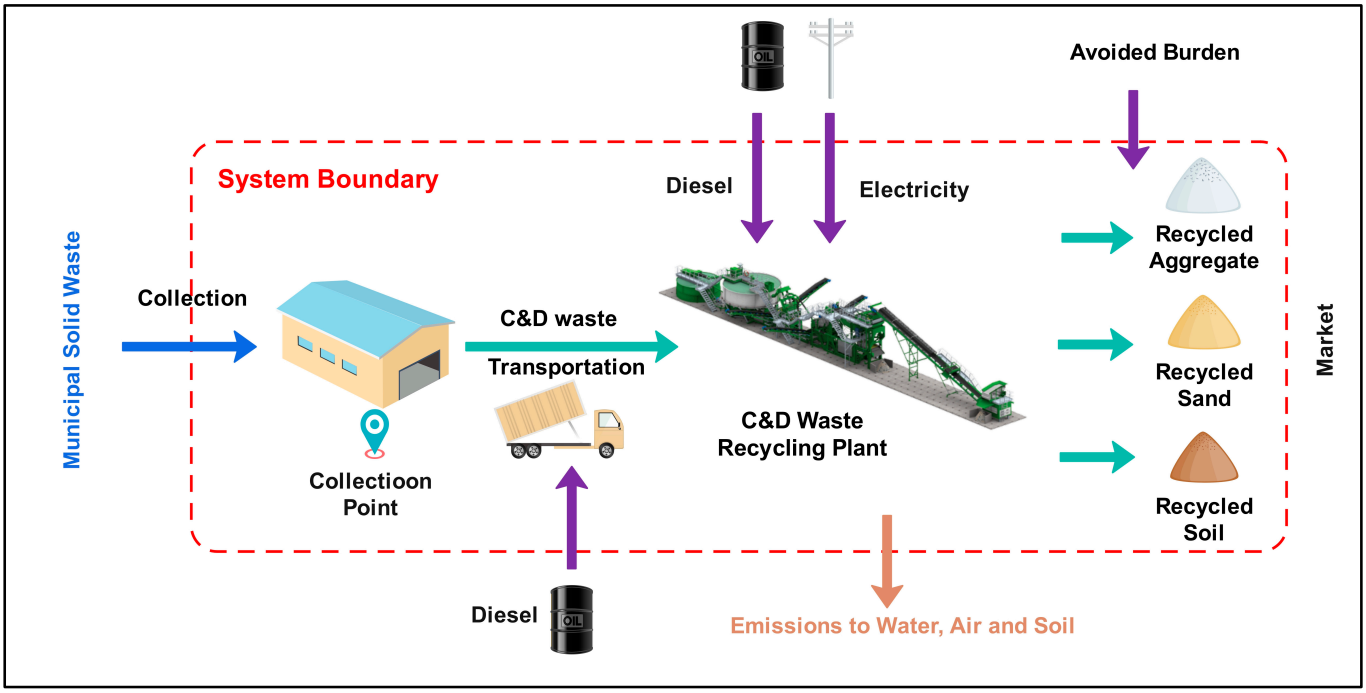


Figure 2. System boundary of C&D waste recycling facility.

2.3.2. LCA System Model

The LCA inventory involves various unit processes that complete the system. Each unit may have one output or multiple outputs to implement LCA calculations. A system model divides and breaks the outputs and multi-output unit processes, integrating them with the system to obtain unified results [26]. Two system models in the Eco-invent database calculate LCA from the same inventory data, and each model uses different assumptions to

evaluate the environmental impacts [28]. Attributional and consequential LCAs are the two models through which any environmental assessment can be carried out. The attributional model approximates the portion of the environmental impacts attributed to the product [29]. The attributional model mainly focuses on assessing a product's environmental impacts at its present state [30].

In contrast, the consequential model calculates the possible outcomes or impacts due to changes in product demand [31]. Regional and local economic factors significantly influence consequential models, posing challenges in communicating their outcomes. At the same time, attributional approaches are simple and thus can produce more interpretable results [26]. The present study selected an attributional model due to the limited availability of C&D waste management data in Pakistan. Secondly, there is no recycling facility for C&D waste in the study area. Thirdly, this study justifies the attributional model by comparing landfilling and recycling of C&D waste with less available data.

2.4. Inventory Analysis

The inventory analysis (Clause 4.3 of ISO 14044:2006), a crucial step in the comprehensive LCA, involves entering all inputs and outputs related to different processes in the LCA software (GaBi version 9.2.1) [24]. The data for the current study were obtained from both market sources and in-built databases of GaBi software, as shown in Table 1. The reference flow was adjusted according to the actual mass of the product and characterization. Quantification of C&D waste was also carried out. According to LWMC, 1 ton (Functional unit) of C&D waste in Lahore contains 800 kg of demolition waste and 200 kg of construction waste. The transportation unit was also customized according to both landfill and recycling scenarios. After customization, water, diesel, and electricity consumption were added as inputs. Finally, the emissions after the whole process were added manually to assess accurate results. Data were collected through interviews and article searching, with primary and secondary data important for the study's comparative nature. Primary data were collected from interviews with concerned authorities about waste collection in Lahore, specifically from LWMC workers who closely follow C&D waste management. Different reports were also collected from LWMC to assess required inventory data [16]. Secondary data were collected from literature, including research articles, academic reports, scientific journals, websites, organizational reports, and print and electronic media [32–34]. Relevant data were then extracted and customized for the Pakistani context.

Table 1. Inventory data of 1 ton C&D waste landfill and recycling.

Landfilling of CDW			
Parameter	**Unit**	**Value**	**References**
Inputs			
Construction waste	kg	200	Present Study
Demolition waste	kg	800	Present Study
Ground water	kg	80	[32]
Diesel	MJ	27	Ecoinvent database
Electricity	kWh	0.013	Ecoinvent database
Outputs			
Construction waste	kg	200	Present Study
Demolition waste	kg	800	Present Study
BOD_5	g	18.16	[35]
NH4–N	g	32.08	[35]
Sulfates	g	32.4	[35]
Ca	g	12	[35]

Table 1. *Cont.*

Landfilling of CDW			
Parameter	**Unit**	**Value**	**References**
Na	g	39.6	[35]
Cr	g	0.0084	[35]
Cd	g	0.00216	[35]
Cu	g	0.00224	[35]
Zn	g	0.02208	[35]
Pb	g	0.07896	[35]
Ni	g	0.00472	[35]
As	g	0.01864	[35]
Hg	g	0.000112	[35]
Recycling of CDW			
Inputs			
Construction waste	kg	200	Present Study
Demolition waste	kg	800	Present Study
Electricity	kWh	3.68	[32]
Diesel	kg	0.7	[32]
Water requirement	liters	15	[32]
Land occupied	m^2	20	[32]
Lubricant	kg	0.00144	[32]
Outputs			
Recycled aggregate	kg	500	Present Study
Recycled Soil	kg	250	Present Study
Recycled Sand	kg	250	Present Study
Wastewater	kg	5	[32]

2.4.1. Transport

In Lahore, landfills are located on the city's outskirts, with an assumed average distance of 25 km from C&D waste generation sites. Lahore has two landfill sites: Mehmood Booti and Lakhodair, near Ring Road Lahore. LWMC currently uses fifty-three hectares of land for waste disposal at the Lakhodair landfill site. C&D waste recycling sites are supposed to be in the city center to reduce the impact of transportation on the environment, with an average distance of 12.5 km from waste generation sites. Recycling sites require less land area than landfills and can be closer to the waste generation sites. By using recycled material as an alternative, C&D waste recycling reduces the transportation of natural materials from extraction sites [33]. The same distance was taken as the transportation of recycled material back into the market.

2.4.2. Electricity

Electricity use was also customized according to regional electricity production and consumption to achieve implementable results. There are two scenarios considered for electricity use in the recycling plant: grid mix and solar. In the baseline scenario, grid-mixed electricity is used in recycling plants. In Lahore's electricity grid mix, there are many sources (non-renewables and renewables) of electricity production. Almost 2/3 of the total grid mix electricity comes from coal and gas, and the remaining 1/3 comes from low-carbon sources like hydro, nuclear, wind, solar, and biomass [36]. In the second scenario, recycling plants expect solar electricity to serve as an alternative to grid mix electricity. Solar electricity is assumed to have less environmental impact than grid-mix electricity in this study.

2.5. Life Cycle Impact Assessment

Life cycle impact assessment, abbreviated as LCIA (Clause 4.4—ISO 14044), is a crucial step in LCA and depends on the life cycle inventory data entered into the software. LCIA includes midpoint and endpoint assessments that break down the results into subcategories. The ReCiPe 2016 method was used in this study due to its major worldwide acceptance [37]. The ReCiPe 2016 method was selected for this study because it provides a comprehensive LCIA framework that integrates both midpoint and endpoint evaluations. This dual approach offers a comprehensive view of environmental impacts, allowing decision-makers to assess both specific environmental flows (midpoint) and broader areas of protection, such as human health, resource scarcity, and ecosystem quality (endpoint) [38]. The combination of these viewpoints enables a better understanding of the environmental trade-offs between recycling and landfill options. The method allowed for various impact modeling possibilities. It was used to study various impact assessment categories, enabling a comprehensive evaluation of every aspect of the life cycle.

2.5.1. ReCiPe 2016

ReCiPe is widely used as an LCIA method worldwide to evaluate different studies. It was initially developed in 2008 by Goedkoop and Huijbregts [38] based on CML 2001 and Eco-indicator 99. ReCiPe 2016 is an updated version of ReCiPe 2008, including extra damage pathways and impact categories. ReCiPe (2016) developed a harmonized technique to cover all the characterization factors using one LCIA method [39]. In ReCiPe 2016, different characterization factors were included to represent LCA results on a global scale. There are two methods in this LCIA approach to assessing characterization factors: midpoint assessment and endpoint assessment [38]. The midpoint approach was assessed from the CML 2001 guide, and the endpoint was derived from the Eco-indicator 99 guide [40]. There are three perspectives in ReCiPe 2016: (i) Individualistic perspective, (ii) Hierarchist perspective, and (iii) Egalitarian perspective [38]. The Individualistic perspective is a short-term (around ten years), optimistic, and adaptable approach for humans compared to other perspectives. The Hierarchist perspective relies on scientists' consensus regarding the impact mechanism time frame (around 100 years). Finally, the Egalitarian perspective is based on the longest time frame (around 1000 years) and comprehensive data available for all impact categories [38].

2.5.2. Midpoint Assessment

ReCiPe 2016 has in-built midpoint and endpoint assessment methods to calculate LCA results. Midpoint characterization factors were found along the impact pathways, where each category was assigned a specific environmental flow [38]. Midpoint assessment is directly linked with environmental flows having less parameter uncertainty. The midpoint characterization factor is denoted by CFm. Sometimes, policymakers require midpoint modeling and endpoint assessment to track the cause–effect chain [41]. There are a total of 18 impact categories in the typical ReCiPe approach, but only 10 categories were selected to capture the environmental impacts associated with C&D waste management.

These categories were assumed to be more relevant to C&D waste management processes, such as transportation, electricity recycling plants, and diesel consumption. Selected categories are climate change as global warming potential (GWP), fine particulate matter formation potential (FPMFP), fossil depletion potential (FDP), freshwater eutrophication potential (FWEP), ionizing radiation potential (IRP), land use potential (LUP), metal depletion potential (MDP), photochemical ozone formation potential (POFP), stratospheric ozone depletion potential (SODP), and terrestrial acidification potential (TAP). This selec-

tion ensures that critical issues such as climate change, smog, particulate matter formation, and resource depletion, which are the key challenges for Lahore, are adequately assessed.

2.5.3. Endpoint Assessment

Midpoint assessment usually represents three areas of protection: human health, resource scarcity, and ecosystem quality. All the subcategories of the endpoint (22 categories) were selected for C&D waste evaluation and interpreted as endpoint assessment in terms of human health, resource scarcity, and ecosystem quality. Endpoint assessment has 22 subcategories, which are totally reliant on the midpoint results. These subcategories are interconnected with each other, and therefore, selection or assumption is not possible. Endpoint characterization factors are easier to understand and interpret than the midpoint due to relevant damage categories [38]. Endpoint characterization factors (*CFe*) originated from midpoint characterization factors (*CFm*) with a constant factor per impact category [42,43].

$$CFe_{x,a} = CFm_x \times F_M \rightarrow {}_{E,a} \quad (1)$$

where a represents the protection area, x represents the significant damage category, and $F_M \rightarrow {}_{E,a}$ represents the mid-to-endpoint constant conversion factor. The constant factor usually remains the same in the midpoint assessment due to identical environmental mechanisms for each stressor. Therefore, there are more chances of uncertainties due to damage modeling in endpoint assessment [41]. Endpoint results give normalized results that can be calculated in a single score without any unit; simple, practical, and easy to present.

2.6. Uncertainty Analysis

Uncertainty analysis was employed using sensitivity analysis and Monte Carlo analysis to test the robustness of the C&D waste recycling results. Sensitivity analysis was performed on key parameters within the defined system boundary, including electricity consumption, diesel consumption, and C&D waste transportation. These parameters were adjusted by $\pm 10\%$ change to identify their impacts on the selected midpoint categories of the system. Adjusting these contributors enables the analysis of how operational variability affects performance indicators and selected impact categories. Monte Carlo analysis was also performed on the selected impact categories to test the robustness of the results further.

2.7. Data Quality Assessment

Data quality assessment (Clause 4.2.3.6 of ISO-14044) was assessed using a pedigree matrix analysis, as suggested by Weidema and Suhr Wesnaes [44]. This approach evaluates data quality on five dimensions: reliability, temporal correlation, completeness, geographical correlation, and technological correlation. Each dimension is scored from 1 (excellent quality) to 5 (poor quality), with an aggregate score indicating the data quality. The pedigree matrix scores for key inputs and outputs are summarized in Table 2 based on the following considerations: (1) Primary data from LWMC surveys and field visits scored high reliability scores because of direct collection from relevant stakeholders. Secondary data, like emission factors from GaBi, were rated somewhat lower due to possible regional differences. (2) Most data points are documented well, with minor gaps in secondary sources for certain emissions, giving intermediate scores for completeness. (3) Data were collected or referenced from recent studies and databases (2018–2024) with assured temporal relevance. (4) Data were adjusted for the Lahore context; however, some inputs, such as recycling processes, were adopted from Indian studies and also provided moderate geographical scores. (5) Technology in data sources (like ReUrban D5100 recycling plant) corresponds with the study scenarios, therefore ensuring technological correlation.

Table 2. Pedigree matrix data quality analysis of C&D waste.

Parameter	Reliability	Completeness	Temporal Correlation	Geographical Correlation	Technological Correlation
Construction Waste (Landfilling)	1	1	1	2	1
Demolition Waste (Landfilling)	1	1	1	2	1
Electricity (Landfilling)	2	2	2	3	2
Diesel (Landfilling)	2	2	2	3	2
Construction Waste (Recycling)	1	1	1	2	1
Demolition Waste (Recycling)	1	1	1	2	1
Electricity (Recycling)	2	2	2	3	2
Diesel (Recycling)	2	2	2	3	2
Recycled Aggregate	1	1	1	2	1
Recycled Sand	1	1	1	2	1
Recycled Soil	1	1	1	2	1

The pedigree matrix table showed the quality of the inventory data applied in this study based on five key dimensions. For inputs like C&D waste, high reliability scores (1) were assigned because these were directly collected from primary sources, including field surveys and interviews with LWMC staff. Completeness was also rated high (1) as the data provided an accurate snapshot of local waste composition. Geographical correlation scored lower (2) or (3) for several parameters from Indian scientific studies, depending upon regional differences. Temporal correlation for many parameters was rated high (1) because the data are recent and relevant to the study timeframe. For secondary data (electricity or diesel emission factors), the scores were slightly lower for reliability (2) and geographical correlation (3), adapted from international databases like Ecoinvent and research in different socio-economic contexts. Outputs such as recycled aggregates and soil derived from the present study were extremely reliable and completely matched with the regional context of Lahore. This pedigree matrix analysis demonstrates the robustness of the data utilized while recognizing the limits of secondary data adaptation. It provides a foundation for determining the inventory's weaknesses and strengths and recommending future changes in information collection and verification.

2.8. Life Cycle Cost (LCC) Analysis

LCC is the assessment of costs over the entire life cycle of a product. LCC consists of two types of costs: (i) Internal cost (IC) and (ii) External cost (EC). It is mostly associated with products that have longer life cycles [45]. LCC gives users, producers, and policy-makers an economic perspective on that product. LCC can have negative and positive costs [46]. The low LCC of any product is a win-win situation for any societal stakeholder. LCA and LCC had the same functional units and system boundaries in this study. LCC was calculated using Equation (2) [42].

$$LCC = IC + EC \quad (2)$$

2.8.1. Internal Cost

Internal cost (IC) comprises two main types: initial capital investment (ICI) and operational cost (OC). The initial capital investment is the cost of the equipment, installations, and construction. Operational costs included management costs (CM), taxes (Ct), transportation costs (Ctr), and manufacturing and purchasing costs. Purchasing costs included utilities (Cu) and raw materials (Cr). Manufacturing costs comprise maintenance costs (Cm) and labor costs (Cl). IC was calculated using Equation (3) [42,43].

$$IC = CM + Ct + Ctr + Cu + Cr + Cm + Cl \quad (3)$$

2.8.2. External Cost

The External cost (EC) represents the potential environmental damage costs associated with emissions from the C&D waste management processes [45]. EC is calculated using an equation that calculates the damage cost based on the willingness to avoid environmental harm [43]. The equation used for EC computation is:

$$EC = \sum_{k=1}^{7} Ck \times Ek, lc \quad (4)$$

In this equation, Ck represents the cost coefficient of emission k, which includes CO_2, CH_4, CO, NMVOC, PM, NO_x, and SO_2. The coefficients were derived from published literature [41]. Ek, lc represents the life cycle amount of emission k, determined using an inventory data modelled in GaBi software [47]. This software facilitated the calculation of emissions for each life cycle stage. By integrating IC and EC into the LCC framework, this study provides a comprehensive evaluation of the economic implications of C&D waste management.

3. Results

The results were evaluated through the ReCiPe 2016 LCIA method, selecting 10 midpoint categories, 22 endpoint categories, and three single scores. Positive values in the results represent an increase in environmental emissions, while negative values show the reduction or saving of environmental emissions in the environment, as shown in Table 3.

Table 3. ReCiPe midpoint results of landfill and recycling.

Impact Categories	Abbreviations	Unit	Landfill	Recycling
Climate change	GWP	kg CO_2 eq.	4.84×10^{0}	-3.71×10^{1}
Fine Particulate Matter Formation	FPMFP	kg $PM_{2.5}$ eq.	7.26×10^{-3}	-1.11×10^{-1}
Fossil depletion	FDP	kg oil eq.	1.77×10^{0}	-9.76×10^{0}
Freshwater Eutrophication	FWEP	kg P eq.	1.21×10^{-6}	-3.35×10^{-5}
Ionizing Radiation	IRP	kBq Co-60 eq. to air	3.04×10^{-4}	-7.83×10^{-2}
Land use	LUP	Annual crop eq. per year	3.25×10^{-3}	-8.13×10^{-1}
Metal depletion	MDP	kg Cu eq.	9.33×10^{-5}	-7.85×10^{-3}
Photochemical Ozone Formation	POFP	kg NO_x eq.	5.02×10^{-2}	-8.20×10^{-2}
Stratospheric Ozone Depletion	SODP	kg CFC-11 eq.	4.92×10^{-7}	-7.72×10^{-6}
Terrestrial Acidification	TAP	kg SO_2 eq.	2.22×10^{-2}	-2.70×10^{-1}

3.1. Midpoint Assessment Results

The study conducted a midpoint assessment by selecting 10 midpoint indicators, as outlined in Table 3. Each indicator represents an individual score as a contribution

to environmental emissions. The landfilling of C&D waste yielded higher results than the recycling of the same waste. Recycling has the highest negative results, which show the enormous potential to reduce the environmental emissions from C&D waste. All the impact categories of recycling, except for human toxicity, non-cancer, and marine ecotoxicity, exhibit lower values than those of landfills. The following are the categories that have the highest impact on the environmental burden.

3.1.1. Climate Change (GWP)

Climate change has the highest impact and continuously influences the environment. The carbon footprint has been calculated to evaluate the ultimate impacts in this category. Landfilling C&D waste has higher results than recycling C&D waste. One ton of C&D waste landfilling generates 4.84×10^{0} kg CO_2 eq. while C&D waste recycling saves the -3.71×10^{1} kg CO_2 eq. Recycling has some individual impacts but results negatively due to the avoided burden of natural aggregates. Lahore generates over 400 tons of C&D waste daily, resulting in a daily landfill impact of 1.94×10^{3} kg CO_2 eq. Recycling, on the other hand, can save 1.48×10^{4} kg CO_2 eq.

3.1.2. Fine Particulate Matter Formation Potential (FPMFP)

The fine particulate matter formation impact category shows the results of organic and inorganic particles (NO_x, NH_3, VOC, and SO_3) that formed due to transportation and other activities in the study. The landfill yielded very positive results, indicating a higher environmental burden compared to recycling. Recycling showed savings of 1.11×10^{-1} kg $PM_{2.5}$ eq. Meanwhile, landfills showed a burden of 7.26×10^{-3} kg $PM_{2.5}$ eq.

3.1.3. Fossil Depletion Potential (FDP)

All the consumption of fossil fuels in transportation has accumulated in this category. Transportation of C&D waste from the waste source to the landfill site contributes greatly to diesel consumption, ultimately negatively impacting the environment. One ton of C&D waste in the landfill contributes 1.77×10^{0} kg of oil equivalent to the potential for fossil fuel depletion. One ton of recycling shows the -9.76×10^{0} kg oil eq. This means that recycling will save almost 1×10^{1} kg of oil, eq., from one ton of C&D waste, which is an avoided burden. Positive FDP results showed that C&D waste recycling has much potential to reduce environmental impacts. Fossil fuels are important drivers of any economy and society, such as energy use in different sectors, transportation of different goods, and climatic impacts.

3.1.4. Freshwater Eutrophication Potential (FWEP)

FWEP occurs when anthropogenic activities lead to an increase in phosphorus in water bodies. Due to soil erosion, the phosphorus rate increases in freshwater bodies. It affects the living organisms in freshwater, like a reduction in fish and other aquatic life. Plants in freshwater uptake high quantities of nutrients, so these organisms create problems and reduce biodiversity. Landfilling of C&D waste also contributes to FWEP, as one ton of C&D waste shows 1.21×10^{-6} kg P eq. C&D waste recycling shows that it will save 3.35×10^{-5} kg P eq. from one ton of recycling.

3.1.5. Ionizing Radiation Potential (IRP)

IRP represents the potential for radiation to cause direct or indirect harm to living organisms. This indicator is also very important in any anthropogenic activity to measure whether it is safe or has an impact on humans. High impacts of IRP can burn or quickly cause the death of any living organism. One ton of C&D waste landfilling causes 3.04×10^{-4} kBq Co-60 eq. to air, while one ton of C&D waste recycling saves

7.83×10^{-2} kBq Co-60 eq. to air. This indicates that recycling yields significant benefits by reducing environmental burdens.

3.1.6. Land Use Potential (LUP)

LUP is the occupation of land for different activities that affect biodiversity. This impact category holds significant importance for biodiversity and the ecosystem, as it reflects the conversion of land into commercial or other harmful replacements for vegetation cover. Land occupation will decrease annual crop production after its use for other activities. One ton of C&D waste landfilling decreases 3.25×10^{-3} annual crop eq. per year, while recycling one ton of C&D waste will save 8.13×10^{-1} annual crop eq. per year. Recycling positively impacts the environment, while landfills result in negative impacts because of an environmental burden on society.

3.1.7. Metal Depletion Potential (MDP)

Metals are critical raw materials, but their extraction through mining causes significant environmental impacts. In this study, landfills showed negative MDP impacts on the environment, while recycling resulted in positive impacts due to the savings from mining. The landfill showed 9.33×10^{-5} kg Cu eq. per ton C&D waste, while recycling of C&D waste has negative values -7.85×10^{-3} kg Cu eq. per ton, which means it will save or reduce these quantities due to recycled material.

3.1.8. Photochemical Ozone Formation (POFP)

Photochemical ozone formation (POFP) is the impact category that encompasses the formation of ozone at the ground level because of various oxides, sunlight, and organic compounds, particularly NO_x. Photochemical ozone affects human health and ecosystems due to its presence at ground level. This potential is caused by the burning of fossil fuels and energy use in the different sectors of society. It also plays a vital role in smog formation during winter and atmospheric pollution. One ton of C&D waste landfilling releases 5.02×10^{-2} kg NO_x eq. in the environment. C&D waste recycling showed -8.20×10^{-2} kg NO_x eq., positively impacting the environment.

3.1.9. Stratospheric Ozone Depletion Potential (SODP)

SODP is due to anthropogenic activities and emissions of harmful substances that lead to ozone depletion. Chlorofluorocarbons (CFCs) have been the main contributors to ozone depletion for many years. These substances react with the ozone layer in the stratospheric region and cause negative burdens on the environment. Ozone depletion causes many problems like global warming, temperature increase, climate change, human health issues, and biodiversity loss. In this study, stratospheric ozone depletion potential is also accounted for when evaluating the landfilling and recycling of C&D waste. Landfilling of one ton of C&D waste showed 4.92×10^{-7} kg CFC-11 eq., while recycling showed -7.72×10^{-6} CFC-11 eq., which means recycling will save the ozone layer from depletion.

3.1.10. Terrestrial Acidification Potential (TAP)

TAP accounts for the gas emissions responsible for the acidification of soil, water, and ground, effects on animals, and biodiversity loss. Different chemicals from soil or water enter biodiversity and affect living organisms. These chemicals enter the environment after some anthropogenic activities. One ton of C&D waste landfilling showed 2.22×10^{-2} kg SO_2 eq., which means it burdens the environment. However, C&D waste recycling showed -2.70×10^{-1} kg SO_2 eq., positively impacting the environment.

3.2. Endpoint Assessment Results

The endpoint assessment evaluated and aggregated different results from the midpoint assessment to conclude on three areas of protection. There are three main categories to consider when deciding on an endpoint assessment: resources, human health, and ecosystem. Endpoint assessment is the normalized form of results that can be easily evaluated to conclude any activity. In this study, landfills showed negative environmental impacts in all three protection areas, as shown in Table 4. Resource consumption has two impact categories: fossil depletion and metal depletion. A one-ton C&D waste landfill utilizes USD 2.34×10^2 only from fossil depletion. The other remaining category, metal depletion, has a negligible impact on the resources. Recycling one ton of C&D waste can save USD 2.53×10^2, reducing environmental burdens and supporting the circular economy. Fossil depletion is also the main contributor to the need for recycling, as a major source of pollution.

Table 4. ReCiPe endpoint results of landfill and recycling.

ReCiPe Endpoints (H)	Landfill	Recycling
Resources (overall impact)	$\mathbf{2.34 \times 10^2}$	$\mathbf{-2.53 \times 10^2}$
Fossil depletion [$]	2.34×10^2	-2.52×10^2
Metal depletion [$]	9.23×10^{-3}	-1.18×10^0
Human Health (overall impact)	$\mathbf{2.98 \times 10^{-3}}$	$\mathbf{-2.86 \times 10^{-2}}$
Climate change, Human Health [DALY]	1.35×10^{-5}	-1.04×10^{-2}
Fine Particulate Matter Formation [DALY]	1.37×10^{-3}	-2.10×10^{-2}
Freshwater Consumption, Human Health [DALY]	6.67×10^{-5}	2.42×10^{-5}
Human toxicity, cancer [DALY]	8.96×10^{-6}	4.98×10^{-5}
Human toxicity, non-cancer [DALY]	1.72×10^{-4}	2.71×10^{-3}
Ionizing Radiation [DALY]	7.76×10^{-10}	-2.00×10^{-7}
Photochemical Ozone Formation, Human Health [DALY]	1.36×10^{-5}	-2.25×10^{-5}
Stratospheric Ozone Depletion [DALY]	7.83×10^{-8}	-1.23×10^{-6}
Ecosystems (overall impact)	$\mathbf{1.04 \times 10^{-5}}$	$\mathbf{-6.69 \times 10^{-5}}$
Climate change, Freshwater Ecosystems [species.yr]	1.48×10^{-10}	-1.13×10^{-9}
Climate change, Terrestrial Ecosystems [species.yr]	5.42×10^{-6}	-4.16×10^{-5}
Freshwater Consumption, Freshwater Ecosystems [species.yr]	7.01×10^{-11}	-5.10×10^{-11}
Freshwater Consumption, Terrestrial Ecosystems [species.yr]	5.42×10^{-7}	3.29×10^{-7}
Freshwater ecotoxicity [species.yr]	2.44×10^{-9}	4.85×10^{-9}
Freshwater Eutrophication [species.yr]	3.25×10^{-10}	-8.97×10^{-9}
Land use [species.yr]	1.15×10^{-8}	-2.89×10^{-6}
Marine ecotoxicity [species.yr]	5.69×10^{-12}	2.08×10^{-8}
Marine Eutrophication [species.yr]	5.09×10^{-12}	-2.52×10^{-10}
Photochemical Ozone Formation, Ecosystems [species.yr]	2.59×10^{-6}	-4.30×10^{-6}
Terrestrial acidification [species.yr]	1.88×10^{-6}	-2.30×10^{-5}
Terrestrial ecotoxicity [species.yr]	2.05×10^{-9}	4.53×10^{-6}

The second endpoint category is human health impact, which is important in any LCA study. Overall, the human health impact of landfills is also more negative than recycling. The human health impact of landfills resulted in 2.98×10^{-3} DALY, which is alarming for society. Recycling has a health impact of -2.86×10^{-2} DALY, which means less burden on the environment and human health. Eight impact categories can contribute to human health. Only two impact categories have major impacts on human health: climate change and fine particulate matter formation. A total of 91% of overall human health impacts in the landfill scenario came from these two categories: 45% from climate change and 46%

from fine particulate matter formation. The other remaining categories have very few negligible impacts. Two categories showed high human health impacts from recycling: human toxicity, cancer, and non-cancer.

The third endpoint assessment category is ecosystem loss due to damage categories or midpoint contributors. There are twelve contributor categories in the overall Ecosystem loss. The overall impact of landfills is 1.04×10^{-5} species/year, while recycling has -6.69×10^{-5} species/year, which means recycling benefits the ecosystem. In the landfill scenario, some categories contribute greatly to overall ecosystem impact, like climate change 5.42×10^{-6} species/year, photochemical ozone formation 2.59×10^{-6} species/year, and terrestrial acidification 1.88×10^{-6} species/year. The remaining categories have very little ecosystem impact compared to these three categories. In recycling, some categories have higher results than the landfill scenario, like freshwater ecotoxicity 4.85×10^{-9} species/year, marine ecotoxicity 2.08×10^{-8} species/year, and terrestrial ecotoxicity 4.53×10^{-6} species/year. The single endpoint scores for both scenarios are represented in Figure 3.

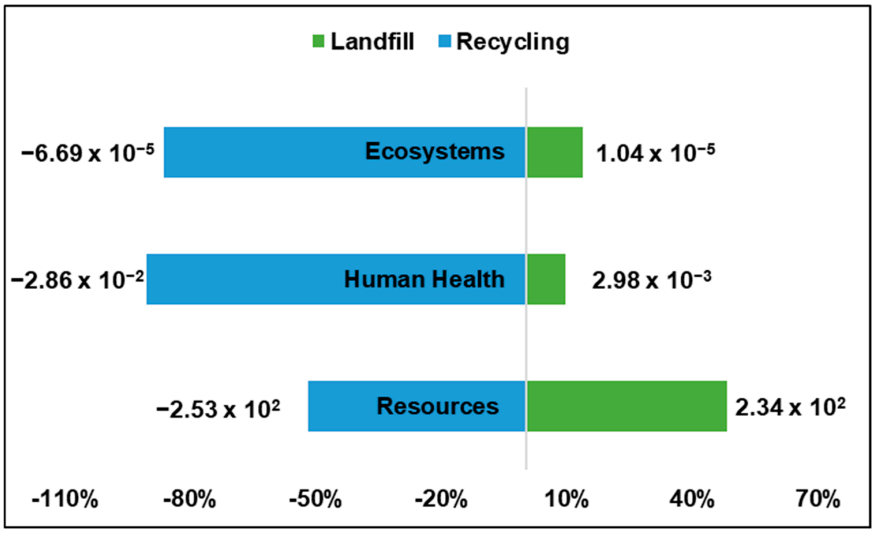


Figure 3. Single score comparison of landfill and recycling.

3.3. Sensitivity Analysis

Sensitivity analysis of the C&D waste management scenarios revealed the variation in environmental impacts due to a ±10% change in key factors, such as diesel, electricity, and transportation distance, as shown in Table 5. Electricity demonstrated the most significant contribution to environmental impact variations. A ±10% variation in electricity resulted in a ±4.42% GWP, ±5.67% FPMP, ±7.13% FWEP, ±9.62% LUP, and ±9.63% IRP. This emphasizes the energy-intensive nature of recycling processes and the importance of incorporating renewable electricity sources, such as solar energy, to mitigate these impacts. Transportation distance also exhibited significant variations, with a ±5.31% change in GWP and ±8.21% in POFP due to the energy demands associated with moving waste to landfills or recycling facilities.

Diesel showed comparatively lower impact variations across most categories, with the highest changes observed in FDP (±1.58%), FWEP (±0.67%), and GWP (±0.28%). These results highlight the critical need to prioritize energy-efficient recycling technologies and optimize transportation logistics to reduce the overall environmental burden of C&D waste management. The findings reinforce the significance of regional energy infrastructure in determining the sustainability of recycling practices, advocating for transitioning to cleaner energy sources to enhance environmental performance.

Table 5. Sensitivity analysis of baseline scenario (recycling with grid mix electricity).

	Diesel	**Electricity**	**Transport**
Variations	±10%	±10%	±10%
GWP	±0.28%	±4.42%	±5.31%
FPMP	±0.17%	±5.67%	±4.16%
FDP	±1.58%	±3.21%	±4.17%
FWEP	±0.67%	±7.13%	±2.20%
IRP	±0.09%	±9.63%	±0.28%
LUP	±0.09%	±9.62%	±0.23%
MDP	±0.26%	±8.87%	±0.69%
POFP	±0.07%	±1.72%	±8.21%
SODP	±0.21%	±5.13%	±4.66%
TAP	±0.19%	±5.47%	±4.34%

The sensitivity analysis in this study focused on key parameters within the defined system boundary, including electricity, diesel, and transportation distance. Factors such as recycling rates and market acceptance were not included in the sensitivity analysis because they lie outside the operational system boundary. However, these parameters are important for understanding the broader aspects of C&D waste recycling. Variations in recycling efficiency can influence the total quantity of recovered materials, while market acceptance directly affects the demand and economic viability of recycled products.

3.4. Monte Carlo Analysis

The Monte Carlo analysis was conducted to assess the uncertainty in midpoint impact categories under the recycling scenario (Table 6). GWP showed a mean impact of -3.71×10^{1} kg CO_2 eq., with a standard deviation (SD) of 4.69%, and ranged between -3.49×10^{1} kg (10th percentile) and -3.93×10^{1} kg (90th percentile). FPMFP averaged -1.11×10^{-1} kg $PM_{2.5}$ eq., with a 5.26% SD. FDP had a mean of -9.76×10^{0} kg oil eq., with a range from -9.09×10^{0} to -1.04×10^{1} kg oil eq. FWEP ranging from -3.15×10^{-5} to -3.52×10^{-5} kg P eq., and IRP from -7.27×10^{-2} to -8.39×10^{-2} kBq Co-60 eq. to air. LUP was found to be -8.13×10^{-1} Annual crop eq. per year, showing limited variability (5.29% SD). MDP ranged from -7.30×10^{-3} to -8.40×10^{-3} kg Cu eq., and POFP from -7.66×10^{-2} to -8.74×10^{-2} kg NO_x eq. While SODP ranged between -7.13×10^{-6} and -8.39×10^{-6} kg CFC-11 eq., and TAP between -2.50×10^{-1} and -2.90×10^{-1} kg SO_2 eq. Overall, the low standard deviations and narrow percentile ranges across all impact categories reveal a high degree of reliability and consistency in the model's outcomes, which assures the environmental benefits of C&D waste recycling even under variable conditions.

Table 6. Monte Carlo analysis of C&D waste recycling (baseline scenario).

Categories	**Unit**	**Default Values**	**SD**	**10%**	**90%**
GWP	kg CO_2 eq.	-3.71×10^{1}	4.69%	-3.49×10^{1}	-3.93×10^{1}
FPMFP	kg $PM_{2.5}$ eq.	-1.11×10^{-1}	5.26%	-1.04×10^{-1}	-1.19×10^{-1}
FDP	kg oil eq.	-9.76×10^{0}	5.33%	-9.09×10^{0}	-1.04×10^{1}
FWEP	kg P eq.	-3.35×10^{-5}	5.21%	-3.15×10^{-5}	-3.52×10^{-5}
IRP	kBq Co-60 eq. to air	-7.83×10^{-2}	5.55%	-7.27×10^{-2}	-8.39×10^{-2}
LUP	Annual crop eq. per year	-8.13×10^{-1}	5.29%	-7.58×10^{-1}	-8.68×10^{-1}
MDP	kg Cu eq.	-7.85×10^{-3}	5.76%	-7.30×10^{-3}	-8.40×10^{-3}
POFP	kg NO_x eq.	-8.20×10^{-2}	5.11%	-7.66×10^{-2}	-8.74×10^{-2}
SODP	kg CFC-11 eq.	-7.72×10^{-6}	5.37%	-7.13×10^{-6}	-8.39×10^{-6}
TAP	kg SO_2 eq.	-2.70×10^{-1}	5.71%	-2.50×10^{-1}	-2.90×10^{-1}

3.5. Main Contributors

The three main contributors to both scenarios (C&D landfill and C&D recycling): energy consumption, transport, and process. Energy consumption included all the electricity and diesel consumed in waste handling. Transport includes the transportation impacts of C&D waste to either a landfill or recycling plant. The process includes the final handling of C&D waste, either through landfill or a recycling process. Both scenarios have different percentages of contribution in the whole life cycle. Transport resulted in the landfill being the major contributor to the landfill due to the distance of the landfill site from the city. Energy consumption is the second main contributor. Some categories result in more than 60% due to transport: TAP, POFP, and FPMFP. Figure 4 represents the contribution of the landfill scenario, while Figure 5 shows the recycling scenario's contribution.

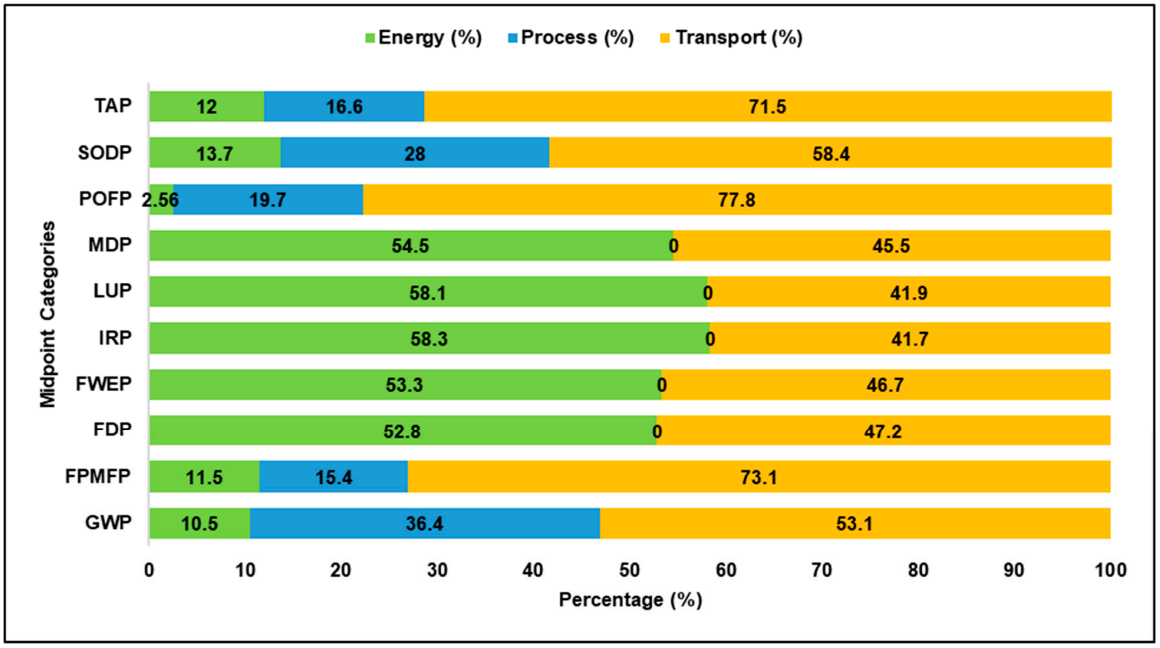


Figure 4. Main contributors in landfill of C&D waste.

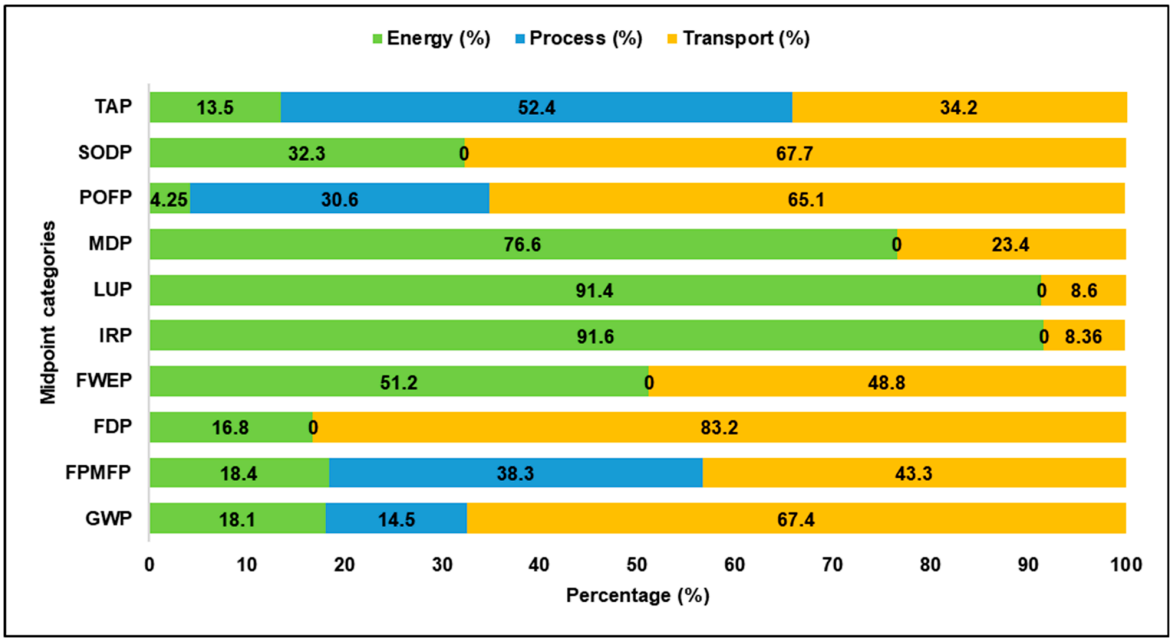


Figure 5. Main contributors in C&D waste recycling.

3.6. Scenarios (Grid Mix Electricity vs. Solar Electricity)

Two scenarios are considered for the recycling plant in this study. The first scenario is a recycling plant with grid mix electricity from Lahore Electricity Supply Company (LESCO), and the second scenario is a recycling plant with solar electricity from solar panels. In the grid mix electricity case, electricity came from different non-renewable and renewable resources like oil, natural gas, coal, hydro, nuclear, solar, and wind, as shown in Figure 6. On the other hand, solar electricity is considered a renewable energy source that reduces the environmental burden. In the scenario analysis, the solar electricity scenario is the best scenario for the recycling plant, based on the midpoint assessment, internal cost analysis, and external cost analysis.

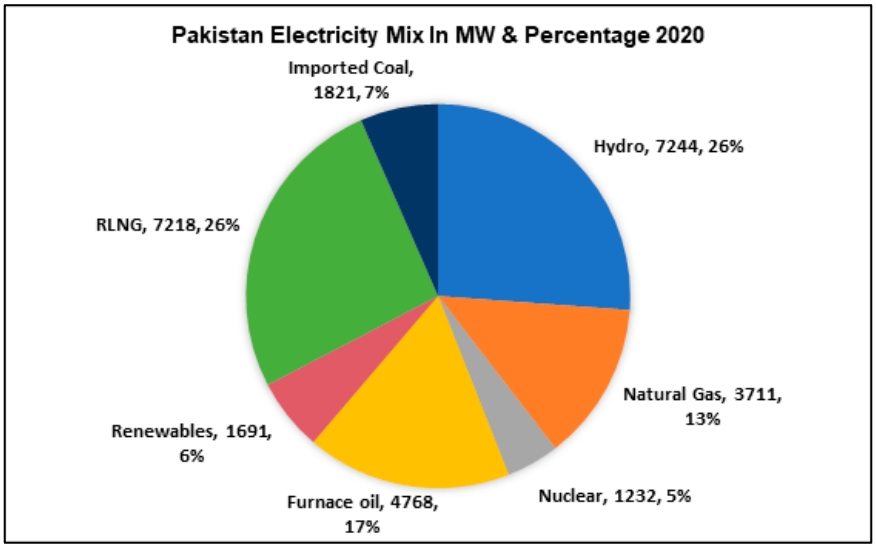


Figure 6. Pakistan's electricity mix 2020 [47].

All the midpoint assessment categories from the grid mix scenario showed less savings than the solar scenario, except the MDP, which is shown in Figure 7. The Grid mix showed -7.85×10^{-3} kg Cu eq, while solar showed -6.17×10^{-3} kg Cu eq. as a saving. This difference in MDP is due to the metals used in solar panel production. In the overall midpoint assessment of both scenarios, there are very few differences in environmental impacts. Some economic indicators were also studied in these two scenarios, and the solar scenario was evaluated as the most suitable. Grid mix has less capital investment than solar, but the solar scenario was economically more feasible during the period. Recycling with solar electricity will save more resources, as it reduces the external cost of the environmental burden.

3.7. Life Cycle Costing

LCC involves internal and external costing that can evaluate whether a project is economically viable. In this case, the C&D waste recycling plant is very efficient in terms of economic indicators. Almost every result from C&D waste recycling came in a negative value, which means this project reduces environmental burdens and avoids impacts due to virgin material in the market. Recycled material replacing new material in the market at a lower price gave positive environmental results. As described earlier in the methodology, LCC is divided into Internal and external costs.

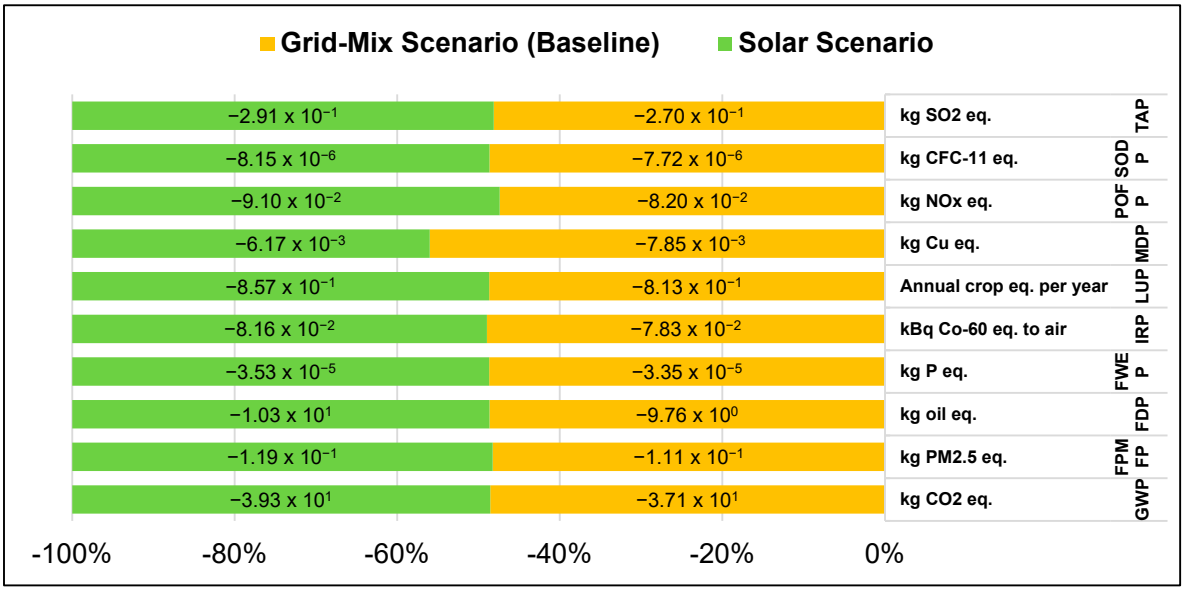


Figure 7. Comparison of grid mix and solar scenarios.

3.7.1. Internal Cost Analysis

Internal cost is calculated using Equation (3), in which different cost heads are included. The internal costs of both scenarios have been calculated to compare them in terms of economic benefits. Capital investment in solar recycling plants is higher than that of the grid mix recycling plant due to the increased investment in solar plates. The capital investment of the grid mix recycling plant is USD 1.25 million, while the solar recycling plant's investment is USD 1.33 million.

The maintenance cost of a solar recycling plant is also higher than that of grid mix recycling. The maintenance cost difference between these two scenarios is USD 3500 per year. The operational cost of the grid mix is higher than that of the solar recycling plant due to the reduction in energy bills. In the grid mix, electricity came from LESCO, which is economically less viable than the solar recycling plant. There are USD 242,443 per year in operational costs of the grid mix recycling plant, while the solar recycling plant has USD 171,471 per year. There is a difference of USD 70,000 between the operational cost of the grid mix and the solar recycling plant, as shown in Table 7.

Table 7. Internal cost analysis of both scenarios of recycling plant.

Cost Parameters	Grid Mix	Solar
Capital investment	USD 1,250,000	USD 1,329,891
Maintenance costs	USD 42,857/year	USD 46,429/year
Operational costs	USD 242,443/year	USD 171,471/year
Discount rate	10%	10%
Inflation rate	5%	5%
Economic indicators		
Payback time (PB)	3 Years	2.7 Years
Net present value (NPV)	USD 1,584,579	USD 1,967,808
Internal rate of return (IRR)	28%	33%

Three economic indicators have been studied in this study: payback time (PB), net present value (NPV), and internal rate of return (IRR). The market value of one ton of C&D material, including sand, soil, and aggregate, is PKR 1910. In this study, the baseline value of recycled material is PKR 1337 per ton, 30% less than the new material. These three

indicators were evaluated by multiplying C&D waste generation by the recycled material's baseline cost (PKR 1337). Solar recycling plants showed more positive economic indicators than the grid mix scenario. PB of the grid mix is almost three years, while the solar case scenario has 2.7 years PB time. These economic indicators were calculated based on the ten-year project lifespan.

NPV of the grid mix scenario also showed fewer economic benefits than the solar scenario due to high operational costs. NPV of the grid mix after ten years is calculated as USD 1,584,579, while the solar scenario is evaluated as USD 1,967,808 after ten years. There will be a total profit of USD 3.8 million after ten years with the grid mix recycling plant, but the solar recycling plants will obtain USD 4.5 million after ten years. IRR is also an important indicator for evaluating a project's future economic benefits. Grid mix showed a 28% IRR rate, while the solar scenario showed a 33% IRR (Table 7). According to internal cost analysis and economic indicators, a solar recycling plant is evaluated as the best-case scenario compared to a grid mix recycling plant.

3.7.2. External Cost Analysis

Using Equation (4), the external cost of landfill and recycling was calculated. Landfills showed negative externalities and environmental burdens. The landfill showed an external cost of USD 0.142 per ton of C&D waste. Recycling showed USD −3.06 per ton of C&D waste, which means that one ton of C&D waste recycling saves USD 3.06 in environmental damage or externalities, as shown in Table 8. C&D waste recycling in Lahore can save USD 0.4 million as an external cost (environmental damage) annually due to low environmental impacts.

Table 8. External cost analysis of landfill and recycling.

Coefficient		**Landfill**		**Recycling**	
Elements	$/kg	Kg	EC ($)	kg	EC ($)
CO_2	0.03	2.76×10^{0}	8.28×10^{-2}	-3.68×10^{1}	-1.10×10^{0}
CO	0.63	4.22×10^{-3}	2.66×10^{-3}	-2.93×10^{-2}	-1.85×10^{-2}
SO_2	3.675	4.15×10^{-3}	1.53×10^{-2}	-2.99×10^{-1}	-1.10×10^{0}
NMVOC	1.335	3.13×10^{-3}	4.18×10^{-3}	-2.41×10^{-3}	-3.22×10^{-3}
CH_4	0.225	8.67×10^{-3}	1.95×10^{-2}	-5.34×10^{-2}	-1.20×10^{-2}
PM	10.905	7.62×10^{-4}	8.31×10^{-3}	-5.80×10^{-2}	-6.32×10^{-1}
NO_x	4.47	6.02×10^{-3}	2.69×10^{-2}	-4.43×10^{-2}	-1.98×10^{-1}
Total			0.142$/ton		−3.06$/ton

At the same time, the landfill cost of C&D waste showed an external cost of USD 16,500 per year to mitigate its negative environmental impacts. Seven elements were selected to calculate external environmental costs from the landfill and recycling cases. These seven elements were selected due to their heavy environmental burden and referred to by Pa et al. [46]. In landfills, CO_2 showed 2.76 kg emissions per ton of C&D waste, while recycling showed −36.8 kg per ton. Replacing one ton of recycled material with new raw material can save 36.8 kg of CO_2 emissions. The mitigation cost or external cost of CO_2 per kg is USD 0.03. PM (particulate matter) has the highest external cost at USD 10.9 per kg. The coefficient values of each element were taken from the literature [45,46]. Emissions of each element in both scenarios were taken from GaBi software.

3.8. Recent Developments in C&D Waste Management

Worldwide studies on the economic and environmental benefits of recycling C&D waste align with the findings. LCA results showed that recycling scenarios reduced GHG

emissions, energy usage, and resource depletion compared to C&D waste landfilling. European studies report similar reductions, such as the integrated plant in Italy, where the use of recycled aggregates achieved significant environmental savings by minimizing transportation distances [48]. Ultimately, studies from Portugal and China underscore the necessity for recycling facilities in cities to minimize emissions and waste transport distances [49,50].

In concrete production, recycled aggregates have the potential to replace natural aggregates. Lu et al. [51] documented that recycled aggregates reduce environmental impacts and costs with optimized processing and transportation. Similarly, a comparative analysis of natural and recycled aggregates in Iran indicated that added recycled materials could bring down CO_2 emissions by 36% [52]. Contamination, inconsistent aggregate quality, and low market acceptance remain major challenges in C&D waste recycling. These kinds of challenges are evident in the European and Portuguese contexts, where policies aimed at quality recycling gradually increased market penetration [49,53].

Despite this promising result, policy interventions have to overcome obstacles such as quality assurance and market acceptance. Comparative studies in the EU and Brazil emphasize the need for government incentives, rules, and public awareness in the circular economy movement [54,55]. Integrating these lessons can assist the proposed Lahore recycling framework in addressing regional issues and contributing to global sustainability objectives. These results underscore the need for systemic C&D waste management, which incorporates technical advancement with policy and market development for long-term effects.

3.9. Policy Insights on C&D Waste Recycling

Particulate matter and GHG from industrial activities, waste mismanagement, and vehicular pollution create smog problems in Lahore. Due to these problems, Lahore has been facing severe smog for the last two years [56]. This study showed how C&D waste recycling can reduce smog-associated pollutants, including particulate matter ($PM_{2.5}$), photochemical ozone precursors, emissions from landfills, and waste transportation. The integration of recycling facilities into Lahore's waste management framework may directly contribute to better air quality and urban smog mitigation. First, dedicated C&D waste recycling facilities processing 500–600 tons per day can reduce the environmental impact of landfills and promote resource recovery. Rather, policymakers should mandate recycling for construction projects and encourage the use of recycled materials in construction. Financial incentives like subsidies for recycling plant development or tax benefits for recycled material usage could promote sustainable practices while reducing natural resource extraction.

Shifts to decentralized recycling facilities closer to waste generation sites could cut transportation emissions and major environmental pollutants. Applying solar power to recycling plants could potentially replace fossil fuels, thereby reducing grid energy consumption and emissions. Such policy measures may improve air quality and urban smog and align Lahore's waste management strategies with international sustainability targets. The study highlights the necessity of dealing with some severe policy gaps in the management of C&D waste in Lahore. Existing policies deal with waste disposal but do not specifically address recycling and resource recovery, as demonstrated in multiple international frameworks in the European Union. For instance, the EU Waste Framework Directive (2008/98/EC) requires 70% recycling of non-hazardous C&D waste with appropriate regulations and monitoring [53,57]. By comparison, Lahore's policies provide absolutely no clear recycling goals or incentives to use recycled aggregates in building projects.

Lessons from worldwide scientific studies demonstrate that C&D waste recycling can deliver both environmental and economic benefits when implemented as national and

regional strategies. For instance, China has enacted recycling policies mandating the use of recycled materials in construction projects, leading to a surge in demand for recycled aggregates [50,51]. Likewise, Brazilian governments have provided monetary incentives and penalties for promoting the recycling units. Establishing recycling targets like EU requirements, offering tax incentives for using recycled aggregates, and incorporating recycled materials into public construction projects can reduce policy gaps related to C&D waste in Lahore. A certification system for the quality of recycled aggregates could also enhance their market acceptance [49,50]. Policy frameworks should encourage public-private partnerships to invest in recycling infrastructure for a sustainable C&D waste management system. With these measures, Lahore can shift to a circular economy, lessening landfills and also contributing to global sustainability goals.

C&D waste recycling can directly support several United Nations Sustainable Development Goals (SDGs). This research contributes to SDG 13 (Climate Action) and SDG 12 (Responsible Consumption and Production) by demonstrating substantial reductions in GHG emissions (37 kg CO_2 eq. per ton saved) and encouraging the use of recycled materials over virgin resources. The focus on improving waste management infrastructure within Lahore, mitigating environmental impacts like smog, and enhancing resource efficiency aligns with SDG 11 (Sustainable Cities and Communities). Implementing the recommended policy measures can thus accelerate progress towards these SDGs and global sustainability targets within Pakistan and offer a model for other developing nations. This study complements the eco-modernist principles through life cycle-based circular economy strategies in construction and demolition waste management [58,59].

3.10. Assumptions and Limitations

This study was performed under some assumptions and limitations due to the economic and environmental impacts of C&D waste management. The functional unit for this study was selected as 1 ton of C&D waste to standardize and compare the study with other life cycle assessments. The system boundaries consist of all processes from waste collection to landfilling or recycling. Transportation distances were assumed to average 30 km according to local landfill sites and collection points. Technological inputs like recycling plant efficiency and emission factors were adapted from the Ecoinvent database v3 and case studies from the literature [49,51]. These assumptions aid the study in implementing realistic scenarios and filling in the gaps in the availability of localized data.

Despite these efforts, the research identifies several limitations. Primary data were collected through surveys and field visits, while secondary data were collected from international studies that might not reflect local practice, climatic conditions, and waste composition. Emission factors for diesel and electricity were taken from Jain et al. [32], and there might be some differences. Another limitation of this study is the selection of a recycling plant from the Indian scenario, as there is no functional recycling plant in Pakistan, specifically in Lahore. Additionally, economic analyses assumed stable market conditions like constant demand for recycled aggregates and fixed landfill tipping fees, which might change with global or regional industry dynamics. The study also assumes that recycled aggregates meet construction quality standards, as supported by case studies from Europe and China [27,50,53,54]. However, the study does not fully implement some advanced sorting and contamination control measures.

This study assumes that recycled products derived from C&D waste are viable substitutes for virgin materials in construction applications, which include non-load-bearing uses such as road sub-base, footpaths, and fill material for large voids. A detailed mechanical strength and contaminant testing were not included within the system boundary of this study. C&D waste in the model was sourced from segregated streams identified as inert

by LWMC. The segregation by LWMC significantly decreases the possibility of hazardous contaminants such as heavy metals or asbestos in the recycled products. In Pakistan, many underdeveloped cities can use these recycled products in non-load-bearing construction applications. Nonetheless, real-world implementation requires quality assurance measures aligned with international standards (e.g., EN 12620) to ensure performance and regulatory compliance. Future studies may consider expanding the system boundary to include physical and chemical testing for a more comprehensive sustainability evaluation.

These limitations and assumptions indicate the need for additional research and localized data collection to bolster the findings. Future studies should use more precise regional datasets, dynamic policy scenarios, and technological innovations that may impact the outcomes. This study emphasizes the need for continual improvements in CDW management methods to obtain maximum environmental and economic benefits.

4. Conclusions

This study used LCA and LCC for C&D waste management in Lahore. The results revealed that recycling can be more sustainable than landfilling and reduce GHG emissions, resource depletion, and environmental burdens. For example, recycling C&D waste prevents smog and is 30% cheaper than virgin raw materials. Solar-powered recycling plants contribute to environmental and economic feasibility, with a shorter payback period and a higher net present value (NPV) compared to grid mix electricity scenarios. Such results highlight the potential of C&D waste recycling in Lahore for a circular economy that reduces reliance on raw materials and promotes resource conservation.

By using recycled materials for construction instead of virgin raw materials, we can conserve natural resources. These benefits drive Lahore's ongoing sustainability work and are concrete steps toward a circular economy. Policies and stakeholders can use these insights to implement sustainable waste recycling technologies that reduce operational costs and environmental footprints. Prioritizing recycling infrastructure along with renewable energy integration could make Lahore a model city for urban waste management in developing countries, especially in Pakistan. While the study is based on localized parameters from Lahore, its methodological framework is adaptable to other regions, particularly in developing countries facing similar problems in C&D waste management. The LCA and LCC approaches used are standardized and transferable, with regional adjustments to factors like energy mix, diesel usage, waste composition, and infrastructure feasibility.

The study makes evidence-based recommendations to policymakers and stakeholders in Lahore for setting up sustainable waste management infrastructure for a greener, more resilient urban environment. The study's novel findings include a quantified demonstration of environmental benefits, such as a saving of approximately 37 kg CO_2 equivalents per ton, and clear economic advantages through substantial resource cost savings. Thus, the study not only enhances existing methodologies but also provides robust, context-specific insights for policymakers to implement circular economy principles in developing cities.

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