Framework to Identify Directions for Future Construction and Demolition Waste Management Technologies

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Abstract. Effective waste management is essential for sustainable urban development, and Construction and Demolition (C&D) waste poses a significant challenge due to its volume and composition in urban regions. In recent years, technological advancements have offered innovative solutions to improve the management of C&D waste. This exploratory study primarily uses secondary data and draws on case studies from 5 Indian cities and global literature on technological innovations in C&D waste management to propose a preliminary framework for identifying how different technologies can play a vital role and where they can be incorporated into the reverse supply chain of C&D waste in the Indian urban context. This paper paves the road for future research that will use this initial framework to identify more practical technological solutions based on a thorough understanding of ground reality, improving chances of technology adoption.

Keywords. Construction and Demolition Waste, Technology, Reverse Supply Chain, Efficient Waste Management, Innovative Solutions

1 Introduction

C&D waste is a common by-product of building and infrastructure construction, renovation, and demolition. Quantum of C&D waste is proliferating worldwide, specifically in emerging economies such as India and China. While over 90 per cent of the C&D waste can be easily reused or recycled, the lack of recycling remains a challenge in many countries worldwide. For example, less than 1% of waste is recycled in India, as per the official estimates [1]. The environmental impact of lack of recycling of C&D waste is concerning, as studies estimate that recycling a metric ton of C&D waste instead of sending it to a landfill prevents the release of approximately 6.41 kg of CO_2-eq emissions into the atmosphere. Moreover, this recycling effort conserves around 89.93 MJ of primary energy and saves 0.32 m^2 of potentially arable land from being utilised for waste disposal [2].

Technologies can potentially play an important role in promoting the efficiency of C&D waste management and alleviating waste disposal's environmental and social effects. For example, a case study in China highlighted challenges in the C&D waste recycling industry, identifying one of the critical challenges as the absence of a technology-enabled effective waste tracing system across the reverse supply chain of the C&D waste [3]. In India, similar challenges in implementing proper C&D waste management may stem from the need for appropriate technologies for handling the C&D waste reverse supply chain. Despite the extensive literature on technological advancements in C&D waste management across reverse supply chains, literature has also provided evidence for low technology adoption among the relevant stakeholders. One of the essential reasons for this is the need for more compatibility between the capability of the technology and the demands of the C&D waste management processes. As such, it is clear that technological innovations must be based on a thorough understanding of the C&D management process on the ground and the concerns and perceptions of the stakeholders involved in order to ensure the successful uptake of any technological advancements. This paper is the first step in this direction. The primary goal of this study is to map the process of C&D waste across multiple Indian cities to identify the potential areas of technology needs and to propose a preliminary framework for C&D waste management using the technologies available. This framework will focus intensely on existing technologies while also identifying various directions for future technological advancements and their vital roles or integration within the existing C&D waste reverse supply chain. The proposed framework will be further validated and strengthened based on direct engagements with stakeholders and primary data collection in the near future.

The structure of the paper is as follows: Section 2 includes the details of extensive literature on the topic. Section 3 outlines the methodology. Section 4 provides case studies and technology mapping. Section 5 delves into the future research area and the critical academic contribution along with the conclusion are presented in Section 6.

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2 Literature Review

A study by C. Zhao Li et al. examines the research on the use of information technologies in C&D waste management from 2000 to 2019 and identifies eight advanced technologies to address C&D waste management [4]. For example, Building Information Modeling (BIM)-based tools and technologies help deal with C&D waste throughout life [5]. However, many of these technologies have primarily focused on the design and construction phases, neglecting post construction aspects [6]. Geographical Information System (GIS) is also one of the technological advancements that are proven to be effective in the identification and evaluation of C&D waste in urban regions and finding the area under potential risk of illegal dumping on a city level [7], [8]. Another study showcases the 100 per cent precision of employing an NIR hyperspectral system for sorting waste under a controlled environment [9]. GIS integrated with technology like Global Positioning System (GPS) can enhance waste minimisation through on-site material and equipment management [10]. A group-based Incentive Reward Program (IRP) aimed at motivating construction workers to minimise material waste based on Radio Frequency Identification (RFID) and Bar Code (BC) technology proves to be effective in reducing waste [11]. Several academic studies have highlighted the application of Computer Vision (CV) techniques in addressing distinct challenges, including the classification problem of various constituents present in the C&D waste in a controlled environment [12], Estimating the waste truck payload volume [13], and Semantic segmentation used to recognise the composition of construction waste mixtures [14]. Image analysis (IA) technology helps conduct quality assessments of recycled aggregate production in C&D waste recycling facilities [15] and predict the landfill landslide [16]. 3D Reconstruction (3DR) is a process of creating a three-dimensional representation or model of an object or scene from two-dimensional images or sensor data. The literature presents two areas in which 3D reconstructions work in C&D waste management; one is to develop a 3D BIM-based framework to improve accuracy and efficiency in deconstruction waste management, focusing on identifying recyclable materials and planning recycling processes [17]. Another is to compute the volumes of C&D waste in landfills by applying mobile mapping technology provided by GeoSLAM (Simultaneous localisation and mapping) [18]. A study demonstrates that an innovative approach effectively integrates various technologies, such as Drones, CV, GIS, and 3DR, which shows better results in the final quantification and mapping of C&D debris [19]. Big Data (BD) is adopted in C&D waste management to analyse massive amounts of information generated from C&D waste to settle landfill management issues [20].

The variety of technologies available suggests the advancement in C&D waste management. However, this body of work often fails to take into consider the ground realities around real needs within the C&D reverse supply chain, or stakeholder perception, preferences, and capacities that can problematize the adoption of technologies. A paper focused on China's recycling industry for C&D waste highlights the absence of an efficient waste tracing system, lack of accurate estimation of waste quantity and distribution and inadequate collaboration among various stakeholders as key challenges [3]. This discussion implicitly showcases the need to assess on-the-ground challenges in order to make the technological advancements more efficient and acceptable to the stakeholders in the system.

3 Methodology

To provide a comprehensive understanding of the current application of technologies in C&D waste management, this study collected secondary data from five Indian cities on their C&D waste management process and visually represented this data as a schematic flowchart. To obtain information on the different municipal corporation reverse supply chains of C&D waste like Delhi, Gurugram, Kolkata and Jaipur, case studies from the Centre of Science and Environment (CSE), India [21], were used. For Chennai, data was collected by field visits to the C&D recycling plant and collection zones of Chennai. Moreover, the study thoroughly examined existing global literature on the use of technology in C&D waste management. The systematic analysis of the gathered literature identified eight technologies as potentially valuable components of the reverse supply chain for C&D waste. These technologies were then mapped vis-à-vis the current C&D waste reverse supply chain for Indian cities based on expert inputs from two of the authors with substantial experience in this field.

4 Analysis

4.1 Case Studies

The generic C&D waste reverse supply chain in Indian cities generally involves waste generation, collection, transportation, weighing, sorting, recycling, landfilling, and selling recycled products, in addition to some degree of illegal dumping, as shown in Fig. 1 for Gurugram and Jaipur. (i) *Waste Generation*: It includes C&D waste generated during building and infrastructure construction and demolition activities. C&D waste generators are commonly classified as either small or bulk generators, depending on the waste quantity they produce; (ii) *Waste Collection*: Waste from small generators is gathered at the source and transported to collection points, whereas waste from bulk generators is directly sent to recycling facilities, bypassing collection; (iii) *Waste Transportation*: Waste generated by small generators is transported by dedicated vehicles from designated collection points to the recycling facility, and waste from bulk generators is directly transported to the recycling facility; (iv) *Waste Weighing*: The waste is carefully weighed to

determine quantities at recycling facilities; (v) *Waste Sorting*: The waste is sorted into categories, such as whole bricks, concrete blocks, and mixed C&D waste; (vi) *Waste Recycling*: Whole bricks are typically sold or used internally, while other materials undergo recycling processes to manufacture recycled products; (vii) *Landfilling*: Any waste deemed unsuitable for recycling is directed to landfills; (viii) *Selling of Recycled Products (Reselling)*: Recycled products are sold to the market or used for various applications, contributing to sustainability and resource conservation.
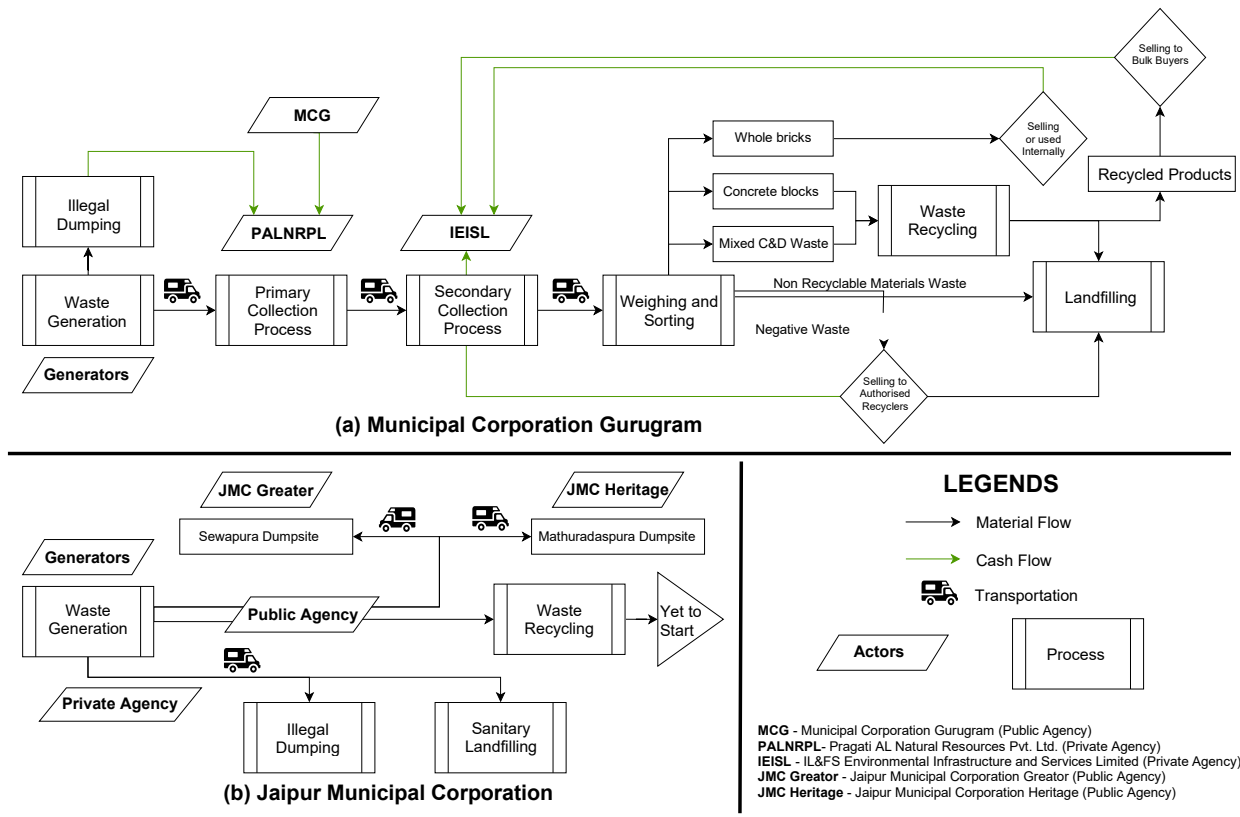
Fig. 1. Schematic diagram of C&D waste reverse supply chain (a) Municipal Corporation Gurugram
(b) Jaipur Municipal Corporation

Each Indian city has variations in its approach and level of development in C&D waste management, as shown in Fig. 1 Gurugram has a well-established system that employs an additional secondary collection process. In contrast, New Delhi closely mirrors Gurugram's approach to management, handles 5000 TPD (tonnes per day) and follows strict bylaws. While facing similar challenges, Chennai requires individuals to obtain permission before depositing waste directly at recycling facilities. Kolkata's system is still in its early stages, with two distinct methods: formal and informal deposition of C&D waste. Despite introducing C&D waste bylaws early on, Jaipur faces challenges, with much of the waste ending up in dumpsites or landfills, and its recycling plant needs to be updated. These differences underscore the diverse strategies and maturity levels in C&D waste management across Indian cities.

4.2 Technology Mapping

After conducting an in-depth analysis of C&D waste reverse supply chains of various cities and reviewing existing literature on integrating technology into supply chains, a technology mapping was performed to evaluate the current state of C&D waste management in India. The mapping was done by initially identifying various processes involved in a typical C&D waste reverse supply chain, as shown in Table 1 Subsequently, among the eight technologies identified from the literature, an evaluation was conducted by two authors with substantial experience in the field of C&D waste related research to determine which one of the technologies is currently available and which areas still require further development. For example, regarding waste generation, literature showcases the prediction of waste generated from the 3D BIM model, the use of GIS for the identification of waste and illegal dumping, the use of RFID/BC for reducing onsite C&D waste and the use of 3DR for deconstruction management but other technologies like CV, IA, GPS, and BD were observed to have no work contributing to the waste generation process. Similarly, all the processes were mapped based on the technology available.

Table 1. C&D Waste Management Process and Technology Mapping

Technology	Waste Generation	Waste Collection	Waste Transportation	Waste Weighting	Waste Sorting	Waste Recycling	Landfilling	Reselling
BIM	Waste Prediction [6]	⊗	⊗	⊗	⊗	⊗	⊗	⊗
GIS	Illegal Dumping & Identification [7], [8]	⊗	⊗+	⊗+	Separation Algorithm [9]	⊗	⊗	⊗
GPS	⊗	⊗	M&E* Management [10]	⊗	⊗	⊗	⊗	⊗+
RFID/BC	Reducing on-site C&D waste [11]	⊗	⊗	⊗	⊗	⊗	⊗	⊗+
CV	⊗+	Monitoring of waste containers[12]	⊗	Estimating truck payload volume[13]	Classification of Different waste [14]	⊗+	⊗	⊗
IA	⊗+	⊗	⊗+	⊗	⊗	Quality Assessment of Recycled Products [15]	Landfill Landslide Prediction [16]	⊗
3DR	Deconstruction Management [17]	⊗+	⊗+	Mapping and Quantification [18], [19]	⊗	⊗	⊗+	⊗
BD	⊗	⊗+	⊗+	⊗	⊗	⊗+	Landfill Management [20]	⊗+

M&E* - Materials and Equipment's

⊗ - Processes where technology do not exist.

+ - Potential processes where technology can be developed.

The results revealed that most technologies benefit waste generators or the initial stages of the waste generation process. Conversely, such technologies have limited applicability or availability for other processes within the reverse supply chain. It is also visible through the technology mapping that there is a need for work to be done in the payment process of selling recycled products.

5 Discussions

Most of the studies on technology remain focused on improving the current state of the technology rather than ensuring that it is acceptable and is being used to its full potential in the reverse supply chain of C&D waste. As such, after mapping technologies vis-à-vis the processes in the C&D waste management, the potential for alternative use of these technologies in different stages of the C&D waste reverse supply chain was explored based on their characteristics.

This exploration revealed the following opportunities for alternative/additional uses of the technologies within the reverse supply chain of C&D waste: (i) *Waste Generation*: CV, IA can be used for quality control of waste incoming at collection points. Light Detection and Ranging (LiDAR) and Photogrammetry can be used at generation points to roughly estimate the quantity of C&D waste, along with a specific semantic segmentation algorithm that can be integrated into the system to identify the contaminants present in the waste; (ii) *Waste Collection*: Another use of 3DR can be the experimental setup to quantify the C&D waste at the collection points. The use of BD can streamline the data collection process for analytical purposes and forecasting future incoming waste volumes by leveraging historical records; (iii) *Waste Transportation*: GPS can be embedded in vehicles for real-time monitoring of C&D waste transportation. Other technologies like IA, 3DR, and BD, which hold lots of potential, can be used to predict the waste to be transported. GPS can record and log data on the movement of waste materials from their source to disposal sites. This data can be used for auditing, compliance reporting, and optimising transportation routes; (iv) *Waste Weighing*: GIS and 3DR technology can map waste storage areas inside recycling plants. Installation of a camera setup around the waste storage area will be helpful for the calculation of volume; CV algorithms can be proposed to predict the volume of waste by photogrammetry, LiDAR, or drones equipped with cameras can be employed for this purpose; (v) *Waste Sorting*: CV systems can also help identify hazardous materials and ensure their safe disposal. Robots equipped with cameras and sensors can be used to automate the sorting process; (vi) *Waste Recycling*: Integration of CV and BD can be incorporated into the recycling process to ensure any deviations from established quality standards can trigger immediate corrective actions; (vii) *Landfilling*: 3DR can be used for virtual inspections, reducing the need for physical visits to landfilling sites and minimising the environmental impact; (viii) *Reselling*: BD can provide information on market demand for recycled products and help the recycling facility identify the consumers and plan production accordingly.

6 Conclusion

The framework developed in this study is a preliminary attempt to develop a matrix that can be a valuable tool for identifying a) where in the C&D waste management process currently available technologies are being used to improve efficiency in the Indian context and b) where else within this reverse supply chain can we potentially use these and perhaps

additional technological innovation. As such, this work contributes to the academic literature by helping researchers identify gaps in the reverse supply chain of C&D waste where there is a need for new technological applications. and where, within the C&D waste management process, alternative uses of existing technologies may be explored. For instance, no technology exists in areas of reselling, waste transportation, and waste collection. Some identified technologies that can be further developed are mobile-based LiDAR or photogrammetry-based rough quantity estimation of waste at the generation point. GPS can be embedded in vehicles for real-time monitoring of C&D waste transportation.

The authors acknowledge that the proposed framework is based on secondary data, and it will be strengthened and validated through primary data, specifically drawing on stakeholder interviews with those involved in the various stages of C&D waste management. Furthermore, the paper currently focuses on the gaps in terms of different stages of the waste management process where technological innovations are missing/lacking. However, future work will consider the gaps in terms of implementation potential so that the framework is more realistic and resonates with ground realities, stakeholder perceptions, and institutional challenges. This will allow future research to develop relevant technologies that are more likely to be adopted within the C&D waste management system across Indian cities and possibly other developing countries.

Acknowledgement

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