Natural Resources for Human Health
eISSN: 2583-1194

Original Research
Received 18 May 2026
Revised 25 June 2026
Accepted 10 July 2026

Natural Resources for Human Health 2026, Vol. 6 (12s): 213–220

KEYWORDS:
Construction and demolition waste management, Thermal recycling, chemical recycling, legal disposal, illegal dumping, Activity-Based Costing.

Mathematical Model for Sustainable Construction and Demolition Waste Management

U. Modenisha[1], W. Ritha[2]*

[1]Research Scholar, Department of Mathematics, Holy Cross College (Autonomous), Affiliated to Bharathidasan University, Tiruchirappalli, Tamil Nadu, India.
[2]Associate Professor, Department of Mathematics, Holy Cross College (Autonomous), Affiliated to Bharathidasan University, Tiruchirappalli, Tamil Nadu, India.
Corresponding author: *ritha_prakash@yahoo.co.in, modenishahcc@gmail.com

ABSTRACT: An estimated 3 billion tons of solid waste (garbage, ashes, residues, combustible and non-combustible, hazardous, and sewage) are generated annually, with 25-30% coming from construction and demolition waste (CDW). Despite relatively high daily waste generation rates per capita, most developing countries do not have a comprehensive waste management system. In order to balance operational costs, environmental effects, and resource recovery, construction and demolition (C&D) waste management necessitates methodical decision-making. This study suggests a generalized Activity-Based Costing (ABC) framework for using a mathematical optimization approach to assess different C&D waste management strategies. The framework unifies recovery benefits, activity costs, environmental and regulatory costs, and costs associated with illegal disposal into a single cost model. Two disposal scenarios are developed: (i) legal disposal that includes resource recovery and recycling, and (ii) illegal disposal that does not include recycling but includes environmental liabilities and regulatory penalties. To allocate recyclable waste in a way that satisfies waste balance constraints and minimizes the overall cost of legal disposal, an optimization model is created. To compare the two disposal strategies' economic performance, a numerical example is provided. The suggested model illustrated the economic benefit of sustainable waste management techniques by showing that illegal disposal led to a significantly higher total cost of Rs. 4,779,060.00, while the legal disposal model decreased the overall waste management cost to Rs. 828,222.50. The result helps converse resource, environmental preservation, and enhanced public health, all of which support sustainable societal development.

INTRODUCTION

Because it uses a lot of raw materials and produces a lot of CDW, which includes inert, non-hazardous, and hazardous fractions, the construction industry is well known for being a significant source of environmental pressure [1]. According to recent reviews, CDW can contain contaminants like heavy metals, fine residues, and persistent organic compounds, so managing it is crucial for protecting human health and the environment in addition to recovering resources [2]. Legal frameworks, financial incentives, and penalties are crucial for changing CDW management from disposal to recovery-based systems at the policy level, according to recent research [3].

Additionally, research indicates that recycling incentives, landfill taxes, and punitive measures can affect contractor behavior, decrease illicit dumping, and boost markets for recovered materials and recycled aggregates [4]. Because it makes it easier to track the costs of recycling, thermal or chemical recovery, landfill use, and penalties across waste-management activities, evaluating legal and illegal disposal using an ABC-based framework is helpful in this situation. This facilitates the assessment of how various policy tools impact CDW management disposal decisions and sustainability outcomes [5]. Activity-Based Costing's ability to assess waste-related activities by connecting operational procedures with their corresponding cost drivers is demonstrated by its effective use in healthcare waste management. According to these studies, ABC offers better cost visibility and encourages sustainable waste management choices, indicating that the methodology can be successfully applied to other waste-intensive industries, such as waste management in construction and demolition [6].

Large amounts of debris are left over from natural disasters and construction and demolition projects. Despite increasing efforts to recycle and reuse CDW, it is estimated that 35% of CDW produced globally ends up in landfills without any further processing. Not all stakeholders, including contractors, building firms, and the general public, acknowledge the significance of recycling CDW. Life expectancy is decreased by illegal waste dumping and non-recyclable waste. It should be mentioned that the Welsh government charges a fine of Rs. 10,000 for improper disposal of waste [7]. Since January 2017, those who have disposed of building debris illegally have been fined Rs. 1.71 crore by civil authorities [8]. The 3-R principle: reuse, recycle, and reduce is crucial for improving the sustainability of construction and demolition waste management [9]. Thermal recycling and chemical treatment are two examples of contemporary recycling methods that can help improve waste management. The process of burning waste in the presence of oxygen to recover energy that can be used to produce heat or electricity is known as thermal recycling. Chemical recycling is the process of converting waste polymeric materials back into materials that can be utilized as raw materials to create new products.

MATHEMATICAL MODEL

Notations

Q_C : Total collected C&D waste (ton)

Q_S : Total sorted waste (ton)

Q_R : Reused waste (ton)

Q_{NR} : Non-reused waste (ton)

Q_T : Thermal recyclable waste (ton)

Q_{CH} : Chemical recyclable waste (ton)

Q_{REC} : Total recycled waste (ton)

Q_D : Waste disposed in landfill (ton)

L : Number of labourers (persons)

W : Monthly wage per labourer (Rs./month)

c_C : Collection cost per ton (Rs./ton)

c_S : Sorting cost per ton (Rs./ton)

c_R : Reuse cost per ton (Rs./ton)

c_T : Thermal recycling cost per ton (Rs./ton)

c_{CH} : Chemical recycling cost per ton (Rs./ton)

c_{TR} : Transportation cost per ton (Rs./ton)

c_D : Landfill disposal cost per ton (Rs./ton)

c_E : Environmental cost per ton disposed (Rs./ton)

c_{EM} : Carbon emission cost per emission unit (Rs./unit)

E : Emission quantity (emission units)

c_{LT} : Landfill disposal tax per ton (Rs./ton)

p_E : Energy recovery price (Rs./MWh)

r_E : Energy recovered per ton (MWh/ton)

p_M : Material recovery price (Rs./ton)

r_M : Material recovered per ton

P_F : Fixed penalty for illegal dumping (Rs.)

P_U : Penalty per ton of illegally disposed waste (Rs./ton)

c_{ULT} : Unauthorized landfill tax (Rs./ton)

c_{REM} : Landfill remediation cost (Rs./ton)

c_{WT} : Waste transfer to legal disposal site (Rs./ton)

T_L : Total legal disposal cost (Rs.)

T_{IL} : Total illegal disposal cost (Rs.)

C : Total activity cost (Rs.)

P : Environmental and regulatory cost (Rs.)

R : Recovery benefit (Rs.)

I : Illegal-disposal-specific cost (Rs.)

Waste balance equations

The total sorted waste is divided into reused waste and non-reused waste.

$$Q_{NR} = Q_S - Q_R$$

The non-reused waste is further partitioned into recycled waste and landfill disposal.

$$Q_{NR} = Q_{REC} + Q_D$$

The recycled waste consists of thermal and chemical recycling.

$$Q_{REC} = Q_T + Q_{CH}$$

Hence, $Q_D = Q_{NR} - Q_T - Q_{CH}$

These equations ensure mass conservation throughout the waste management process.

Activity Cost Equations

The labour cost is $C_L = LW$

Collection cost is $C_C = c_C Q_C$

Sorting cost is $C_S = c_S Q_S$

Reuse cost is $C_R = c_R Q_R$

Thermal recycling cost is $C_T = c_T Q_T$

Chemical recycling cost is $C_{CH} = c_{CH} Q_{CH}$

Transportation cost is $C_{TR} = c_{TR} Q_S$

Landfill disposal cost is $C_D = c_D Q_D$

Therefore, $C = C_L + C_C + C_S + C_R + C_T + C_{CH} + C_{TR} + C_D$

Environmental and Regulatory Cost

Environmental cost is $P_E = c_E Q_D$

Emission cost is $P_{EM} = c_E M_E$

Landfill tax is $P_{LT} = c_{LT} Q_D$

Hence, $P = P_E + P_{EM} + P_{LT}$

Recovery Benefits

Energy recovery is $R_E = r_E Q_T p_E$

Material recovery is $R_M = r_M Q_{CH} p_M$

Hence, $R = R_E + R_M$

Generalized ABC Objective Function

The total cost of a waste-management strategy is represented as

Model 1 – Legal Disposal

$$T_L = C + P - R$$

Model 2 – Illegal Disposal

For illegal disposal there are no recycling benefits.

Natural Resources for
Human Health
eISSN: 2583-1194

The illegal-disposal-specific costs are

$$I = P_F + P_U + c_{ULT} Q_D + c_{REM} Q_D + C_{WT} Q_D$$

Therefore,

$$T_{IL} = C + P + I$$

Optimization Model

$$\min T_L$$

Subject to $Q_T + Q_{CH} + Q_D = Q_{NR}$

Waste balance : $0 \leq Q_T \leq Q_T^{max}$

Recycling capacity: $0 \leq Q_{CH} \leq Q_{CH}^{max}$

Disposal: $Q_D \geq 0$

Non-negativity: $Q_T, Q_{CH}, Q_D \geq 0$

where Q_T, Q_{CH}, Q_D are decision variables.

PROBLEM DESCRIPTION

Large amounts of waste are produced by C&D operations, which call for effective management to lessen their negative effects on the environment and the economy. There are several ways to dispose of waste from sites, including direct reuse, thermal recycling, chemical recycling, and landfill disposal. Each of these methods has unique operational costs, environmental externalities, regulatory fees, and recovery benefits. Conventional cost-estimation techniques handle these pathways independently and do not provide an integrated framework to compare the best allocation of recyclables, illegal disposal, and legal disposal. This study creates an ABC framework for the management of C&D waste that allocates costs to particular activities and integrates recovery benefits, landfill taxes, environmental costs, and illegal-disposal costs into a single mathematical model. Two scenarios are developed: Model 1, which combines recycling and resource recovery with legal management, and Model 2, which involves illegal disposal without recycling and includes fines, unapproved landfill taxes, and remediation expenses.

NUMERICAL EXAMPLE

The quantities of waste produced, activity costs, environmental costs, recovery benefits, and costs associated with illegal disposal were all chosen as model parameters. These values are used as input data for optimization and for assessing the models of legal and illicit disposal.

Table 1. Waste quantities

Parameter	Value
Collected waste	495 ton
Sorted waste	495 ton
Reused waste	90 ton
Non-reused waste	405 ton
Thermal recyclable waste	150 ton
Chemical recyclable waste	75 ton

Recycled waste	225 ton
Landfill disposal	180 ton

Table 2. Activity cost parameters

Parameter	Value
Labour wage	10,000 Rs./month
Number of labourers	8 persons
Collection cost	170 Rs./ton
Sorting cost	170 Rs./ton
Reuse cost	170 Rs./ton
Thermal recycling cost	300 Rs./ton
Chemical recycling cost	400 Rs./ton
Transportation cost	284 Rs./ton
Disposal cost	693 Rs./ton

Table 3. Environmental parameters

Parameter	Value
Landfill tax	553 Rs./ton
Environmental cost	682 Rs./ton
Emission cost	430.625 Rs./emission unit
Legal emission quantity	900 units
Illegal emission quantity	3200 units

Table 4. Recovery and illegal disposal parameters

Parameter	Value
Energy recovered	1.0 ton/ton
Energy selling price	1600 Rs./ton
Material recovered	0.8 ton/ton
Material selling price	2000 Rs./ton
Fixed penalty	10,000 Rs.
Unauthorized landfill tax	828 Rs./ton
Landfill remediation	2293 Rs./ton

A 495-ton C&D waste stream is represented by the numerical example. After sorting, 405 tons are available for additional treatment, and 90 tons are immediately reused. There are 225 tons of recycled material and 180 tons that need to be disposed of in a landfill after 150 tons of the non-reused waste are set aside for thermal recycling and 75 tons for chemical recycling. Using the parameter values shown in Tables 1-4, the ABC framework calculates all activity costs, environmental costs, recovery benefits, and costs associated with illegal disposal [10,11]. The best recycling allocation under the legal disposal model is then determined by comparing the legal and illegal disposal scenarios using these input data.

RESULT AND DISCUSSION

The economic performance of legal and illicit C&D waste management strategies was assessed and compared using the suggested ABC framework in the numerical example. The illegal disposal model resulted in a significantly higher total cost of Rs. 4,779,060.00, whereas the legal disposal model produced a total management cost of Rs. 828,222.50. This comparison shows that, when environmental liabilities, regulatory fees, and recovery benefits are fully included in the cost evaluation, legal waste management with recycling offers a more economically viable option than illegal disposal under the presumptions of the suggested framework.

By assigning 150 tons of waste to thermal recycling, 75 tons to chemical recycling, and the remaining 180 tons to landfill disposal, the optimization model further determined the lowest-cost legal disposal strategy. This allocation reduced the total cost of legal management while meeting the waste balance requirements. The optimization result attests to the fact that efficient use of the recycling pathways that are available significantly lowers the overall cost of waste management without going against operational restrictions.

The recovery of valuable resources through recycling and the avoidance of additional environmental and regulatory liabilities associated with illegal disposal are the main reasons for the legal strategy's economic advantage, according to a comparison of the two disposal models. The framework allows for systematic cost estimation, comparison of disposal scenarios, and identification of economically efficient waste allocation strategies by combining mathematical optimization with Activity-Based Costing. The suggested model can support sustainable decision-making in construction and demolition waste management because it is sufficiently adaptable to accommodate various waste quantities, cost parameters, and regulatory conditions.

CONCLUSION

By combining operational activities, environmental costs, recovery benefits, and costs associated with illegal disposal into a single mathematical formulation, this study proposed a generalized ABC framework for assessing C&D waste management strategies. The optimization results confirmed that the suggested mathematical model effectively determines how to allocate recyclable waste in a way that minimizes costs while meeting waste balance requirements. Additionally, when environmental liabilities and regulatory costs are included in the costing framework, the comparative analysis revealed the substantial financial burden of illicit disposal. When assessing alternative C&D waste management strategies, researchers, policymakers, and waste management practitioners can use the transparent and methodical decision-support tool offered by the proposed model.

REFERENCES

[1] Tan, R., Wu, Y., Su, P., Liao, R., & Zhang, J. (2023). Optimal dynamic incentive mechanism design for construction and demolition waste recycling with Bayesian learning. *Journal of Cleaner Production*, *412*, 137371. https://doi.org/10.1016/j.jclepro.2023.137371

[2] Lee, S., Chang, H., & Lee, J. (2024). Construction and demolition waste management and its impacts on the environment and human health: Moving forward sustainability enhancement. *Sustainable Cities and Society*, *115*, 105855. https://doi.org/10.1016/j.scs.2024.105855

[3] Wang, Q., Jiang, T., Liu, L., Zhang, S., Kildunne, A., & Miao, Z. (2023). Building a whole process policy framework promoting construction and demolition waste utilization in China. *Waste Management & Research*, *41*(4), 914-923. https://doi.org/10.1177/0734242X221126393

[4] Calvo, N., Varela-Candamio, L., & Novo-Corti, I. (2014). A dynamic model for construction and demolition (C&D) waste management in Spain: Driving policies based on economic incentives and tax penalties. *Sustainability*, *6*(1), 416-435. https://doi.org/10.3390/su6010416

[5] Rocha-dos-Santos, W. J., Leite, W. C. D. A., & Schalch, V. (2022). Application of activity-based costing in solid waste management: a case study. *Engenharia Sanitaria e Ambiental*, *27*, 1105-1111. https://doi.org/10.1590/S1413-415220220104

[6] Lawal, G. S. (2024). Activity-Based Costing Models for Sustainable Healthcare Waste Reduction. https://www.researchgate.net/profile/Lawal-Anand/publication/396593897_Activity-Based_Costing_Models_for_Sustainable_Healthcare_Waste_Reduction/links/68f2b656ffdca73694b89dbf/Activity-Based-Costing-Models-for-Sustainable-Healthcare-Waste-Reduction.pdf

[7] Welsh Government. (2024). *Landfill disposals tax rates*. Retrieved September 29, 2024, from https://www.gov.wales/landfill-disposals-tax

[8] Times of India. (2019, November 9). *Corpn to set up two units to process construction waste*. https://timesofindia.indiatimes.com/city/chennai/corpn-to-set-up-two-units-to-process-construction-waste/articleshow/71976138.cms

[9] Invest India. (2024). *Waste to wealth*. https://static.investindia.gov.in/s3fs-public/2020-01/agb_3_waste.pdf

[10] Muthu Selvi, K., & Ritha, W. (2023). Mathematical model to improve the environmental performance of construction waste management. *Tuijin Jishu/Journal of Propulsion Technology, 44*(3), 2561–2570. https://doi.org/10.52783/tjjpt.v44.i3.749

[11] EPEM S.A. (2024). *Cost data for waste collection and transport*. WASTE-C-CONTROL Database. https://www.epem.gr/waste-c-control/database/html/costdata-00.htm