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# Disposal of Waste in Construction Sites: A Comprehensive Review and Framework for Sustainable Practices

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***Abstract— Construction and demolition waste (CDW) is estimated to make up one-third of the total solid waste in the world, which is a significant problem in terms of environmental, economic and social impacts. The existing disposal modalities with special reference to landfilling and open dumping contribute to the depletion of resources and increase risks to the health of people. This review clarifies how the key principles of a circular economy, life-cycle analysis, and the waste hierarchy can be used to increase the sustainability of CDW management. Among the major policy interventions, regulatory reforms supported by economic incentives, full stakeholder involvement, and application of digital platforms, including Building Information Modeling (BIM), the Internet of Things (IoT), and blockchain technology to enhance waste tracking and transparency, should be mentioned. The use of technological innovations, such as artificial intelligence, unmanned aerial vehicles, robotic sorting systems, and so on, can additionally allow making the recovery of resources optimized, planning early, and also modular design and pre-demolition inspection minimize waste production at the outset. The attainment of sustainable CDW management requires a combined set of policies, technological breakthrough and synergistic behavior change. The next generation of priorities should be based on the establishment of global harmonized standards, improving the data interoperability and scaling digital tools to establish a low-waste, circular building industry in line with the sustainability goals of the world at large.***

**Key words**: Construction and Demolition Waste (CDW), Circular Economy, Sustainable Waste Management, Digital Technologies, Resource Efficiency

## 1. INTRODUCTION

Construction and demolition waste (CDW) are one of the most important problems globally, and the construction industry is estimated to produce around 30-40 percent of all waste in the world [1]. The high volume also creates a set of considerable environmental, economic, and social consequences necessitating proper management interventions and a sound insight into the challenges and opportunities underlying them [2, 3]. The construction industry is considered one of the biggest sources of waste in the world, with an estimated usage of about 40 percent of natural resources, 36 percent of global energy, and 33 percent of global greenhouse gases [4, 5]. The size of CDW alone is estimated to hit 2.2 billion tons in the world in the coming 9 years, assuming current trends do not decline; hence, the compulsion to change the traditional linear economic systems to sustainable economic systems like the circular economy [6, 7]. CDW makes up 15–30% of the total waste produced in certain areas like Nigeria [8]. Nations or countries that are rapidly urbanizing, such as China, have huge problems with the waste of construction, which has long surpassed the capacity of domestic processing, which has frequently resulted in landfills or burning, thus leading to wastage of resources and subsequent pollution of the environment [9]. There are far-reaching environmental effects of CDW that are noted. The process of landfilling CDW uses huge pieces of land and may cause soil and groundwater pollution as a result of the leaching of toxic elements [10, 11]. All these problems are worsened by the fact that mixed waste streams are being disposed of, such as concrete, bricks, wood, metals, plastics, and gypsum [4].

An example of organic carbon in municipal solid waste incinerator (MSWI) bottom ash, which is a product usually linked to the construction process, can result in high dissolved organic carbon (DOC) emissions and release of ammonium and copper to the environment when not properly treated [5]. Poor disposal of construction waste may have a direct impact on lowering the quality of water, and hence human health, as well as disruption of the natural ecosystems [3]. Moreover, the mining of raw materials to construct the building also leads to depletion of resources and destruction of habitats, so that the reuse and recycling of CDW should be urged to sustain the environment [6, 7]. The manufacturing process of certain construction materials, e.g., cement, is energy-intensive and a significant source of greenhouse gas emissions [8]. Examples of reutilization of materials, such as the use of reservoir sediments to create soil fertilizers, can be used to show how waste can be used to create a resource that will, in turn, help to reduce the environmental impact of waste disposal as well as the extraction of raw materials [9]. Inefficient CDW management leads to huge financial losses. Waste disposal is very expensive, both in terms of transportation, landfill charges, and cleanup of the environment [1, 10]. As an illustration, poor waste management in the construction sector, especially in the Nigerian construction industry, causes time and cost overruns when constructing buildings [10].

The lack of proper strategies for final waste disposal in certain countries like Chile translates to the loss of possibly reusable, recyclable, or recoverable materials, hence a wasted economic opportunity [11]. On the other side, the principles of the circular economy and appropriate waste valorization systems can convert waste into useful secondary materials and decrease the need for virgin materials and create new economic opportunities based on the recycling and reuse industries [12, 13]. Imposing disposal-charging schemes like those that are aimed at discouraging the production of waste must be carefully designed to consider the economically driven behaviors of the contractors so as to be effective [1]. The social impacts of CDW are equally significant. Improper waste management systems may bring risks to the health of the population, e.g., because of air pollution due to dust, noise due to waste processing, and the release of toxic materials [1, 3]. The quality of life of the local people can be compromised by the aesthetic degradation of the landscapes caused by unlawful dumping or due to an overflowing landfill [4]. Furthermore, the fact that waste disposal faces environmental injustices, with marginalized groups commonly having the misfortune to suffer the most in terms of pollution, is a severe social issue. Well-managed CDW systems can help create jobs within the recycling and reprocessing industries, and this will allow the local economy to grow and further improve the social welfare [1]. The concept of sustainability and circular economy implementation in construction waste management, therefore, has a positive effect on social equity and the health of people [5, 6].

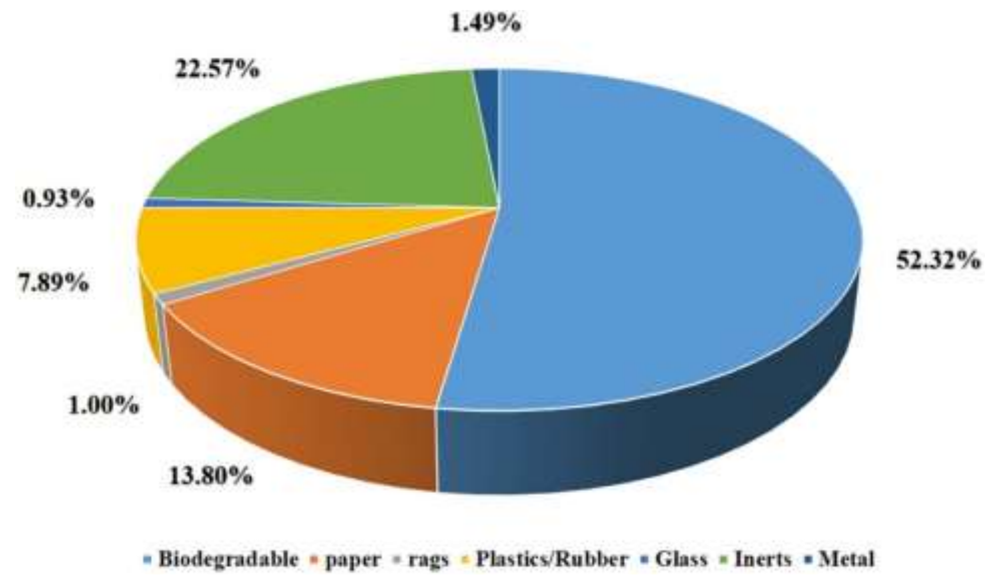


Figure 1. A pie chart or bar chart showing the contribution of construction waste to total solid waste in different regions. [14].

### 1.2 Research Gaps and Significance

Despite the fact that significant studies have focused on CDW management in the last four decades, there are still gaps that can be considered relevant, particularly as far as an integrative approach is concerned [15, 16]. One of the most significant gaps is related to the systematic identification and elimination of the obstacles to the development of the green supplier programs, which are essential in terms of sustainable supply chain management in manufacturing sectors [17]. On the same note, the lack of detailed scientometric investigations that specifically target CDW management in the construction industry has been noted with respect to the integration of the circular economy principles [18]. A large part of the literature available is quite discrete-based, as opposed to a whole system view of waste production, which links waste generation to construction stages, causative factors (men, materials, machines, methods, and measurement, the so-called 5M framework), and their effects [18]. In order to close these gaps, it is important to develop comprehensive frameworks. These frameworks are able to incorporate the principles of a circular economy (CE) into the construction waste management (CWM) and include the whole material lifecycle, including design and end-of-life [19, 20]. An Analytic Hierarchy Process (AHP) framework is one example that has been suggested to incorporate CE principles in CWM, thus enabling waste-management strategies to be prioritized [21].

A systematic study, which builds an ontological model of CDW management, aims at modeling interconnected elements in an unequivocal way and leading a comprehensive strategy [22]. Waste-management tools, especially blockchain technology, are inexpensive to innovate, and they provide transparency and traceability, which are essential in achieving a circular economy in the building industry. However, the synthesis between the concepts of blockchain, waste management, and the concept of a circular economy is still little [23, 24]. Moreover, a systematic review of the environmental effects of CDW, with an analysis of science-mapping methods, is also identified as a necessity to map the research territory and outline the future research directions [25]. The theoretical framework of the circular end-of-life options of wind-turbine blades, which incorporates the principles of the circular economy into the building materials, is also an example of how the waste-management solutions can be used across the sectors [26]. The other important gap is related to the evaluation of the construction-waste reduction management, both in the design and construction phases. The existing studies mainly focus on the design or the construction process and not on providing a holistic assessment model that can improve a comprehensive evaluation of the overall reduction results [27]. Also, the absence of proven, effective, and ductile ties between Concrete-Filled Steel Tube (CFST) columns and reinforced concrete foundations is one deficit of research and practice that prevents the broader use of these beneficial structural components [28].

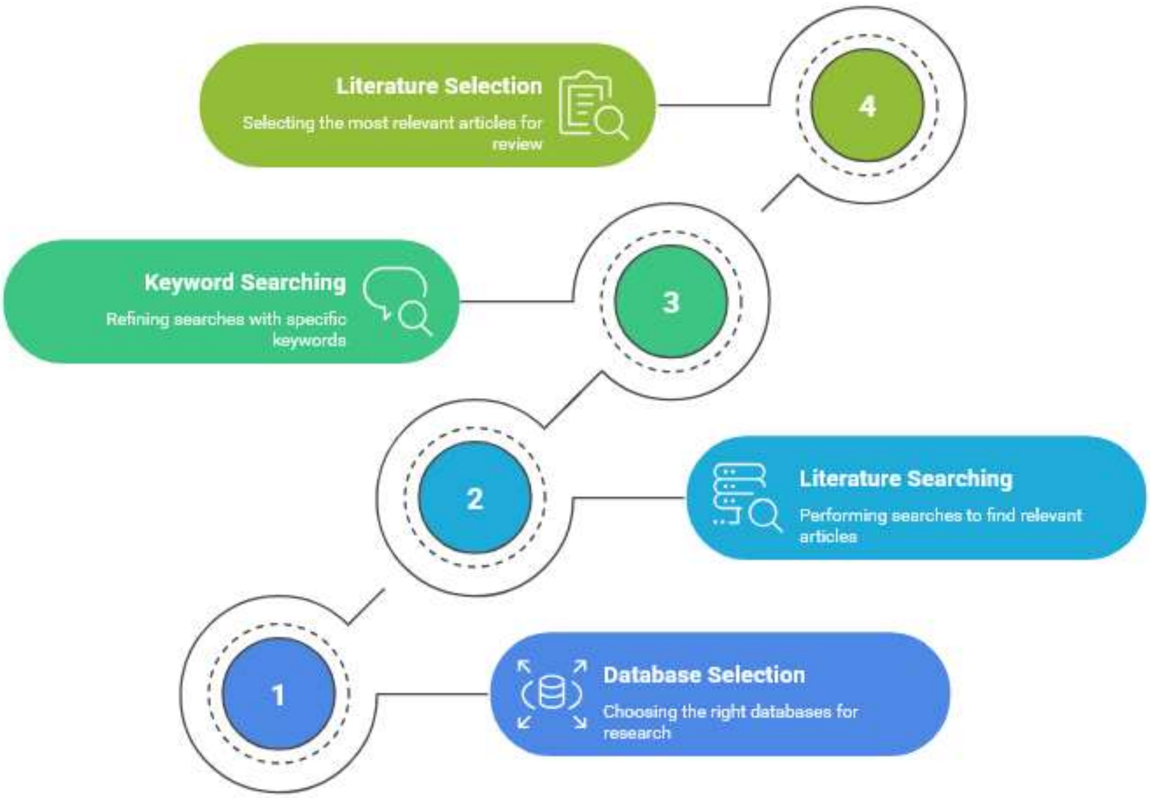


Figure 2. Flowchart on process of conducting a literature review on construction and demolition waste management.

The first phase of the literature review was associated with the careful selection of databases. Four major sources, namely, PubMed, Scopus, Web of Science, and ScienceDirect, were chosen as the core sources of the scholarly publication's retrieval. Google Scholar and Google were added to these databases, as they served to expand the search horizon. The choice of these repositories was a landmark move, as it formed the basis on which relevant literature would then be found. The second phase, which followed the selection of databases, was a preliminary literature search. In this stage, relevant studies were systematically searched in the identified databases. This step was the beginning of the data-gathering phase, which ensured that the search was organized and extensive. The third step involved the search of keywords, and this comprised the major part of the retrieval process. A complete list of keywords that relate to the waste management of construction and demolition was also utilized. These terms were related to a variety of aspects of the subject, including waste management hierarchy (the 3R principles: reduce, reuse, and recycle) or methodologies, tools, frameworks, legislation, policy, quantification, performance measurement, economic evaluation, and sustainability. This systematic procedure allowed identifying 198 articles, thus showing the vastness of the literature on the topic. The selective exploitation of specific keywords helped provide a wide scope of the range of studies available in the field on various dimensions. The fourth step entailed a two-stage sample selection process. At the initial stage, 137 papers out of the original corpus of 198 were shortlisted after a preliminary screening of titles and abstracts was performed to determine whether they had basic relevance. At the second stage, a more extensive review of 121 papers was done. This involved a thorough analysis of keywords, abstracts, conclusions, and discussion parts to analyze their content further. The endpoint selection was done in such a way that only the most relevant and contextually important studies were left to be included in the review.

## 2. OVERVIEW OF CONSTRUCTION WASTE

Construction and demolition waste (CDW) are an enormous product of the construction industry, and it requires a clear definition and classification to enable its effective management. The CDW stream is heterogeneous, consisting of various materials, the properties of which determine an impact on the environment and valorization opportunities. Extensive knowledge of the sources of CDW and worldwide and regional trends in the composition and volume is the prerequisite for the development of sustainable waste management strategies [29, 30].

### 2.1 Construction and Demolition Waste definition and classification.

The concept of CDW is generally described as waste released as a result of building, refurbishing, and demolishing buildings and infrastructure [31]. Effective handling, treatment, and recycling of materials cannot take place without appropriate classification of the materials, which is usually done by physical properties, hazards, and reusability. The key categories include hazardous waste, inert waste, recyclable waste, and biodegradable waste.

#### *2.1.1 Hazardous Waste*

Materials that are toxic, corrosive, reactive, or flammable are classified under this category since they can be hazardous to human health or the environment [31]. Typical examples of CDW include asbestos-containing products, lead-based paints, some chemicals, and poisoned soils [32]. Inadequate disposal of the hazardous CDW may lead to extreme contamination of soil and groundwater, thus causing long-term environmental and human health hazards [33].

#### *2.1.2 Inert Waste*

Inert waste materials are those that are not subjected to a significant physical, chemical, or biological change during disposal and are not considered to be a significant threat to the environment or human health [31]. This type is usually characterized by large amounts of concrete, bricks, tiles, ceramics, and stones [32, 33]. In spite of being non-hazardous, the sheer volume of the inert waste often takes up a lot of area in the landfill, which highlights the significance of recycling and reuse [34].

#### *2.1.3 Recyclable Waste*

A significant part of CDW can be recycled, which means that it can be reconstituted and recycled as secondary raw materials into the production cycle [35]. The most prevalent types of materials that are recyclable include metals (steel, copper, and aluminium), wood, plastics, glass, and gypsum [36, 37]. The reuse of these materials reduces the demand for virgin resources, saves energy, and minimizes the reliance on landfills, and, therefore, agrees with the principles of the circular economy [38, 39].

#### *2.1.4 Biodegradable Waste*

This category encompasses organic materials that can decompose by means of biological processes naturally [31]. In the context of the CDW, this mainly means wood, paper, cardboard, and some landscaping debris produced in the course of site preparation or demolition [32]. They are biodegradable, but when they are deposited in landfills, they can produce methane, a powerful greenhouse gas, and this makes composting or energy recovery essential [33]. The existence of heterogeneity in CDW is due to the different types of waste generated by construction projects [34]. Good sorting and separation at the source are essential in ensuring the recovery is greater and environmental impacts are low [35].

### 2.2 Sources of Construction and Demolition Waste

The construction demolition waste (CDW) is generated throughout the lifespan of the construction process, including the design stages, the construction stages, and the demolition stages; the outcome of each stage has different typologies and volumes of waste [31].

#### *2.2.1 Design Errors*

Failure to plan and design is an example of salient antecedents of waste production [40]. As an illustration, mid-construction design changes, poor choice of materials, and inaccurate material estimates trigger the loss of materials [41]. In addition, design errors may hinder further deconstruction or even reuse of materials in the terminal phase of the life cycle of a structure, thereby increasing the amount of waste during the process of demolition [42].

#### *2.2.2 Over-ordering*

Purchasing material more than is needed, usually in the form of insurance against shortages or a delay in the schedule, is a major source of extraneous waste [1]. Unused or excess material often ends up as waste, especially in cases where there is a lack of storage capacity or when the materials are damaged on the ground [43].

#### *2.2.3 Demolition*

Destructions are major sources of CDW, producing a large volume of heterogeneous materials such as concrete, masonry, timber, and metal [41, 44]. The description of the volume and composition of waste depends on the age of a building, construction techniques, and material components [45]. The traditional destructive type of construction often creates mixed wastes, thus making segregation and recycling processes difficult [44].

#### *2.2.4 Excavation*

During the site preparation and foundation work, excavation cases produce large amounts of soil, rock, and inert material [1]. Even though a large percentage can still be reused at the location or in other construction projects, excess or polluted excavated material makes up a significant portion of CDW streams [45].

#### *2.2.5 Packaging*

Construction materials are often supplied in large quantities of wrappings, which include plastics, cardboard, wooden pallets, and metal straps [41]. Although this type of packaging material is necessary in transportation and protection, it turns out to be a waste when opening the package [42]. The disposal of packaging waste, therefore, forms a particular problem and generally requires specific collection and recycling channels. Other causes are poor material handling, unintentional damage, and inefficiencies in the construction practice, which all add to the heterogeneous and complex nature of the CDW [46,47].

### 2.3 Trends in Composition and Volume Globally and Regionally

The amount of construction and demolition waste (CDW) in the world is great and keeps growing with the increased rates of urbanization and the progress of infrastructure construction [47, 48]. The construction industry is estimated to generate 300-400 percent of the overall waste generated across the globe [49]. It is estimated that global CDW would be 2.2 billion tons in the next nine years in case current trends continue, which is why there is a dire necessity for sustainable practices [48].

#### *2.3.1 Increasing Volume*

The accumulated amount of waste on the global level is a major issue, yet reporting is inconsistent because of the different terms and approaches [50, 51]. Although the increase in the generation of CDW is difficult to measure, it is a worldwide phenomenon because of the fast urbanization and the development of infrastructure [52, 53].

#### *2.3.2 Dominance of Inert Waste*

Inert materials like concrete, bricks, and asphalt in the world are usually the heaviest constituents of CDW by weight [54]. It is especially pronounced in developed economies that are experiencing a high level of demolition or massive construction of infrastructure [55].

#### *2.3.3 Shift Towards Recycling*

The trend of shifting CDW out of landfills to recycling and reusing is gaining momentum in the world as more people become conscious of the environment and tougher rules are enforced [55, 56]. It is also a growing trend that the circular economy is an appropriate approach to resource management, where resources are reused, reduced, and regenerated [57, 58].

#### *2.3.4 Technological Integration*

Complex technologies are also being pursued and developed to enhance the management of CDW. As an illustration, blockchain technology can bring benefits of increased transparency and traceability in waste management processes, which would contribute to the efforts of the circular economy in the construction industry [58, 59].

### 2.4 Regional Variations

#### *2.4.1 Developed Countries*

Regions with developed economies tend to have properly developed regulatory policies and structures specifically focused on the management of construction and demolition waste (CDW) and concurrently lead to increased rates of recycling and recovery [60]. However, these regions still face challenges related to particular waste streams such as complex demolition debris and threatening materials. An example is Europe, which is proactively implementing the principles of the circular economy to reduce the amount of waste as well as to maximize the use of resources, and now household food waste is also included in the wider range of waste-reduction measures [61].

#### *2.4.2 Developing Countries*

In the third world countries, the construction activity is often growing faster than the ability to manage the CDW properly [61]. Traditional waste management practices continuously lead to poor utilization of resources and more reliance on landfilling [62]. Some developing countries like China that are experiencing large-scale urbanization have seen the volumes of CDW that are already way beyond their domestic processing capacity, hence adding to environmental pollution by landfill or incineration [63]. The management of waste in such cases tends to be left behind modern-day sustainability paradigms, which explains the urgency of comprehensive frameworks and specific policy interventions [64]. In China, empirical studies on urban construction land use, e.g., have found that there are complex interdependence relations between land intensity and carbon-emission efficiency, thus highlighting the larger environmental implication of the high-speed development [65].

#### *2.4.3 Compositional Shifts*

The CDW composition has a geographical variation, which is indicative of the most used construction materials and construction methods in the particular region [61]. As an illustration, a locality that has a high percentage of timber construction will have a higher percentage of wood waste as compared to areas that have a high reliance on concrete, as they will produce more of an inert material. The rise in the use of new construction materials, including composites, also creates new issues regarding classification and recycling [62]. As a result, the successful management of CDW requires a complex understanding of its definition, various classification schemes, various sources, and the dynamic tendencies that determine its structure and mass, making it possible to implement strategic changes to keep the global sustainability agenda and local specific requirements in balance [65].

Table 1. Classification of Construction Waste with Examples and Typical Disposal Routes.

| Waste Class | Examples | Typical Disposal / Recovery Routes |
|---|---|---|
| Inert / Non-Hazardous Solid Waste | Concrete, bricks, tiles, ceramics; soil, stones, dredging spoil; untreated wood; glass (uncontaminated); plastics (non-hazardous); asphalt without tar or coal residues. | • Recycling / crushing for aggregate, sub-base or fill material. • Reuse for construction (leftover blocks, bricks). • Land reclamation, site formation. • Landfill designated for inert waste when reuse/recycling not feasible [66] |
| Hazardous Construction Waste | Paints, varnishes, adhesives, solvents; treated wood; asbestos materials; bituminous mixtures containing coal tar; fuel/oil contaminated materials; electrical waste containing heavy metals. | • Segregation on-site; special handling protocols. • Secure storage; licensed hazardous waste handlers. • Treatment or neutralization (chemical / physical) where applicable. • Disposal in hazardous waste landfill or specialist incineration / safe treatment facility [67]. |
| Mixed / Composite Waste | Mixtures of concrete/bricks with wood, plastics; mixed packaging; debris with contaminants. | • Sorting / separation of components (separating wood, metal, concrete). • Recycling of clean fractions. • When mixed waste can't be fully separated, treatment or selective disposal of hazardous parts; remainder may go to appropriate landfill [68]. |
| Liquid or Semi-Liquid Waste | Water with concrete washout; oils, fuels, solvents; chemical cleaning agents; slurry from cutting / grinding. | • Collection in sealed containers. • Treatment (settling / filtration / neutralization) if non-hazardous. • If hazardous, sent to specialized liquid hazardous waste treatment facilities. • Disposal according to environmental regulatory requirements (e.g., avoid discharge into drains without treatment) [69]. |
| Organic Waste / Biodegradable Materials | Exposed soil, vegetation removed during site clearance; packaging board/cardboard; food waste from site; wood that can decompose. | • Composting / mulching (for vegetation, wood). • Recycling of cardboard / paper. • Use as biomass / fuel (where permissible and safe). • Disposal in general waste streams or sanitary landfill for non-usable organic waste [70]. |

## 4. CURRENT DISPOSAL PRACTICES IN CONSTRUCTION SITES

The traditional techniques used in disposing of the construction and demolition waste (CDW) are mainly landfill, open dumping, and incineration, all of which pose significant environmental problems. Instead, a paradigm shift is taking place towards more sustainable options like recycling, reusing, and recovering, which are aligned with circular economy (CE) principles [71]. There are regional differences regarding the use and effectiveness of such approaches, as they depend on differences in economic progress, regulations, and technological potentials [71, 72].
In the United States, individuals have traditionally disposed of waste materials through the use of traditional disposal techniques.

### 4.1 Traditional techniques

#### *4.1.1 Landfilling*

Landfilling has continued to dominate in the management of CDW, particularly where other management resources have limited scope due to their cost or availability [71]. Though it may be simple, landfilling requires a large area of land and may trigger drastic environmental deterioration, such as soil and groundwater contamination through the leaching of dangerous materials in heterogeneous waste streams [72]. Methane, which is a strong greenhouse gas, can also be produced as the organic compounds in the landfills decompose, thus contributing to climate change [73].

In the developing countries, the underutilization of resources tends to create high reliance on landfills [74]. Indicatively, urbanization in China has led to the generation of volumes of CDW that are way beyond its processing capacity, which has ended up as a major contributor to landfilling [75].

#### *4.1.2 Open Dumping*

Open dumping is an unregulated and unlawful disposal method that does not have environmental protection and is commonly linked to the informal activities in the developing world [76]. The approach poses direct hazards to the health of people by polluting the air and water, degrading aesthetics, and breeding vectors of diseases [76].

It also creates irredeemable destruction of habitat and disappearance of natural resources.

#### *4.1.3 Incineration*

Incineration involves burning CDW as a volume reduction method and, at times, energy recovery. Although this is an effective way of reducing the amount of waste, incineration may cause deleterious emissions to the atmosphere, such as dioxins, furans, and heavy metals, especially when proper emission controls are not in place [77].

The ash left behind after incineration can also contain poisonous elements and thus requires careful handling procedures. Although there is a possibility of energy recovery, the environmental footprint of incinerating mixed CDW is more likely to be larger than the benefits of recycling, especially in comparison to material recovery options.

### 4.2 Recycling, Reuse, and Recovery Methods

The hierarchy of waste management prioritizes reduction, reuse, and recycling over disposal, with the circular economy (CE) framework gaining significant traction in the construction sector [78, 79]. This approach aims to minimize waste generation, extend material lifecycles, and reintroduce materials into the production cycle [80].

#### *4.2.1 Recycling*

Recycling involves processing waste materials into new products, reducing the demand for virgin resources and conserving energy [81, 82]. Common CDW materials that are widely recycled include concrete, bricks, asphalt, metals (steel, copper, aluminum), wood, plastics, and gypsum [83]. Recycled concrete aggregates, for example, can be used in road bases, new concrete mixes, or as fill material [84]. Metals are highly valuable and are readily recycled.

The effectiveness of recycling is heavily dependent on efficient segregation of waste at the source [81].

#### *4.2.2 Reuse*

Reuse involves using materials again in their original form or with minimal processing, directly extending their lifespan and avoiding the energy and resource consumption associated with recycling [81]. Examples include using salvaged bricks, timber beams, or structural steel from demolished buildings in new construction projects [81].

This method is particularly effective for high-value components that retain their structural integrity or aesthetic appeal. Design for deconstruction and modular construction facilitate easier reuse of components [82].

#### *4.2.3 Recovery*

Recovery encompasses processes that extract value from waste that cannot be directly reused or recycled, often through energy recovery or conversion into secondary raw materials [81]. For instance, wood waste can be chipped for biomass energy or composted. Other non-recyclable inert materials might be processed into aggregates for lower-grade applications. The goal is to maximize resource utilization and minimize landfill dependence [82].

### 4.3 Regional Differences in Adoption

The trend of implementing sustainable CDW management practices is quite different in various regions, which depends on economic development, regulatory frameworks, technological infrastructure, and awareness of the population [81, 82].

#### *4.3.1 Developed Countries*

Areas that have developed economies, as seen in Europe, North America, and some areas in Asia, tend to have higher recycling and reuse rates since they have well-developed regulations, sophisticated sorting methods, and economic benefits [85]. These nations usually levy harsh taxes on landfills and have waste diversion targets and requirements, which drive creativity in CDW management [86]. As an example, Europe is actively introducing the principles of the circular economy, which leads to high recovery rates of CDW [87]. However, there are still difficulties, especially when dealing with complicated or risky waste streams; resource use optimization is still a continuing process [88].

#### *4.3.2 Developing Countries*

Conversely, a developing country is often faced with significant challenges in controlling CDW due to the high rates of urbanization, limited finances, poor infrastructure, and less strict environmental policies [89, 90]. The common methods used include the landfilling process and open dumping, which lead to poor resource utilization and an increase in environmental pollution [91, 92]. Lack of a thorough planning of waste management can almost always cause loss of possible valuable materials, hence resulting in the loss of economic opportunities [91]. However, an increasing awareness and active attempt to incorporate the main principles of the circular economy, often with the help of international relations and the development of new policy frameworks, is increasing [91, 93]. As an example, China, simultaneously struggling with high quantities of CDW, is also investing in research and technology that would enable complete recycling [93]. The sharp difference in the management practices in CDW implies that specific approaches are required to consider the regional contexts but in line with the global sustainability goals. This is due to the fact that the gap in the transition between the conventional disposal and the circular economy solution should be addressed by integrated frameworks supported by the policy and technological developments [91, 94].

## 5. ENVIRONMENTAL AND SOCIO-ECONOMIC IMPACTS OF IMPROPER DISPOSAL

The mismanagement of disposal, in turn, gives rise to a complex set of environmental and socioeconomic impacts, including greenhouse gas (GHG) emissions, soil and water pollution, loss of biodiversity, and associated health risks. The further growth of animal production systems has significantly increased the degradation of the environment [95]. These systems are the principal sources of GHG release, such as $CO_2$, $CH_4$, and $N_2O$, thus increasing the rate of climate change. Furthermore, the current increase in the demand for land and water to grow fodder triggers deforestation and soil erosion, which aggravate the negative environmental consequences.

Under the context of an oil exploration, intense land and water pollution is recorded in the Niger Delta area, where oil mining operations are a major threat to biodiversity and health hazards that include cancer and respiratory diseases [96]. The socioeconomic impacts are significant: the polluted resources reduce agricultural performance and interfere with the livelihood of local people, requiring the timely response of both governmental and business organizations to engage in the best environmental practices.

The above is also emphasized by the emergent studies that discovered the critical role of progressive computational systems in the environmental issues. An example is that the challenges of translating natural language into SQL queries are a reminder of the relevance of user-friendly systems in handling big data regarding the environment [97].

Effective querying and analyzing of environmental data can streamline more considerate decision-making and resource management and eliminate certain counterproductive consequences linked to the misuse of disposal techniques.

Additionally, a new system of translating natural language to graph query language (NL2GQL) has been suggested, which handles the semantic complications of environmental data [98]. This framework improves the accuracy of query generation and allows running semantic searches to aid in the identification and analysis of environmental impacts, thus helping to make better policies and allocate resources efficiently.

Table 2. Impacts of Different Disposal Methods on Environment, Health, and Economy.

| Disposal Method | Environmental Impacts | Health Impacts | Economic Impacts |
|---|---|---|---|
| Landfill (Sanitary / Controlled) [99, 100] | • Methane emissions from decomposition of organic matter → contributes to greenhouse gas (GHG) emissions. • Leachate formation → risk of heavy metals, persistent toxins contaminating soil & groundwater • Land degradation, habitat loss, ecosystem disruption due to large land area requirement. | • Exposure to contaminated water (via leachate) → gastrointestinal diseases; possible heavy-metal poisoning. • Air pollution: odors, release of gases like hydrogen sulfide, ammonia; respiratory impacts in nearby communities. • Increased risk of birth defects, cancers in populations living close to poorly managed landfills. | • High costs for land acquisition, construction, lining, leachate treatment, monitoring. • Loss of land for other productive uses. • Depreciation of nearby property values; possibly lower real estate demand near landfills. |
| Incineration (Energy Recovery) [101,102] | • Reduction in waste volume; can recover energy (electricity / heat) which offsets some fossil fuel use. • Emission of $CO_2$, NOx, sulfur oxides, dioxins/furans, particulates. • Ash (bottom & fly ash) containing concentrated toxins which must be managed. | • Respiratory illnesses due to particulate matter, exposure to heavy metals, dioxins/furans.<br>• Potential long-term effects: cancer risk, effects on vulnerable populations (pregnant women, young children) depending on emissions control. • Worker exposure during operation especially if pollution controls are weak. | • High capital and operational costs; investment in pollution control, ash disposal. • Revenue generation potential through energy sales. • Possible negative effects on property values in surrounding areas; cost of regulatory compliance. |

| | | | |
|---|---|---|---|
| Open Burning / Uncontrolled Burning [103,104] | • Uncontrolled emissions of $CO_2$, black carbon, particulate matter, volatile organic compounds (VOCs), dioxins. • No energy recovery; high environmental cost per unit of waste processed. • Contribution to air pollution, smog formation, regional climate impacts. | • Acute respiratory problems; eye/nose irritation; exacerbation of asthma and other pulmonary diseases. • Long-term health effects from persistent organic pollutants; possible carcinogenic effects. • Increased burden on local health services. | • Low (or negligible) infrastructure cost initially. • But high health care costs from illness; environmental cleanup costs; loss in productivity. • Negative impact on tourism, livability, and sometimes legal liabilities. |
| Recycling / Reuse [105, 106] | • Conserves natural resources; reduces demand for virgin materials. • Lower energy usage compared to producing new materials; lower GHG emissions. • Reduces volume of waste sent to landfills or incinerators. | • Generally, fewer adverse health impacts compared to open burning or poorly managed disposal. • But potential occupational hazards (dust, handling of contaminants) if recycling is informal or lacks safety controls. | • Costs associated with collection, sorting, processing; infrastructure required. • Potential revenue from recovered material; savings in waste disposal costs. • Job creation in the recycling sector. |
| Composting (for organic waste) [107,108] | • Reduces organic waste going to landfills → lower methane emissions. • Produces useful soil amendment; can improve soil fertility. • But may emit $CO_2$, ammonia; smells; potential leachates if not properly managed. | • Exposure to bioaerosols, dust; respiratory irritation; odor annoyance. • Health risks if compost is contaminated (pathogens, chemicals). | • Moderate operational costs (collection, management). • Benefits via production of compost; improved soil yields; possible cost savings for agriculture. • May be less costly than high tech treatment or incineration. |

## 6. GLOBAL POLICIES, REGULATIONS, AND STANDARDS

The global systems, like the EU Waste Framework Directive (WFD 2008/98/EC), introduce a hierarchical system of garbage usage aimed at enhancing resource reuse and reducing the negative impact of waste on the environment. However, their effectiveness is often limited by confusion in the definitions of the relevant measures and overlaps between prevention, reduction, and reuse, which complicate the proper implementation of the policy and involvement of stakeholders [109].

The national and regional policies, such as the example of legislative actions in Australia and Indonesia, prove that the success of waste policy usually relies on the skills and competences of the enforcement mechanisms, the increase in the awareness of the population, the effective infrastructure, and the combination of various policy tools.

The implementation of integrated or multimodal policy models is associated with a higher rate of recycling, and enforcement and lack of understanding about the importance of regulations may weaken the purpose of the regulations in the population [110].

Regulatory models and performance indicators such as the sunshine regulation in Portugal and the tariff-setting models are also becoming widely used to control and reward efficiency and service quality in waste treatment.

These changes highlight the importance of standardized measures and cost-effective regulation to rectify market failures and inefficiencies [111].

When it comes to electronic waste, international goals (65% target set by the EU in its policy), financial incentives, traceability solutions, and the most innovative technologies should be embraced to maximize the recycling rates and reduce environmental effects, but empirical validation will be necessary [112].

Many of the modern waste policies include the principles of a circular economy and extended producer responsibility (EPR), ensuring the shift toward the environment of circular flows of resources. However, these programs will only be successful when there are clear regulatory guidelines, adherence by the stakeholders, and adequate infrastructural provisions [113].

Generally, global and regional regulations are critical in ensuring that they set the necessary standards, but their effectiveness will, in the end, rely on the clarity of the regulatory provisions, the stringency of their enforcement, the participation of the stakeholders, and the harmonious integration of the economic and environmental priorities [114].

## 7. TECHNOLOGICAL AND INNOVATIVE APPROACHES

Design to break down, lean construction, and BIM (Building Information Modelling) waste prediction are more and more combined in order to avoid construction and demolition waste. BIM with lean concepts helps to engage stakeholders at early stages and thoroughly plan selective dismantling in order to reduce uncertainties and make the most of extracting and reusing building materials

[115]. Intelligent structures with image-to-BIM technologies and UAVs (drones) improve data acquisition and modeling and facilitate the effective planning of demolition, waste measurement, and economic analysis [116].

BIM-based tools have the ability to forecast and measure the amount of construction waste in the design project, real-time simulation of design options can be done, and wise choices can be made to reduce the amount of waste [117]. Research shows that a combination of prefabrication, modularization, and system dynamics modelling combined with BIM and lean construction has seen a decreased amount of material waste, costs, and carbon emission, and an increase in labor efficiency and coordination of the project [118]. Still, there are still some difficulties, such as the lack of international standards of BIM-based end-of-life planning and the necessity of enhanced interoperability of BIM applications and waste management systems [119, 120].

### 7.1 Recycling/Recovery

The construction waste reduction practice of integrating design to deconstruction, lean construction principles, and Building Information Modelling (BIM) waste prediction are increasingly being used to reduce construction and demolition waste. With the inclusion of lean ideas, BIM will include the stakeholders at the early phases and will make it easier to plan the selective dismantling extensively, diminishing uncertainties and enhancing the possibilities of extracting and reusing building materials [115]. Image-to-BIM and unmanned aerial vehicles (UAVs) assist in improving the data acquisition and modelling, allowing the efficient planning and waste measurement, as well as economic analyses [116].

BIM-based software can predict and measure the quantity of construction waste at the stage of design; real-time models of design options can allow informed decision-making that can reduce waste production [117].

Empirical data also shows that prefabrication, modularization, and system dynamics modelling, together with BIM and lean construction, have contributed to cutting down the waste of material, costs, and carbon emissions and have also enhanced labor efficiency and coordination of the project [118].

However, there are still some issues, such as the lack of standards on the international standard of BIM-based end-of-life planning and the necessity of greater compatibility of BIM programs and waste management systems [119, 120].

### 7.2 Digital Solutions

The Internet of Things (IoT), artificial intelligence (AI), and blockchain technologies are radically transforming waste management, complementing efficiency, transparency, and traceability. Smart bins and the corresponding sensors based on IoT allow real-time tracking of waste levels and, therefore, optimize the routes when predicting analytics and minimizing losses. At the same time, AI algorithms, such as machine learning and deep-learning methods, assist in waste sorting and recovery of resources, as well as classification [125, 126]. Blockchain technology offers safe, unalterable, and transparent data storage and thus facilitates the capability to track waste generation through disposal, as well as build trust among stakeholders [127, 128].

Some of the empirical foundations attributed to the integration of the systems have been increased sorting efficiency, a decrease in operational costs, increased levels of public confidence, and enhanced compliance with regulatory frameworks [127, 129]. To illustrate, IoT systems based on blockchain have been utilized in the process of tracking electronic waste, tracking nuclear waste, and tracking urban waste streams to provide secure records and real-time information to every stakeholder [130, 131]. This synergistic combination of technologies facilitates the creation of circular-economy and sustainable waste-management ecosystems in smart cities [132].

Table 3. Emerging Technologies for Sustainable Construction Waste Management.

| Technology | Description / How It Works | Potential Benefits / Challenges |
|---|---|---|
| Digital & Intelligent Technologies [133] | Includes AI (Artificial Intelligence), ML (Machine Learning), Computer Vision, Robotics, IoT (Internet of Things), BIM (Building Information Modeling), Blockchain etc. Used for forecasting waste generation, classifying and sorting waste, monitoring on-site operations, tracking waste flows, optimizing resource use. | *Benefits:* Improved efficiency in sorting and separation; reduction in labor and error; enhanced decision-making; better transparency and waste traceability. *Challenges:* High upfront cost; need for technical capacity; data/infrastructure requirements; maintenance. |
| Mobile / On-Site Recycling / Processing Units [134] | Portable units deployed on or near construction sites to process construction waste (e.g., crushing concrete, separating materials, preparing recycled aggregates) thereby reducing transport and handling. | *Benefits:* Lower transportation costs and emissions; faster turnaround; reduced space needed for storage of waste; more immediate reuse of material. *Challenges:* Scale limitations; ensuring quality of recycled outputs; cost vs benefit depending on volume of waste; regulatory compliance. |

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| | | |
|---|---|---|
| Use of Recycled / Alternative Materials in New Builds [134] | Incorporating recycled aggregate, using industrial by-products (e.g. fly ash, slag), biocomposites, biodegradable materials, or waste plastics in construction materials; also, 3D printing with waste-derived feedstock. | *Benefits:* Reduces demand for virgin materials, lowers embodied carbon, diverts waste from landfills. *Challenges:* Meeting performance / structural standards; long-term durability; market acceptance; cost of processing waste materials to acceptable quality. |
| Modular / Prefabricated & Design for Disassembly [136,137] | Prefabricating building modules off-site under controlled conditions; designing buildings so components can be dismantled and reused; reducing waste from cutting, trimming etc. | *Benefits:* Better material efficiency; reduction of on-site waste; faster construction; easier reuse / recycling at end of life. *Challenges:* Logistics of transport; standardization; regulatory or code compliance; higher precision required in design and manufacture. |
| Advanced Sorting & Waste Stream Automation [138,139] | Automated sorting systems using optical sensors, AI/computer vision, robotics etc., to better separate different types of construction waste (wood, plastics, metals, concrete, gypsum, etc.). | *Benefits:* Higher recycling rates; reduced contamination; less manual labor; potentially lower costs long term. *Challenges:* Technology cost; need for calibration/maintenance; dealing with mixed or contaminated waste; false positives/negatives in sorting. |
| Biodesign / Bio-based Materials & Biodegradable Alternatives [140, 141] | Use of biological processes or natural materials: e.g. mycelium composites, biodegradable materials, bio-based insulation, etc.; material design that allows natural degradation or easier recycling. | *Benefits:* Reduced toxicity, lower environmental impact, carbon sequestration, improved end-of-life behavior. *Challenges:* Scaling up production; ensuring structural integrity; cost; sometimes shorter lifespan; susceptibility to moisture, pests, etc. |

## 8. BARRIERS AND CHALLENGES

### 8.1 Institutional and regulatory gaps.

Lack of institutional and regulatory mechanisms is a significant challenge to the effective disposal of construction waste. These gaps take the form of disjointed or incomplete regulatory processes, lack of clear guidelines on waste classification, lack of effective enforcement procedures, and poor policing of legislation compliance, which only creates confusion amongst the stakeholders and leads to poor recycling habits [142]. In a variety of jurisdictions, rules are generally biased towards domestic waste and do not address the unique issues of construction waste or specify detailed sorting, recycling, and use of second-hand materials [143]. Other issues include the lack of governmental will or incentive to encourage recycling, the use of poor landfilling and illegal dumping, and the lack of harmonized targets or systems of sustainable waste management [144]. These deficiencies often result in the wasted chance at recovering the resources and adopting the circular economy approach, which is why the issue of detailed, binding rules that target construction waste directly in particular and the improvement of institutional control in the specified direction in particular deserve the highest priority [145].

### 8.2 Financial and cost benefit challenges.

Economical and cost-benefit analyses are critical to the construction waste disposal aspect and often make the sustainable alternatives less enticing compared to traditional methods. Initial expenses of facilities in recycling, technology improvements, and full waste-management systems may be prohibitive to adoption, especially when direct landfill disposal seems less expensive in the short term [146]. However, the results of empirical studies have shown that on-site recycling and full use of construction debris can produce significant economic benefits in the long term, including cost savings and, in some cases, profitability by contractors when government compensation or incentives are provided [147].

Innovative methods, like Building Information Modelling (BIM)-based waste management, are cost-effective by up to 57 percent compared to traditional methods, but the technology is expensive and time-intensive and demands organizational transformation [148]. The policy support, financial subsidies, and the possibility to access those materials that could have value define the economic viability of recycling centers and sustainable ways of disposal even further; the payback period of large-scale recycling projects is estimated to be about ten years [149].

In spite of these potential advantages, most building developments continue to experience a cost escalation that can be explained by wasting, and the lack of appropriate financial incentives or improperly developed disposal-charging programs may limit the implementation of waste-management practices that are environmentally sustainable [150].

### 8.3 Lack of awareness and training.

Lack of awareness and training is a major setback to the effective disposal of waste in the construction industry. According to empirical research, poor awareness of the critical competence together with insufficient training of construction professionals fosters suboptimal waste minimization and waste management practices [151]. Many contractors and employees demonstrate insufficient knowledge of the best practices or the partial adoption of the latter, which proves in the form of the occasional disposal and inhibited adoption of the environmentally friendly waste management measures [152].

Regular sensitization initiatives, special training modules, and supervisory control have proven effective in alleviating waste disposal habits and enhancing the integration of environmentally friendly approaches at construction sites [153]. Waste prevention efficacy is inherently intertwined with the knowledge, attitudes, and behaviors of construction practitioners, and thus, there is a need to continuously educate and build capacities [154]. By intervening in these gaps via legislative measures, corporate programs, and communal educational campaigns, we can make a significant contribution to the waste minimization and compliance with the regulatory requirements [155].

### 8.4 Technical and logistical limitations.

Disposing of construction waste is, to a great extent, hindered by technical and logistical constraints. Such typical issues are the lack of adequate infrastructure to collect, transport, and process the collected waste and inefficient routes and schedules of transport, which may lead to unlawful dumping and higher expenses [156]. The lack of an adequate waste classification program, capacity at approved landfills, and their inadequate incorporation of automation or information technology make safe and effective disposal complex [157].

Transport bottlenecks, inadequate communication between actors, and ineffective streamlined systems to monitor and control construction and demolition of waste are other challenges [156].

Also, dangerous waste in old buildings requires professional control and segregation that complicates logistics and demands technical skills and careful deconstruction planning [157]. These limitations can be mitigated by investing in infrastructure and establishing more robust regulatory frameworks as well as embracing modern technologies to track and process waste [157].

## 9. PROPOSED FRAMEWORK FOR SUSTAINABLE WASTE DISPOSAL IN CONSTRUCTION SITES

### 9.1 Principles.

The core components of the circular economy, life-cycle thinking, and the hierarchy of 3R (reduce, reuse, recycle) are the elements of the basic framework of sustainable construction and demolition waste (CDW) management. The goal of the circular economy plans is to keep the materials and resources in closed cycles, which reduces the amount of waste and environmental impact by encouraging reuse, recycling, and material recovery in the life cycle of a building [158, 159]. Life-cycle thinking is an additional approach to this one because it considers the environmental impacts of construction materials and processes from the design phase to demolition and in doing so encourages informed decisions that minimize waste at each phase of a project [160, 161].

The 3Rs chain of command puts waste avoidance (reduce) as the most important, with the reuse of materials and recycling coming next, and is integrated into European and global CDW management frameworks [162]. It is possible to note practical applications of these principles in approaches like modular design, standardization of materials, the pre-demolition audit, and introduction of new technologies, which help to increase the efficiency of resources and contribute to the achievement of sustainable development objectives [163, 164]. In addition to decreasing the use of landfills and extraction of virgin resources, the combination of these methods evokes the innovation, enhances the environmental performance, and leads to the development of the economical construction industry [165].

### 9.2 Core Components

The proper construction waste management (CWM) is a systematic pattern that consists of actions: prevention, on-site management, recycling and recovery, and, finally, safe disposal. The most effective strategy is prevention, or source reduction, and it is realized by means of the careful process of the selection of the materials, the efficient design of the constructions, and the effective construction processes. This is the phase that has been generally recognized to be critical in promoting sustainable results [166]. Strict compliance with project plans, reduction of design changes, segregation of waste streams, and maximization of on-site reuse are additional practices of on-site management that reduce generation of waste and increase efficiency of the project as a whole [169].

Recycling and recovery are the supplementary alternative measures to prevention and on-site management. It has been shown that recycling and segregation at the source greatly decrease environmental effects and costs of disposal and, in the process, recycle valuable materials [170, 171]. Waste that cannot be prevented, reused, or recycled only needs to be disposed of in a safe manner, preferably in controlled landfills that are designed in such a way that they reduce negative impact on the environment and human health [172, 173].

Combining these elements, which are strengthened through the supportive policy actions and financial incentives, is what sustainable CWM is built upon. This strategy is not only reducing the environmental footprint of the construction industry, but it also provides efficiency in the use of resources and economic sustainability in the long run [174, 175, 176].


Figure 3. The Four Stages of Waste Management

### 9.3 Enablers

Construction waste management (CWM) is effective depending on the sound policy frameworks, monetary incentives, stakeholder partnership, and intensive training programs. Clear national, regional, and municipal policies supported by explicit regulations, guidelines, and governmental control are essential towards creating standards and promoting best practices [177]. Contractors and interested parties may be encouraged to engage in sustainable behavior through monetary instruments in the form of subsidies, incentives, and other types of economic mechanisms, but the effectiveness of these instruments mostly depends on their careful design and implementation [178].

Stakeholder engagement is another key component, as it will require synergetic work from the government, the industry, and citizens to achieve closed-loop waste management and accelerate the process of transition to a circular economy. Often the state plays the major role of coordinating such cooperation [179]. In addition, awareness and competency are increased through educational initiatives and training programs for construction workers, contractors, and project managers.

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Figure 4. Driving success through Enablers

**9.4 Monitoring and Feedback.**

A cyclical process of continuous enhancement that includes frequent monitoring, feedback, and adjustment is essential to attaining long-term development in construction waste management. Consistent audits and checks and the introduction of new technologies enable the stakeholders to monitor the performance, spot inefficiencies, and perfect the management strategies in the long run [180]. This is a cyclic mechanism that makes policies, financial mechanisms, and cooperative efforts relevant, efficient, and receptive to the changing needs of the industry and environmental goals [181, 182].

## 10. FUTURE DIRECTIONS AND RESEARCH GAPS

**10.1 Standardized global datasets on construction waste.**

The standardizedstandardized global data on construction and demolition waste (CDW) are few, and the procedures of collecting and reporting about data used show a lot of variety in sovereign states and geographic regions. Although the European Union has undertaken the necessary steps towards harmonizationharmonization by submitting annual national reports and by using the EUROSTAT data, the varied methods of data collection, the fact that waste coding systems are different across the states, and the fact that various countries still use the term "backfilling" are the obstacles to achieving true cross-country comparability and the creation of a completely integrated dataset [183].

On the regional or metropolitan level, there are a few large datasets. A good example is the study of 4.9 millennium CDW loads in Hong Kong, which provides useful information but is still not consistent with the global standardizationstandardization actions [184]. More recent developments include the Construction and Demolition Waste Object Detection Dataset (CODD), which represents a collaboratively developed benchmark aimed at enabling automated waste sorting, as well as being adaptable towards research priorities. Literary surveys also highlight the need to have a standardizedstandardized information protocol and unified data structure, as well as interoperability of digital platforms such as Building Information ModellingModelling (BIM) systems and waste knowledge basesbases to enable automated, consistent quantification of projects and regions [185, 186].

In general, though these efforts are an important step in the right direction, global CDW dataset standardizationstandardization still has not been achieved and, therefore, requires a greater level of international cooperation and collective action towards achieving digital standardizationstandardization [187, 188]. 188].

**10.2 Integration of AI/ML for predictive waste management.**

However, the combination of artificial intelligence (AI) and machine learning (ML) is transforming predictive waste management through the ability to monitor, predict, and optimizeoptimize waste collection, sorting, and recycling operations in real time. Waste generation rates, collection routes, and the types of waste can be prognosticated andprognosticated and classified with a high degree of accuracy at an early stage bystage by means of AI-driven models, frequently paired with Internet of Things (IoT) sensors, which will enable a company to increase its operation efficiency and reduce its impact on the environment [189, 190, 191]. To take examples, random-forest models and combined deep-learning models have demonstrated over 90% accuracy in terms of bin fill levels and waste classification and result in timely interventions and more efficient resource distribution [192, 193].

The use of AI-powered systems also helps with automated waste sorting and increases recycling rates, whereas advanced constructs that use genetic algorithms and reinforcement learning can optimizeoptimize scheduling and adapt to changing conditions [194]. According to reviews, such technologies promote the principles of the circular economy and correspond with the objectives of global sustainability; however, there are still certain issues, including those related to the quality of data, privacy, and the absence of common datasets [195, 196]. Further investments in AI/ML integration, interdisciplinary cooperation, and digital infrastructure areare hence the only way to make the most of the benefits of predictive waste management, especially in urban and smart-city settings [197, 198].

### 10.3 Biodegradable and Circular Building Materials.

According to recent research, there has been a growing trend towards using biodegradable and circular construction materials as a way of minimizing environmental impact and promoting a more sustainable agenda. Geopolymer concrete is one of the most popular eco-friendly substitutes forfor traditional Portland cement-concrete andcement-concrete and is made of industrial, municipal, and agricultural wastes, which is in line with the goals of a circular economy and also has a positive impact on various objectives of the United Nations Sustainable Development Goals (SDGs) [199]. Likewise, the biomass (agricultural waste) in the form of rice husk ash and sugarcane bagasse ash is being valorized into bio-based construction materials such as cement, concrete, and bricks, with a good provision of environmental gain as well as an economic opportunity [200].

Moreover, recycled thermoplastic wastes are being introduced in composite building materials and are improving the performance of the mechanical properties along with aiding the recovery of resources and minimizing dependency on virgin polymers [201]. All these developments underscore an increasing tendency towards a circular economy in the construction industry, i.e., material reuse, recycling, and life-cycle assessment as elements of sustainable development improvement [200, 201].

### 10.4 Policy Innovations.

Policy innovation is crucial in creating the shift towards circular construction. Demonstrated to provide trust, decrease time spent on negotiations, and promote sustainable development in the construction and demolition waste (CDW) management, green procurement strategies such as innovative types of public-private partnerships and relational contracting have been established [202]. Legislation can help to change the situation, e.g., by imposing minimum levels of reuse and recycling, incentivizing stakeholders to implement circular practices, etc. [203]. Moreover, the green credit policies are also important in reducing financing constraints and enhancing green innovation among the construction firms [200]. Despite the fact that the literature, particularly on waste credit trading in the construction industry, has been less researched, available literature places significant emphasis on the need to enhance government policies and encourage cross-sector collaborations to enhance the aspects of circularity and long-term sustainability [201].

Table 4. Identified Research Gaps and Proposed Research Directions.

| Research gap | Why it matters | Proposed research directions | Representative in-text citations |
|---|---|---|---|
| Poor quantification & inconsistent metrics for C&DW flows | Inconsistent measurement of generation, composition and fate prevents cross-study comparison and scaling of solutions. | Develop standardized protocols and open datasets for C&DW quantification; harmonize metrics across regions; integrate real-time monitoring (sensors, IoT). | [204] |
| Limited life-cycle (LCA) evidence for recycled / alternative materials | Without robust comparative LCAs, recycled substitutes may appear beneficial but could shift impacts elsewhere in the life cycle. | More comparative LCAs of recycled vs virgin materials including regional supply-chains and end-of-life scenarios; build open LCA databases for construction materials. | ([205,206] |
| Gaps in translating circular-economy theory into practice | CE frameworks are abundant but adoption is limited by technical, contractual and market barriers. | Actionable case studies, pilot projects, business-model research (design for deconstruction, take-back schemes), and policy experiments to align incentives. | [207] |

| | | | |
|---|---|---|---|
| Performance / quality uncertainty of recycled C&D materials | Lack of long-term performance data reduces engineers' willingness to specify recycled materials for structural and finish uses. | Long-term material performance tests, standardized certification procedures, durability and contaminant risk studies for reused aggregates, insulation and other materials. | [208] |
| Weak integration of digital tools (BIM, CircularBIM, material passports) | Digital design & disassembly data could enable reuse, but workflows, standards and interoperability are immature. | Research on Circular-BIM standards, digital tagging / material passports, lifecycle data integration and BIM ↔ asset-management interoperability. | [209] |
| Fragmented stakeholder collaboration & supply-chain barriers | Poor coordination between clients, contractors, recyclers and regulators blocks circular strategies. | Studies on multi-stakeholder governance, contractual forms that share responsibility (procurement models, shared risk/reward), and supply-chain mapping for material loops. | [230] |
| Policy, regulation and market incentive gaps (esp. in developing contexts) | Policies differ widely and many regions lack infrastructure or regulatory drivers for proper CDW management. | Comparative policy studies (developed vs developing), regulatory pilots (deconstruction permits, landfill taxes), and economic modelling of incentives/subsidies. | [231] |
| Social sustainability and community impact under-studied | Environmental indicators alone miss social outcomes (jobs, health, equity, community resilience). | Integrate social indicators into sustainability assessments; participatory research with affected communities; evaluate social value from circular projects. | [232] |
| Knowledge gaps on construction defects, rework and behavioural causes of waste | A large share of on-site waste comes from rework, poor planning and human factors, not just material choice. | Research linking human factors, training and process redesign to measurable waste reduction; ergonomics, lean construction and behavioural interventions. | [233] |
| Limited evidence on whole-project waste-avoidance (not just downstream recycling) | Waste hierarchy prioritizes avoidance yet most studies focus on end-of-pipe solutions rather than demand reduction. | Research on design choices, modular/offsite prefabrication, and procurement strategies that minimize material demand before waste occurs. | [234] |
| Insufficient standards, certification and market-acceptance mechanisms | Even with evidence, lack of fit-for-purpose standards and accreditation slows adoption of reused/recycled materials. | Develop performance-based standards and accreditation procedures for reused materials; industry trials to build trust and risk-sharing mechanisms. | [235] |
| Emerging materials & technologies (bio-based, low-carbon binders, hydrochar) need scaling and risk assessment | Promising new materials require techno-economic, environmental and health risk studies before deployment at scale. | Pilot deployments, environmental & health risk assessments, techno-economic analyses and supply-chain sourcing studies to evaluate scalability and circularity. | [236] |

## 11. CONCLUSION

The management of construction and demolition waste should be given a great deal of importance to promote sustainable development and reduce negative environmental effects related to the construction industry. Since this sector is a major source of waste and resource expenditures, it is vital to implement integrated approaches based on the principles of a circular economy, i.e. waste minimization, reuse, and recycling, in order to increase the efficiency of resources and minimize ecological footprints.
Effective policy frameworks with transparent regulations, incentives, and stakeholder involvement are key aspects in the control of sustainable waste practices. However, issues like loopholes in regulations, lack of uniformity, insufficient institutional capability are some of the challenges that hamper improvements. Besides, the lack of an international system of data and unified reporting systems makes it more difficult to evaluate the trends of waste production and the efficiency of waste management practices in different regions. To solve these problems, it is necessary to focus on efforts aimed at creating common standards of data, interoperable digital platforms, as well as international collaboration to enable proper benchmarking and the development of policy based on evidence.
The use of technological innovations is becoming critical in the development of construction waste management. Building Information Modeling (BIM), artificial intelligence (AI), robotics, remote sensing, and blockchain technology are the new opportunities in enhancing the waste sorting, tracking, and recycling processes. Automated systems using data are able to save on labor, improve accuracy and real time monitoring hence improve the organization as a whole. Indicatively, robotic sorting and AI-powered waste detection systems have shown a lot of potential in the optimization of waste sorting and minimization of contaminants.
Moreover, online technologies like unmanned aerial vehicles (UAVs) and intelligent sensors may be used to engage in the site monitoring and pre-demolition surveys and reduce waste production by implementing better planning. Research and automation initiatives to standardize the practices of waste quantification and management on a global scale are facilitated by the creation of exhaustive datasets of such data, such as the Construction and Demolition Waste Object Detection Dataset (CODD).
Notwithstanding these developments, there are still the barriers including high costs of implementation, complexities of the technology, and resistance to change. Governments and other stakeholders in the industry should work together to offer financial incentives, capacity-building programs, and awareness programs that help in the adoption of sustainable practices by many people. The long-term economic gains, such as the expenses of transportation of waste and waste landfill, and social gains of the better environmental condition, support the importance of investing in new waste management technologies.
Going forward, it will be important to focus on the development of common, open, global datasets and standards of digital ecosystems to be able to make more accurate data-driven decisions. Further development of studies of new materials, secondary resource markets, and design practices that are eco-efficient will assist in the switching to circular models of construction. Sustainable construction waste management requires a complex set of strategies that will include the effective policies, technological development, collaboration with the stakeholders, and data management. Through collaboration, the construction industry can develop into a resource efficient, environmentally conscious and economically viable future.

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