Asian Journal of Water, Environment and Pollution. Vol. 22, No. 4 (2025), pp. 18-27.
doi: 10.36922/AJWEP025090061

ORIGINAL RESEARCH ARTICLE

Post-war solid waste management in Adigrat, Ethiopia

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Received: February 28, 2025; 1st revised: March 6, 2025; 2nd revised: May 24, 2025; 3rd revised: May 31, 2025; Accepted: June 9, 2025; Published online: June 30, 2025

Abstract: Waste is a general term used to describe materials or products considered largely worthless. This study assesses the current post-war state of solid waste management in the city of Adigrat, Ethiopia. It aims to evaluate household waste generation patterns, disposal practices, and community perceptions toward municipal waste services, identifying gaps and proposing strategies for sustainable recovery. A total of 165 households were chosen randomly from the target demographic using a mixed-method research strategy that combined quantitative surveys and qualitative interviews for comprehensive insight. The study found that the average solid waste generation rate among the 165 randomly selected households was 1.087 kg/household/day. Most respondents (81.8%) disposed of their waste in open areas or drainage systems, and 51.2% expressed dissatisfaction with municipal solid waste collection. These practices have significant implications for public health, urban hygiene, and environmental sustainability. To rebuild the system, governments, non-governmental organizations, and concerned citizens should cooperate through coordinated planning and resource mobilization.

Keywords: Solid waste; Post-war; Households; Adigrat

1. Introduction

Waste refers to materials or products discarded as unwanted or valueless by their owners, regardless of potential use to others.[1] Solid waste, which consists of non-liquid waste resulting from human activities, has always existed but has become increasingly problematic due to urbanization and industrialization.[2,3] Improper disposal – such as open dumping and burning – poses serious environmental and health risks globally. These risks are intensified in urban settings where population densities and consumption levels are high, often overwhelming the capacity of local waste management systems. Moreover, the informal sector, while contributing to waste recovery, often operates in unsafe and unhygienic conditions, compounding health hazards.

Solid waste management (SWM) is a critical public service that municipalities provide to maintain urban cleanliness.[4] Effective SWM systems not only improve environmental quality but also contribute to public health, urban esthetics, and economic productivity. However, cities in developing and post-conflict contexts often face compounded challenges. In Libya's Misrata, inefficient municipal systems have led to uncontrolled waste disposal, creating unsanitary conditions.[5] In Kabul, inadequate funding, governance, and infrastructure undermine effective SWM.[6] Similarly, municipal authorities in many cities struggle with growing waste volumes and high management costs, lacking knowledge

of the interconnected components of waste handling systems.[7] These include waste generation, segregation, storage, collection, transportation, processing, and final disposal. In many cases, weak inter-agency coordination and the absence of long-term planning also contribute to persistent inefficiencies.

Waste composition often varies with income. Low-income households produce more organic waste, whereas higher-income groups discard more paper, metals, and glass.[8] This distinction significantly impacts the choice of waste treatment technologies, as organic-dominant waste is more amenable to composting and anaerobic digestion, whereas recyclables require sorting and market linkages. Common SWM techniques include recycling, composting, incineration, and landfilling. Each of these techniques has advantages and drawbacks depending on local context, climatic conditions, economic feasibility, and social acceptance. Post-disaster and post-conflict waste management largely follow standard procedures but must also handle hazardous and construction waste.[9,10] In such scenarios, the urgency of restoring public services must be balanced with the safe handling of toxic substances, unexploded ordnance, and biomedical waste.

In Abuja, Nigeria, logistical and institutional issues hinder efficient waste collection.[11] In Iraq, post-Islamic State of Iraq and Syria conflict waste, particularly from construction, poses significant management challenges.[12] The prompt removal of debris and hazardous material is crucial in post-war recovery.[13] Failure to address this can delay rebuilding efforts, pose health threats, and erode public trust in institutions. Furthermore, uncollected debris may clog drainage systems, causing secondary disasters such as urban flooding and outbreaks of vector-borne diseases.

Despite rising waste generation (up to 5% annually), low-income countries such as Ethiopia still report moderate per capita rates (e.g., 0.32 kg/day), with organic matter dominating the waste stream.[14] This high organic content offers opportunities for decentralized composting initiatives that can serve as both waste treatment and soil fertility enhancement methods. Recycling efforts are generally limited, often informal, and predominantly inefficient.[15] Informal waste collectors play a critical role in recovering recyclable materials, but they often lack social protection, health coverage, and access to formal market systems. Ethiopia, like many countries, faces inconsistent waste control amid growing urban waste loads.[16] Institutional fragmentation, limited technical capacity, and weak enforcement of environmental laws exacerbate the problem, leading to illegal dumping and burning of waste.

International experiences highlight both problems and solutions. Singapore has long relied on central governance, while Lebanon – post-war and post-2006 conflict – faces unmanaged waste sites and coordination failures.[17,18] These comparative insights reveal that policy consistency, investment in infrastructure, and public awareness are all essential components of an effective SWM system. In Misrata, household waste generation averages 0.552 kg/person/day, largely composed of organic material (52%) and plastics.[19,20] This trend is reflective of many urban centers in the Global South, where changing consumption patterns are increasing the volume of non-biodegradable waste.

The absence of waste infrastructure, such as transfer stations, significantly weakens SWM systems.[21] Without intermediate facilities, waste collection trucks must travel long distances to disposal sites, reducing collection frequency and increasing operational costs. In Bosnia, waste mismanagement in mining areas has led to water contamination and health impacts.[22] Urban population growth has made SWM a global concern, especially in developing nations where collection dominates while strategic planning is minimal.[23] The emphasis on collection often sidelines critical aspects such as waste reduction, reuse, and environmentally sound disposal.

The shift toward privatization in cities such as Hyderabad and Nairobi reflects efforts to improve services through public–private partnerships, though outcomes vary by local governance capacity.[24] In Namibia and Sri Lanka, outsourcing has helped tackle inefficiencies in urban waste management.[25] Successful public–private partnerships depend on regulation, funding, and community engagement. Where governance is weak or public resistance is high, privatization may lead to unequal service delivery or exclusion of low-income neighborhoods. Therefore, regulatory oversight and public participation are essential to ensure equitable access and sustainability.

In India and Kenya, differing state roles affect outcomes – India's centralized control contrasts with Nairobi's donor-driven, grassroots waste initiatives.[26] However, the contributions of informal recyclers often remain overlooked. These workers, who are frequently marginalized due to their class, ethnicity, or immigration status, make up an important but under-appreciated part of the waste economy. Integrating them into formal systems with protective legislation can enhance efficiency while promoting social inclusion.

Studies suggest that waste is not just a technical challenge but reflects deeper issues of social marginalization and environmental justice.[27] Conflicts, such as in Ukraine and Syria, have caused long-lasting damage to waste infrastructure, resulting in uncontrolled disposal and health risks.[28,29] Disrupted governance, displaced populations, and damaged logistics pose challenges in restoring waste services post-conflict. Moreover, international humanitarian responses may inadvertently generate additional waste, stressing already fragile systems and further complicating recovery. Lebanon's 2015 waste crisis highlighted the failures of decentralized governance and the urgency of integrated SWM.[30,31] In many African cities, non-governmental organizations, community-based organizations, and the private sector now play vital roles in SWM due to municipal limitations.[32] These key players often bring innovation, community engagement, and localized knowledge, which are essential to adaptive and context-specific solutions. Bangladesh's experience shows that structured public–private partnerships can enhance urban governance and waste services.[33] Lessons from such examples can inform recovery planning in conflict-affected areas, where institutional rebuilding must go hand-in-hand with service delivery and long-term sustainability.

In line with global trends, many Asian countries are adopting the 3R principles – reduce, reuse, and recycle – to transition toward more sustainable waste systems.[34] These efforts are part of a broader shift toward a circular economy that aims to decouple economic growth from environmental degradation.

Given this context, this study focuses on post-war SWM in Adigrat, Ethiopia, to examine current practices, identify challenges, and recommend sustainable recovery strategies. Adigrat, like many secondary cities, has borne the brunt of war-related disruptions in basic services. Understanding its waste management dynamics in the post-war phase can offer broader insights into similar urban contexts undergoing recovery and reconstruction.

2. Methodology

2.1. Study area

The city of Adigrat is located in the Tigray National Regional State, within the Eastern Tigray Zone of northern Ethiopia. The city is situated 894 km from Addis Ababa and 114 km from Mekelle, the regional capital (Figure 1). It shares boundaries with several neighboring areas: Woreda Gantafeshum Tibia, Tabia

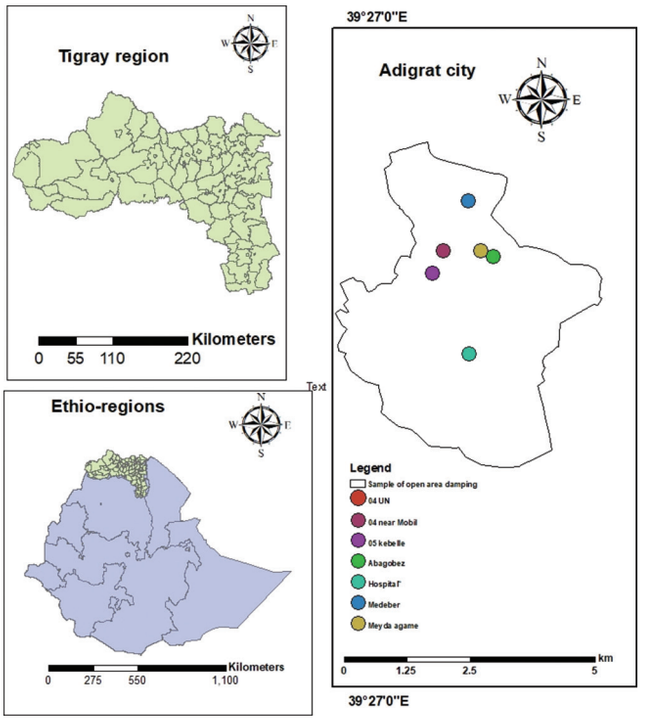

Figure 1. The study area's map

Gola-Genahti to the east, Tabia Sasun to the south, Tabia Beati-Maymesanu to the north, and Tabia Bukot to the west. Geographically, Adigrat is positioned at latitude 14° 20' North and longitude 39° 29' East. The city covers a total area of 4,933 hectares.[35] At present, Adigrat has a population of 90,658 people.[36]

Adigrat covers approximately 4,933 hectares, stretching 5.2 km east–west and 6.8 km north–south. Recently, it has expanded to 63 km east–west and 13 km north–south. An additional 3,055.9 hectares have been designated for the city's 10-year future expansion. The city is divided into six kebeles (wards 01 – 06) and lies along the old Mekelle – Adigrat highway, giving it an elongated form that limits space and infrastructure development.[37]

Elevation in Adigrat ranges from 2,530 m in the southeast to 2,660 m in the west. High elevations are mostly in the eastern and western edges, whereas the proposed expansion zones are lower in elevation. About 36.2% of the town has a slope of <5%, indicating a majority of the land is suitable for urban development.[38] The city experiences a temperate highland climate, which influences both waste decomposition rates and drainage dynamics. Field observations showed widespread disposal of solid waste in open spaces and drainage areas throughout the city (Figure 1).[39] The lack of designated disposal sites, combined with limited

public awareness and insufficient municipal oversight, has contributed to this growing environmental concern. In particular, uncollected waste often clogs stormwater channels during the rainy season, increasing the risk of flooding and waterborne disease outbreaks in low-lying areas.

2.2. Sampling design and method

This study employed a mixed-method approach, combining quantitative and qualitative methods to assess post-war SWM in Adigrat. A total of 165 households were selected using simple random sampling. The sample size was calculated using Kothari's formula,[40] assuming a 95% confidence level and a 5% margin of error (Equation I):

$$s = \frac{Nz^2PQ}{E^2(N-1) + z^2PQ} \quad \text{(I)}$$

Where N represents the estimated population size, *z* corresponds to the *z*-value associated with the desired confidence level, *P* denotes the estimated proportion or prevalence of a characteristic in the population, Q is the complementary probability of *P*, andE signifies the desired margin of error or maximum acceptable sampling error.[40]

2.3. Participant description and field observation

Participants for focus group discussions and interviews included elders, women, youth, religious leaders, and local officials to ensure diverse perspectives. Six kebeles were randomly selected for field observations to represent different parts of the city. The participant age distribution is presented below in Table 1.

Table 1. Demographic characteristics of the participants

Demographic characteristics	*n*	Percentage
Age group		
18 – 30 years	20	12
31 – 45 years	30	18
46 – 60 years	90	54.5
61 years and above	25	15.15
Household size		
1 – 2	20	12.1
3 – 4	50	30.3
5 – 6	80	48.5
≥7	15	6

2.4. Type of data collected during field observation

Both primary and secondary data were collected. The research instruments used to collect data in this study included: (i) a field survey questionnaire, (ii) an interview and focus group discussion, (iii) an observation checklist, and (iv) a document review.

2.5. Qualitative data analysis

Qualitative data were transcribed and coded to identify key themes and patterns. The analysis involved thematic coding, organization into sub-themes, and cross-validation through research team discussions. The Statistical Package for the Social Sciences software (version 20) supported data coding and organization.

2.6. Quantitative data analysis

A linear regression model was used to assess the relationship between respondents' age and their perceptions of the health impact of waste disposal in open spaces. The model evaluated the statistical significance and direction of this relationship. Household solid waste generation rates were derived from both self-reported estimates and physical measurements. During the field survey, a representative subsample of households was selected for direct waste collection and weighing over 3 consecutive days using calibrated scales. These measurements were used to validate and adjust the self-reported data obtained through structured questionnaires. Linear regression was used for statistical analysis in the study.

This mixed approach, combining self-estimates with actual weighing, enhances reliability and is commonly used in contexts with limited infrastructure, such as post-conflict or low-income urban settings.[41] However, it is acknowledged that self-reported data may still underestimate actual waste generation due to social desirability bias or recall inaccuracies.

3. Results

3.1. Family size and waste generation rates

Table 2 illustrates the relationship between household size and daily waste generation. Households with 1 – 2 members generated the least waste at 0.32 kg/household (hh)/day, whereas those with more than seven members generated the most at 1.4 kg/hh/day. The average waste generation rate across all households was 1.087 kg/hh/day.

Table 2. Family size and waste generation rate

Family size	No. of families	Percentage	Waste generation rate (kg/household/day)
1 – 2	20	12.1	0.32
3 – 4	50	30.3	1.29
5 – 6	80	48.5	1.34
>7	15	6	1.4
Total	165	100	4.35 (average: 1.087)

3.2. The municipal solid waste disposal system

According to Table 3, 48.5% of respondents disposed of waste in open areas, 33.3% in drainage channels, and only 18.2% utilized official waste collectors. Field observations confirmed widespread illegal dumping due to a lack of waste bins and irregular collection services, a consequence of infrastructure destruction during the Tigray war. This has led to unsanitary conditions, unpleasant odors, and the proliferation of disease vectors (Figure 2).

According to Figure 2, solid trash is disposed of in open areas and drainage systems (Figure 2A-F). This results in foul odors, unhygienic conditions, and the spread of disease vectors. In addition, it causes drainage blockages, increasing the risk of runoff exposure in surrounding areas. Near the Abagobez site, condominiums are affected by foul odors, an issue exacerbated by their proximity to the drainage system, as shown in Figure 2B. The situation is worsened by the proximity of the Adigrat General Hospital fence.

Figures 2 and 3 illustrate typical solid waste accumulation sites observed across Adigrat, highlighting the extent of environmental degradation and infrastructure challenges faced in the post-war period.

3.3. Satisfactory rating of the municipal SWM

When asked about satisfaction with the municipal waste management services, 51.2% of households expressed dissatisfaction, 24.2% rated the service as poor, and only 24.2% reported being satisfied or rating it as good. This indicates a general lack of confidence in the current waste management system as shown in Table 4.

3.4. Municipal SWM and its environmental impact

As indicated Table 5, respondents identified several consequences of unmanaged solid waste: 48.5% reported odor problems, 22.2% suffered from disease outbreaks, 18.2% cited blocked drainage, and 12.1% noted waste accumulation beside roads. These results indicate that poor waste management has direct public health and environmental implications

Table 3. The municipal solid waste disposal system's frequency and cumulative frequency

Disposal system	No. of respondents	Frequency (%)	Cumulative frequency (%)
Open dump	80	48.5	48.4
To the waste collector	30	18.2	18.18
Throwing into the drainage	55	33.3	33.3
Throwing beside the pond	0	0	3
Covered dustbin	0	0	6
Total	165	10	42.4

Figure 2. Solid waste disposal. (A-F) Images taken in different areas.

3.5. Household solid waste collection

Table 6 reveals that 72.7% of respondents reported irregular municipal waste collection, whereas only 3% received weekly service. This distribution highlights a significant service gap. The predominance of irregular

Table 4. Satisfactory rating of the municipal solid waste management

Satisfaction level	No. of respondents	Frequency (%)	Cumulative frequency (%)
Poor	40	24.24	24.24
Good	20	12.12	12.12
Satisfied	20	12.12	12.12
Unsatisfied	85	51.2	24.24
Total	165	100	100

Table 5. Consequences of the dispersed solid waste management

Problems	No. of respondents	Frequency (%)	Cumulative frequency (%)
Odor problem	80	48.5	48.5
Blockage of drainage	30	18.2	18.2
Waste beside the road	20	12.12	12.12
Diseases	35	22.21	22.21
Total	165	100	100

Table 6. Frequency of household solid waste collection by the municipal authority

Collection period	No. of respondents	Frequency (%)	Cumulative frequency (%)
Daily	0	0	0
Weekly	5	3	3
Monthly	40	24.24	24.24
Irregular	120	72.7	72.7
Total	165	100	100

collection, with a margin of error of ±6.8% at a 95% confidence level, suggests inconsistency in municipal operations. Such unreliability undermines routine waste removal, increasing risks of illegal dumping and public health hazards. The lack of daily or even regular weekly service points to systemic inefficiencies and poor logistical planning by municipal authorities.

3.6. Regression analysis: Age and perception of waste impacts

A linear regression analysis was conducted to examine the relationship between respondents' age and their perception of the health and environmental impacts of dispersed solid waste. The model revealed a statistically significant relationship ($p<0.001$). The adjusted R^2 value was 0.513, indicating that age accounts for 51.3% of the variation in perception (Figure 4).

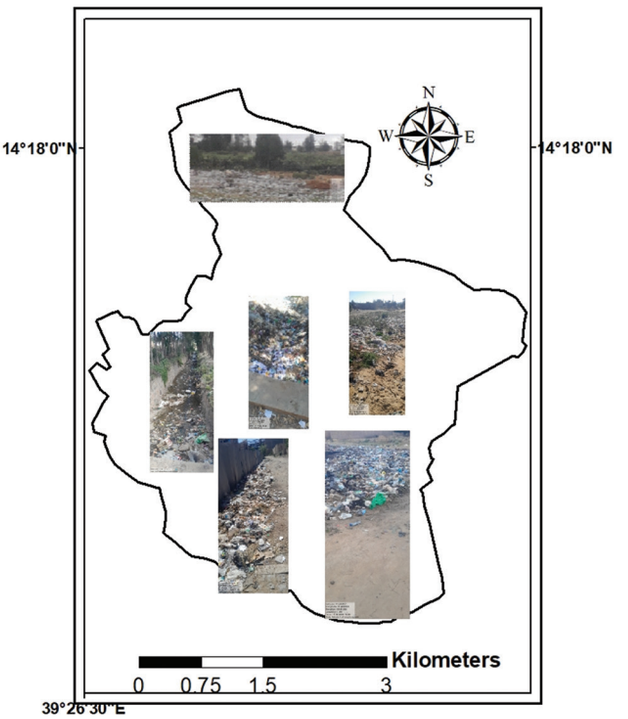

Figure 3. Sample photo of solid waste dumped in open places

4. Discussion

The findings highlight systemic weaknesses in post-war solid SWM in Adigrat, reflecting broader challenges observed in war-affected urban environments. Rather than merely describing disruptions, the data points to a breakdown in service continuity, infrastructure maintenance, and institutional coordination. The observed waste generation rate (1.087 kg/hh/day) aligns with trends in other post-conflict cities, such as Misrata, Libya, where household size and disrupted logistics contribute to increased waste output.[42] This underscores how war-related displacement and demographic shifts can intensify urban waste burdens.

Beyond generation rates, the study exposes acute deficiencies in waste handling practices. With over 80% of households resorting to open dumping or using drainage systems, the city faces escalating public health and environmental threats. These practices are not isolated. Similar behaviors have been reported in Kabul and Mosul, where conflict-induced governance voids led to informal and hazardous waste disposal.[43,44] In

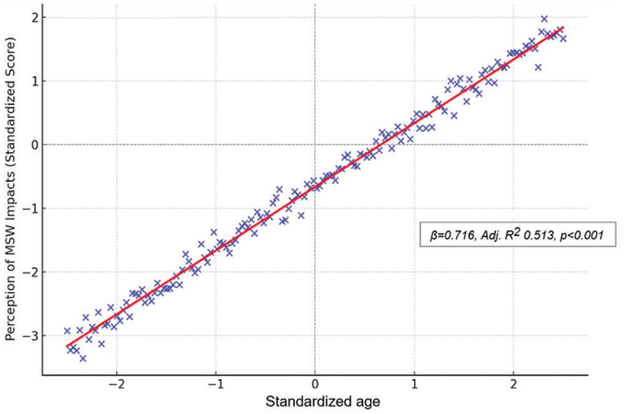

Figure 4. Linear regression analysis shows the relationship between standardized age and perception of the health and environmental impacts of dispersed municipal solid waste

Adigrat, such patterns are caused not only by service interruption but also by limited public awareness and a lack of basic infrastructure such as collection bins and trucks.

Only 18.2% of respondents reported using formal waste collection services, and 72.7% indicated irregular collection. This lack of service continuity reflects deeper issues of governance, capacity, and funding, as also observed in Abuja, Nigeria.[45] Weak institutional frameworks, inconsistent municipal budgets, and fragmented urban planning often lead to erratic waste services. The absence of reliable collection systems leads to waste accumulation in public spaces, which residents linked to bad odor (48.5%), disease (22.2%), and blocked drainage (18.2%). Such localized environmental degradation contributes to declining urban quality of life and often perpetuates a cycle of neglect and disengagement from both citizens and authorities. In flood-prone areas, blocked drainage due to solid waste increases the frequency and severity of urban flooding, exacerbating vulnerabilities, especially for low-income households living in informal settlements.

These outcomes align with patterns documented across other post-conflict and under-resourced urban areas. In Port-au-Prince, Haiti, for instance, similar challenges in post-earthquake recovery were compounded by misaligned donor priorities and a lack of integration with existing municipal systems. The result was an overreliance on temporary waste solutions that failed to transition into sustainable, long-term services. Moreover, the health impacts linked to accumulated waste, ranging from waterborne diseases to respiratory illnesses, disproportionately affect children, the elderly, and immunocompromised individuals.

Satisfaction with municipal waste services was low, with over 75% of respondents expressing dissatisfaction or rating the service as poor. This dissatisfaction reflects a breakdown in trust between the public and local authorities, a challenge also identified in Lebanon and Syria, where municipal services have struggled to regain functionality post-crisis.[46,47] A weak feedback loop between service providers and residents hinders both accountability and responsive planning. In many instances, a lack of transparency regarding collection schedules, service coverage, and complaint mechanisms further alienates communities. When residents perceive no benefit from government services, they are less likely to participate in collective initiatives, comply with regulations, or support user-fee systems, creating a self-perpetuating cycle of failure.

The regression analysis showed a significant correlation between age and perception of health/environmental impacts, with older participants more likely to recognize the dangers of poor waste management. This finding suggests a gap in awareness among younger populations and highlights the need for targeted public education and community engagement programs.[48] Younger residents may be less informed about long-term environmental consequences or may have normalized poor service conditions due to growing up with systemic deficiencies. School-based programs, social media campaigns, and youth-centered clean-up drives can be effective in cultivating environmental responsibility. Moreover, involving local youth in waste audits, awareness campaigns, and monitoring initiatives can foster both engagement and skill development.

These results underscore the urgent need for systematic reconstruction of waste management infrastructure, restoration of service regularity, and inclusion of public outreach. Infrastructure investments must prioritize equipment procurement, route optimization, and personnel training. Furthermore, monitoring tools such as Geographic Information System mapping and mobile reporting apps can help track service delivery and ensure transparency. Public–private partnerships and decentralized waste collection models, successfully implemented in parts of Bangladesh and Kenya, could provide a viable path forward.[49,50] These models often allow for more responsive, cost-effective, and community-driven approaches. In Bangladesh's Dhaka North City Corporation, neighborhood-based micro-collection centers run by cooperatives have improved service efficiency while generating employment.

Similarly, in Kenya, community groups contracted for door-to-door collection have demonstrated increased reliability and stronger resident rapport.

Decentralized models are particularly effective in settings with fragmented urban morphology, where centralized systems struggle with accessibility and resource constraints. However, their success depends on regulatory oversight, incentives, and capacity building. Formalizing informal waste workers through training, protective equipment provision, and integration into official supply chains can bridge service gaps and enhance livelihoods. Encouraging citizen participation through forums, mobile platforms, and waste reduction incentives will also be crucial to fostering a sense of shared responsibility. Ultimately, a multi-pronged strategy combining infrastructure rehabilitation, institutional reform, behavioral change, and community partnership offers the most sustainable pathway for restoring and advancing post-war SWM systems.

5. Conclusion

This study assessed post-war SWM practices in Adigrat City, Ethiopia, using both quantitative and qualitative methods. The findings revealed a high average household waste generation rate of 1.087 kg/hh/day, with a strong correlation between family size and waste output. The majority of households rely on improper disposal methods, such as open dumping and drainage discharge, largely due to inadequate infrastructure and irregular waste collection services following conflict-related damage.

Public dissatisfaction with municipal solid waste services is widespread, and environmental consequences, such as bad odors, blocked drainage, and increased disease risk, are prevalent. The regression analysis showed that age significantly influences perceptions of waste-related impacts, underlining the need for targeted awareness and community involvement.

To improve waste management in post-war settings such as Adigrat, coordinated efforts are needed to rebuild infrastructure, establish regular collection systems, and promote public participation through education and policy reform. Strengthening municipal capacity and encouraging public–private partnerships could also support a more sustainable and inclusive approach to urban waste management.

Acknowledgments

None.

Funding

None.

Conflict of interest

The authors declare they have no competing interests.

Author contributions

Conceptualization: All authors
Formal analysis: Fikre Belay
Investigation: All authors
Methodology Fikre Belay
Writing – original draft: Fikre Belay
Writing – review & editing: All authors

Availability of data

Data will be made available upon request to the corresponding author.

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