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State-of-the-art on Recycling of Construction and Demolition Waste in a Circular Economy: An Approach Towards Sustainable Development

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INFORMATION

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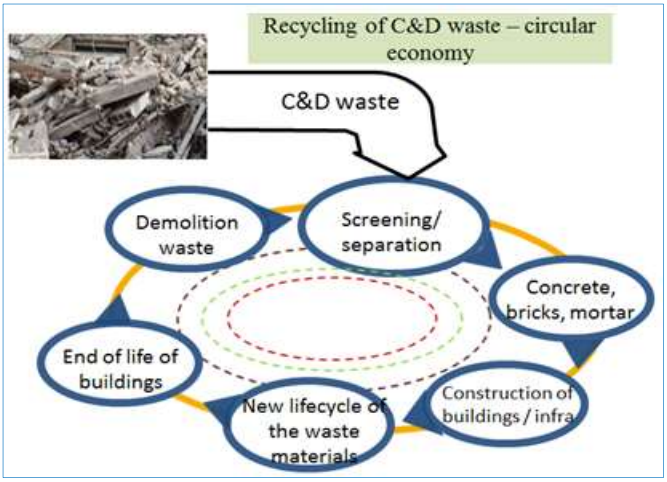
GRAPHICAL ABSTRACT



ABSTRACT

The exponential growth of global population, economic development, and urbanizatio has demanded more infrastructure and utilities, causing the accumulation of a larg volume of construction and demolition (C&D) waste and subsequently increasing pressu on natural construction materials with a high depletion rate. Various research studies hav proven that C&D waste has enormous potential to use it as construction materials. Acros the globe, the recycling rate of C&D waste is varying from 5% to 95%; worldwide, th current economy towards C&D waste management is not in a favorable position, mainl raising more demand of the raw materials, the construction the sector needs to take seriou measures on fulfilling the demand gap of raw materials and increase resource efficiency The development of technology to recycling of C&D waste as secondary materials ca supplement natural construction materials and would be a viable solution to eliminat environmental pollution, alleviate the problem of waste, and meet the demand fo construction materials. Worldwide at present generation of C&D waste is almost 10 billio tonnes, only 9% is recycled, and rests have remained as the unmanaged condition. T promote recycling facilities of C&D waste on a large scale, policymakers, and Governmer authorities should be informed about various options and the scope of the recycling an valorization of C&D waste. This paper describes the present state of the art of recyclin and valorization opportunities of C&D waste through the circular economy principl leading to replenishing the depletion of natural construction materials and increasing th sustainability of the natural resources.

List of Abbreviations and Symbols

C&D	Construction and Demolition
CE	Circular Economy
GDP	Gross Domestic Production
GHGs	Green House Gasses
IBPs	Industrial by Products
SMEs	Small and medium-sized enterprises
UN	United Nation

1. Introduction

1.1. General background

On our planet earth, resources are limited, increasing consumption and growing accumulation of waste materials; adopting the strategies for integrated and sustainable waste management and recycling & reuse of waste is essential for sustainable development (Zorpas, 2020; Das et al., 2019; Corona et al., 2019).

On the one hand, the increasing waste accumulation has overburdened the biosphere to an unsustainable level, so much so that it has lost the auto regeneration capability; on the other hand, natural resources have depleted to a level of scarcity.

In an increasingly global population and infrastructure development have greatly accelerated the waste generation rate (Duan et al., 2019; Wang et al., 2021); since last few decades, globally, the overall expansion and development of urbanization have reached 54.3% in 2016, and today it is more than 55% (UN Report, 2018; Aslam et al., 2020).

A report published by "Global Construction (2030)" stated that *"Volume of construction output will grow by 85% to $15.5 trillion worldwide by 2030, with three countries – China, US and India – leading the way and accounting for 57% of all global growth"*. Worldwide, building and construction influence the three major environmental, social, and economic factors primarily related to sustainable development. This sector creates significant employment opportunities and major revenue generators (Smol et al., 2015).

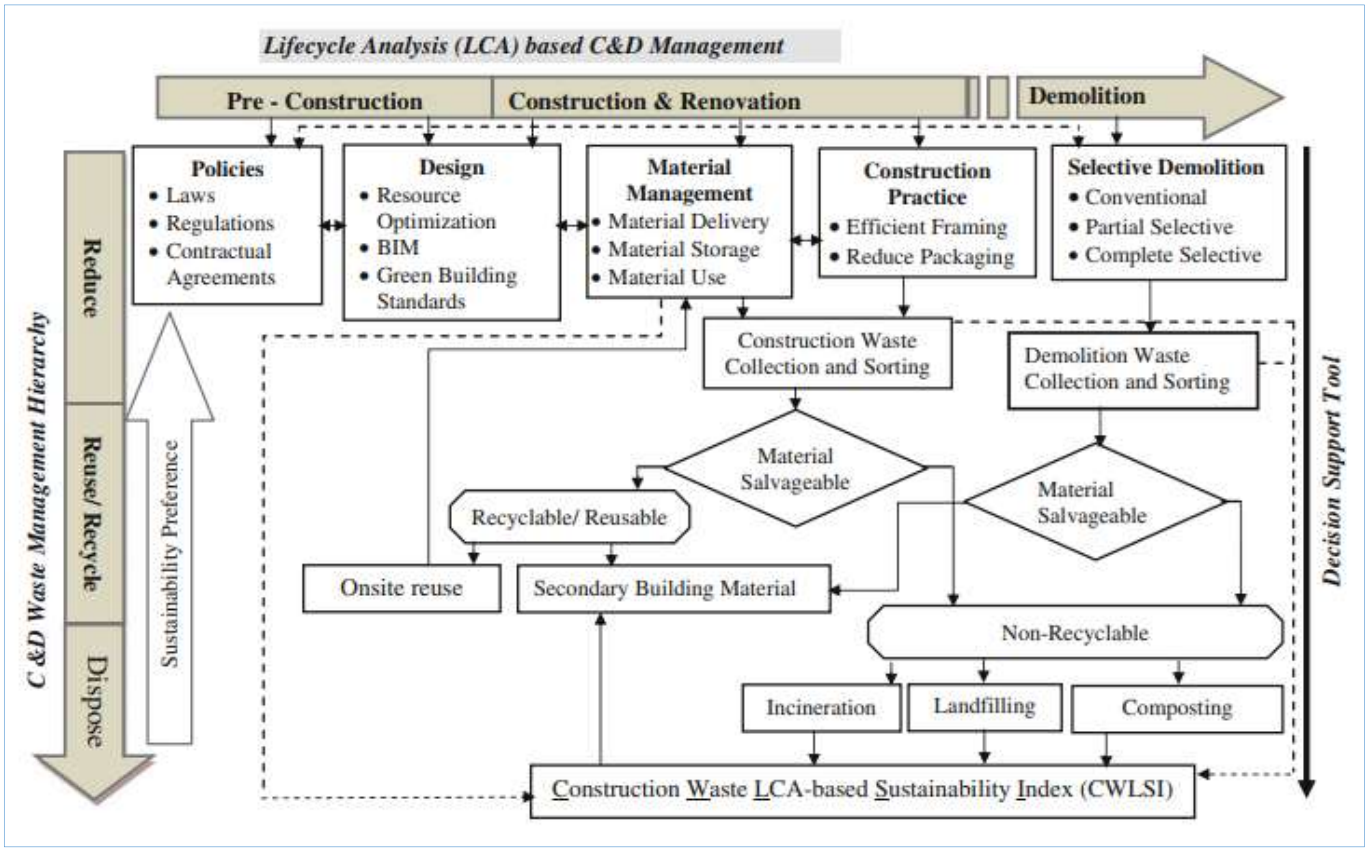


Fig. 1. Concept of lifecycle-based integrated C&D waste management (Yeheyis et al., 2013)

In 2016, the building, construction, and infrastructure sector contributed 6.2% of the world's GDP (Balemba et al., 2020). However, besides the several economic and social benefits, the C&D waste from the building and construction sector creates significant environmental issues and challenges during the whole lifecycle phase of the buildings (Geng et al., 2017; Ghisellini et al., 2018). Worldwide C&D waste has led to severe problems on environment and resource management (De Meloa et al., 2011), the overwhelming volume of C&D waste generated out of the construction activities in different phases of construction and demolition activities called construction and demolition waste (C&D waste) has increasingly unfolded serious challenges, which detrimentally affects global sustainability. Supplementing the already scarce natural resources with the reuse of C&D waste can potentially reverse this trend and bring in sustainability. Globally, the generation of C&D waste is increasing rapidly, and at present, it reached 10 billion tons per anum (Ali et al.,

2019). The enormous amount of waste generally results from the new construction, maintenance works, demolition, and renovation of the buildings, structures, bridges, roads, and utilities (Silva et al., 2019). Worldwide, the increasing rate of C&D waste has become a serious issue and challenge from economical cost and its detrimental effect on the environment and biodiversity (Duan et al., 2019; Jin et al., 2019).

To protect the earth's climate and increase the sustainability of the natural resources and the construction sector worldwide, many countries and Nationals have developed various regulations, standards, and initiatives to minimize C&D waste with proper strategy

However, the implementation of necessary rules, guidelines, and provisions requires a clear understanding of magnitude with the feasibility of material composition of the C&D waste in the waste stream. C&D wastes have enormous potential to use it in different applications. Since the last two decades, worldwide, many research studies have been developed process technology on recycling and reusing C&D waste in various applications such as recycled aggregate concrete, coarse aggregate and fine aggregates, road base materials, soling materials, and so on.

Through the integrated management process of C&D waste, tremendous opportunities are lying to reduce the volume of junk and increase the recycling and reuse potential of C&D waste; three life cycle stages with 3R policy can manage better and use the full potential of C&D waste, Fig. 1 presented the schematic flow of "Concept for lifecycle-based integrated C&D waste management system" proposed by Yeheyis et al. (2013).

1.2. Global perspectives

The rapid growth of the global population and economic development irrespective of many developed and developing countries has led to increasing the demand for infrastructure development (Avtar et al., 2019), causing the increase in construction and civil engineering activities leading to fast depletion of non-renewable resources. On the one hand, due to the growing demand from urbanizations and the infrastructure sector, natural construction materials are depleting very fast; on the other hand, managing a large volume of C&D waste is a serious challenge faced by the global community. Recycling C&D waste through the circular economy principle can mitigate both the issues and partly supplement the replenishment of natural resources depletion (Esa et al., 2017).

Worldwide, C&D waste has been recognized as a significant component of solid waste, almost 30%-40% of total global solid waste generated every year (Du et al., 2020). Worldwide, the rate of C&D waste generation is constantly increasing, as it was 3.0 billion tonnes annually until 2012 (Akhtar and Sarmah, 2018). At present, it is reached 10 billion tonnes (Ali et al., 2019). Table 1 presents the C&D waste generation for a few selected countries from different research studies.

Table 1. Worldwide generation of C&D waste materials

No	Country	C&D waste generation (million tonnes)	Area (km^2)	Population in 2018 (million)	GDP 2018 (billion USD)	References
1	Hong Kong	18.12	1,050	7.4	363	Bao et al., 2020
2	India	112 to 700	3,287,263	1352	2713	Ramanathan and Ram, 2020
3	Israel	1.5	21,400	9	387.71	Seror and Portnov, 2020
4	Europe	500	10,180,000	741	18000	Seror and Portnov, 2020
5	Australia	20.4	7,692,020	25	1,434	Menegaki and Damigos, 2018 Kabirifar et al., 2020 The World Bank, 2018a; 2018b; 2018c
6	Netherlands	22	33,690	17.2	914	
7	Italy	39	294,140	60.5	2,084	
8	UK	58	241,930	66.5	2,855	
9	France	65	547,557	67	2,778	
10	Germany	86	349,360	83	3,948	
11	United States	534	9,147,420	327	20,544	
12	China	1130	9,388,210	1393	13,608	

Research findings reported that around 40% of the resources of the world economy are practically consumed in the construction industries (Hoang et al., 2020), another way, per year, about 3 billion tons of virgin resource is used for the construction sector (Hossain et al., 2016). Globally, around 35% of C&D waste is remained used for landfilling purposes (Kabirifar et al., 2020). However, country-wise quantity (percentage) of C&D waste of their total solid waste generated every year varies.

Proper planning towards managing a large volume of C&D waste is a key challenge facing all nations across the globe, aiming to increase resource efficiency and minimize resource exploitation; the circular economy is the best concept to managing C&D waste in the various application and productive purposes, however, due to the various crisp barriers, including lack of proper policy, stakeholder initiatives, transitioning from linear economy to circular economy concept in C&D waste management is getting hindered (Mahpour, 2018).

It has been reflected from the different literature that there is huge potential yet to be explored in the context of recycling and reuse of C&D waste for the sake of resource optimization and global sustainable development respectively (Ding et al., 2016; Zheng et al., 2017; Jin et al., 2017; Meng et al., 2018; Duan et al, 2019; EUROSTAT, 2019b; Islam et al., 2019; Mistri et al., 2020; Wu et al., 2020).

Managing C&D waste, particularly in fast emerging economic countries, is gaining global attention. Infrastructure development leads to massive construction without proper planning and capacity to manage associate waste, such as C & C&D waste (Bao and Lu, 2020). The appropriate framework for managing C&D waste is essential in developing infrastructure, economic growth, and renovation of populated areas and urban areas (De Melo et al., 2011). Unsustainable management of C&D waste is a major environmental concern. Landfill and open dumping of C&D waste result in serious consequences, including environmental degradation (air, water, soil, and land pollution), resource exploitation, incurred economic cost, and reduced sustainability on natural resources (Crawford et al., 2017; Akhtar and Sarmah, 2018); also there are many negative consequences of C&D waste, on the flip side various research studies revealed that C&D waste has huge potential to use it in different application especially for building materials and road construction, etc. (Hossain et al., 2016).

2. Potential Advantages of C&D Waste

Using C&D waste through the recycling process is a sustainable approach towards supplementing natural resources, reducing pollution and GHGs, energy optimization, and enhancing economic development, Potential advantages of C&D waste in the different applications presented in Table 2.

3. Best Practiced of C&D Waste from Different Case Studies

Worldwide, Scientists, Researchers, Industrial ecologists, emphasizing the adverse effects and impact of industry on the environment, have developed optimization strategies, including the recycling and reusing of waste materials. Globally, the optimization in consumption of natural resources is considered an essential plan in the strategic planning for the industries. It has found best practices in respect of sustainable development. Recently, effective utilization of C&D waste has been considered a best practice concerning sustainable development, presented in Table 3 from various research studies.

4. Circular Economy Approach Towards Valorization of C&D Waste

The increasingly multidirectional problem of C&D waste causes global concerns towards the sustainability of future resource management. The best approach aims to effectively utilize non-renewable resources and energy optimizations, transforming from a linear economy to a circular economy in the global context. In the present situation of C&D waste accumulating in the biosphere leads to a serious environmental impact on the biodiversity, ecology, and flora & fauna, which are mainly associated with the demolition of building and construction elements, processing new construction & building materials and dumping of huge C&D waste with low recovery rates.

To mitigate the situation arising out of C&D waste, the approach of the circular model on production and consumption is a potential solution towards managing the bulk amount of C&D waste for productive purposes, as the principle of circular economy is a sustainable approach towards resources and energy optimization and minimization of the environmental impacts of the product life cycles.

However, the circular economy principle implementation towards managing C&D waste is hindered by many critical bottlenecks that are to be found and addressed to overcome the obstructions to manage this kind of waste. Based on various literature definitions, the circular economy business model offers an advantage to the traditional linear "take-make-use-dispose" economy, which pollutes and degrades the environment, damaging biodiversity and diminishing natural resources. A circular economy is a sustainable model to mitigate resource crisis, reduce environmental pollution and energy consumption by closing the circularity gap, and increase sustainability on virgin resources.

Table 2. C&D waste, its type, and recycling potential (Yeheyis et al., 2013)

Waste component from C&D waste	Potential to use in different applications
Concrete	Concrete production from C&D waste and used for road, building, and other applications
Steel	Used in construction and other sector and recyclable steel
Brick and block	Used as building materials, Backfilling application and, recycled aggregate
Insulation	Used as recycled materials where ever applicable
Glass	Used as pozzolans in cement
Ceramic	As an aggregate (Coarse and fine) for concrete and filling materials
Aluminum	Used for secondary aluminum production
Plastic	For construction materials
Paint	For concrete admixture
Wood	Used in paper & pulp industries
Gypsum board	Used to produce new board/partition tiles
Cardboard	Paper production, fire kindling

5. Zero Waste Concepts for the Industry Through Circular Economic Policy

Globally, the annual generation of C&D waste is 10 billion tonnes; the same can be converted into value-added products with fewer efforts and energy, utilization of C&D waste can supplement replenish of virgin resources used for many essential and relevant applications, reduce energy consumption and GHG through circular economy route, favorable policy framework, regulation can increase the utilization of C&D waste for production applications.

Government intervention on policy framing towards managing and utilizations huge volume of C&D waste would have been playing a vital role in respect of transition of global economies towards closing the gap of circularity and making waste as a resource; proper policy and regulation can lead to the use of 100% C&D waste to a productive application such as building construction, road & highways, and other infrastructure sectors. CE model of C&D waste utilization can increase the availability of resources, minimize waste generation, and replenish the depletion of natural construction materials. While forming the policy, framework, and regulations for enhancing C&D the utilization facilities of C&D waste, the following bottleneck needs to be addressed.

- ✓ Favorable policy formation
- ✓ Implementation of Code and Standard
- ✓ Promotion of public awareness
- ✓ Restriction to landfilled by C&D waste
- ✓ Incentives for the users of C&D waste
- ✓ Tax facilities for setup of C&D waste processing unit
- ✓ Flexible licensing systems for setup of the C&D processing unit

Despite the potential of C&D waste as secondary raw materials in the present market, the reuse and utilization of C&D waste into the built environment is still hindered by many barriers. Ghaffar et al. (2020) published data in respect of difficulties on utilization of C&D waste areas *"Highest setback being logistics (41%), followed by cost (29%), time/H&S regulations (12%), and other (6%). Other studies have identified the lack of C&D waste recycling and reuse certification standards, effective sorting, and the lack of balance between the demand and supply in the recycling and reuse market as other impeding factors to the circular construction concept. Additionally, project stakeholders' attitude towards implementing on-site sorting and the associated management efforts influence the on-site sorting and processing of C&D waste"*. Major bottlenecks on implementing the circular economy principle to manage the large volume of C & C&D waste are as follows.

Table 3. Best practiced of C&D waste from different research studies

Construction Phase	Description (Best practiced)	References
Design	Planning to use soil from C&D waste in the inside construction activities	Begum et al., 2009
Design	Best way to provide a separate space/storage arrangement in the construction site for efficient management of C&D waste	Wang et al., 2010
Design	Proper planning to use directly C&D waste in different construction activities or where ever applicable to use in the same worksite	del Río Merino et al., 2010
Design	Use prefabricated components/elements of the construction systems that can be a way to reduce limited C&D waste or industrialized systems generating limited waste	Tam et al., 2007; Shen et al., 2009
Design	Optimize all design basis systems so that it can be possible to reduce materials consumption and subsequently reduce the C&D waste generation	Osmani et al., 2008
Design	Design the constructive systems and elements in such a way that segregation of the element of the C&D waste at the end of useful life would be easy and can be recycled and reduced with minim cost of the processing	Shen et al., 2009
Design	Select the materials category for construction activities that must have the potential to use as secondary material	Poon et al., 2001; Wang et al., 2010
On-site	Dedicated cell for managing C&D waste at work site	Ghisellini et al., 2018
On-site	On-site segregation facility for each C&D waste category results would be maximum recovery rate of recycling and reuse of C&D waste	Gangolells et al., 2014; Wang et al., 2010
On-site	Using portable crushers and plants for or on-site processing of CDW	Wang et al., 2010
On-site	Proper monitoring and coordination of C&D waste management	Gangolells et al., 2014
On-site	Register and record the generation of quantities of C&D waste materials and manage them properly	Lu and Yuan, 2010
On-site	Vendors, Contractors, and suppliers should manage their product waste	Tam, 2008
On-site	Planning to store C&D waste categorically in the specified spaces	del Río Merino et al., 2010

- ✓ Lack of appropriately and well-planned recycling facilities
- ✓ Absence of advanced technology on recycling facilities
- ✓ Lack of awareness among the generator and user
- ✓ Lack of government initiatives
- ✓ Lack of proper code and standards to implement the uses of C&D waste through the recycling process
- ✓ Knowledge gaps on potential utilization of C&D waste and business opportunities towards valorization of C&D waste
- ✓ Lack of initiatives on the collection of C&D waste from the source
- ✓ The private parties' lack of interest in developing process technology towards processing and recycling C&D waste
- ✓ Lack of training facilities and awareness programs to the stakeholders, publics that C&D waste is wealth and valuable resources
- ✓ Government should form a region-wise policy on the C&D waste utilization
- ✓ Deficiency in implementing of integrated C&D waste management plan
- ✓ Lack of initiatives to promote and develop C&D waste processing plants with advanced technology.
- ✓ Improper treatment of C&D waste
- ✓ Low collection efficiency of C&D waste

- ✓ Lack of pre-waste treatment facilities
- ✓ Low penetration of advanced technology for processing C&D waste
- ✓ Insufficient investment of private player
- ✓ Low adoption of C&D waste materials for the construction and building sector
- ✓ Lack of a sustained campaign
- ✓ Lack of policy guidelines on restricting to use of natural construction materials
- ✓ Subsidy on using C&D waste materials
- ✓ There is no favorable price based on the location for selling C&D waste valorization.
- ✓ Unfavorable market forces
- ✓ Lack of investment opportunities for value chain establishment
- ✓ The presence of an informal market
- ✓ Consumer forces Commodity prices
- ✓ Lack of initiatives and infrastructure for collection, storage, and processing of C&D waste
- ✓ Unfavorable market forces affecting utilization of C&D waste
- ✓ Lack of legal framework, policies, and incentives facilities for valorization approach of C&D waste
- ✓ Lack of political support and low level of awareness of environmental and economic
- ✓ Benefits of recycling, most of the cases, recycling are not considered a priority in government programs and budgets,
- ✓ Lack of support for collection systems to ensure that the demand for utilization of C&D waste is met.
- ✓ Legislation is not enforced; policy decisions are not in line with legislation.
- ✓ Development or revision of legal instruments
- ✓ Adoption of supportive policies
- ✓ Measures to raise awareness among politicians, stakeholders, private sector, SMEs, and civil society
- ✓ Strengthening enforcement through global, regional networks and partnerships
- ✓ Strengthening of cross-border cooperation
- ✓ Different national regulatory requirements for the management of recyclable materials
- ✓ Engagement through global or regional trade agreements
- ✓ Possible approaches to support capacity building and funding
- ✓ Legal, policy, and governance challenges at the international, national and sub-national levels
- ✓ Disposal capacity and process
- ✓ There is no strict law and regulation to prevent landfilling and open dumping of C & C&D waste.
- ✓ Less interest on significant investments
- ✓ Lack of Government Initiative in respect of promoting mission zero waste (C&D waste)
- ✓ Delay in necessary approval and responses from the Government official pertaining to the operation of processing plant
- ✓ Lack of policy frameworks, especially in the context of Managing IBPs such as C&D waste
- ✓ Transparency of information systems among the Government and Industry partner
- ✓ Introduce code and standards on the secondary product from C&D waste as building materials so that users can use the products from C&D waste from the market

6. Role of Stakeholders Towards the Implementation of Circular Economy Principle for the Sake of Global Sustainable Development

The transition from a linear economy to a circular economy is one of the essential components for changing industry culture to achieve global sustainable development specified by the United Nations. The stakeholder should play a vital role in finding a sustainable approach towards protecting ecosystems, resource conservation, and mitigating global warming and climate change. The following few essential points about the role of stakeholders, defined by the United Nations (UN Report, 2015), are as follows.

- ✓ Established a dedicated R&D center to deal with C&D waste
- ✓ Stakeholders should recommend appropriate policies and regulations to utilize the full potential of C&D in the valorization context.
- ✓ All stakeholders jointly organized an awareness program for C&D valorization.
- ✓ Promote technology development cell and startup facilities
- ✓ Participate in setting clear goals and policies towards managing and recycling C&D waste through the circular economy business model
- ✓ Cooperation to form standards and codes for user convenience for the materials and products developed out of the C&D waste recycling process
- ✓ Initiatives to open up a processing plant to create valuable products through the recycling of C&D waste
- ✓ Initiatives to open up the circular economy industrial park to utilize 100% potential of C&D waste
- ✓ Investor facilities
- ✓ Foreign collaboration to establish a more scientific, advanced, and efficient recycling processing unit
- ✓ Implementing the circular economy principle in the industrial process by the comprehensive collaboration of stakeholders would be a viable solution towards sustainable development.

7. Policy Relevance in the Global Context Towards Managing C&D Waste

The suitable model for policy and regulatory framework on managing C&D waste is an urgent need globally. The future policy options available with the policymakers for managing C&D waste are to promote necessary schemes and facilities within the framework of policy and regulation by the Government with the alliance of industry partners and R&D experts. Few issues in managing C&D waste causing barriers, which need to be addressed at the earliest while forming the necessary policy about the valorization of C&D waste with the circular economy principle to promote sustainable development, are as follows.

- ✓ Strengthen the policy in respect of environment governing land issues
- ✓ Strengthen and reformation needs on existing policy so that private parties can join and develops process

technology towards recycling and reuse of C&D waste
- ✓ Government should form a region-wise policy on the C&D waste recycling, reuse, and utilization
- ✓ Policy on mandatory adoption/utilization of C&D waste to reduce dependency on natural construction materials.
- ✓ Fixation of proper buying and selling price of C&D waste
- ✓ Reform market regulations and strengthen market functioning across states
- ✓ Reinforce existing policy initiatives already underway for the valorization of C&D waste
- ✓ Clarify organization structure, roles, and responsibilities at the Government level by bringing key policies and regulations under a single umbrella
- ✓ Flexible licensing systems to promote C&D waste recycling and processing plant.
- ✓ Favorable environmental law in respect of C&D waste recycling process
- ✓ Insurance scheme, Start-up facilities
- ✓ Financing facilities to set up a plant
- ✓ Emerging circular economic concept
- ✓ Policy to Introduce Code and Standard
- ✓ Guideline to design LCA to reduce waste
- ✓ Policy for compulsory use of C&D waste as secondary products wherever applicable
- ✓ Policy for restricting the use of natural resources
- ✓ Policy for limiting the use of certain unsustainable methods or technology to specific Industries
- ✓ The particular policy required for penalties wherever applicable

Conclusions

Effective valorization of C&D waste can be possible through the circular economy business model with the coupling of advanced recycling technologies, which leads to producing many value-added raw materials and compensating the demand-supply gap of the building materials in the construction sectors. There is an urgent need for dedicated research to find out the hinders, barriers, knowledge gap, and policy deficiency towards utilization of the full potential of C&D waste, leading to accelerate the valorization of C&D waste and increase sustainable development. Government intervention and stakeholder initiatives are essential for proper policy formation towards managing a massive amount of C&D waste, accelerating the valorization process in many folds, thereby supplementing a portion of virgin construction resources, boost-up economic growth, increasing national GDP, opening up entrepreneurial opportunities, create more employment opportunities, and improve overall sustainability.

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