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Original Research Article

From Household E-Waste Stocks to Circular Recovery: Integrating Material Flow and Behavioral Evidence in Bangil District, Indonesia

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Abstract

Electronic waste (e-waste) management is often examined as either a material-flow or behavioral issue, with limited integration at the district level. This study integrated stock-based material flow analysis (MFA), household management pathways, knowledge–attitude–practice (KAP) assessment, socioeconomic analysis, and stakeholder interviews in Bangil District, Indonesia. Data were collected through a systematic survey of 200 households and semi-structured interviews. Potential e-waste generation was estimated using device ownership, average weight, and service lifespan, while KAP relationships were analyzed using chi-square tests and Spearman's rank correlation. The estimated potential e-waste generation was 3,727.98 kg year^{-1}, equivalent to 4.94 kg capita^{-1} year^{-1}. Informal collection was the dominant reported pathway, with 74% of respondents selling obsolete devices to informal collectors, while 47% stored unused devices, and only 11% used formal recycling channels. Knowledge and practice levels were moderate (60.48% and 50.66%), whereas attitude was high (78.85%), indicating an attitude–practice gap. Integrating material stocks with behavioral and pathway evidence reveals mismatches between potential material recovery and household management practices. The findings support localized circular economy strategies through accessible collection systems, community-based aggregation, incentives, and stronger links between informal collectors and formal recovery networks.

Keywords: Bangil, electronic waste; material flow analysis; waste management

1. Introduction

Electronic waste (e-waste) has become one of the fastest-growing waste streams worldwide due to rapid technological advancements, increasing consumption of electrical and electronic equipment (EEE), and shortened product lifespans. The Global E-waste Monitor 2024 reported that global e-waste generation reached a record high of 62 million tons in 2022 and is projected to increase to 82 million tons by 2030. Despite this rapid growth, only 22.3% of e-waste generated in 2022 was documented as being properly collected and recycled, leaving approximately US$62 billion worth of recoverable resources unaccounted for. This widening gap between e-waste generation and formal recovery highlights the urgent need for improved collection systems, recycling infrastructure, and local-level management strategies, particularly in developing regions where formal recovery systems remain limited (Balde et al.,

2024). However, only 17.4% of the generated e-waste was formally collected and recycled, while the remaining amount was either undocumented, improperly managed, or handled by the informal sector (Forti et al., 2020).

The rapid growth of e-waste poses serious environmental and public health concerns because electronic devices contain both valuable and hazardous materials. Components such as printed circuit boards, batteries, cathode ray tubes, and fluorescent lamps contain toxic substances, including heavy metals and brominated flame retardants. Improper disposal practices, such as open burning, uncontrolled dumping, and informal recycling, may release these hazardous substances into soil, water, and air, causing adverse impacts on ecosystems and human health (Heacock et al., 2016; Lebbie et al., 2021; Andeobu et al., 2023). At the same time, several electronic components contain valuable and critical materials, including copper, aluminum, precious metals, and rare earth elements (Ni'am et al., 2019; Ni'am et al., 2020a; Ni'am et al., 2020b). These findings indicate that household e-waste should not be viewed merely as residual waste, but also as a potential source of recoverable materials within a circular economy framework.

Asia remains a major contributor to global e-waste generation owing to rapid economic growth, urbanization, increasing purchasing power, and expanding ownership of electrical and electronic equipment. These trends are also evident in Indonesia, one of the largest and most populous countries in Southeast Asia, where household ownership of electronic devices has increased substantially over the past decade (Forti et al., 2020). Previous estimates indicated that Indonesia generated approximately 1.62 million tonnes of e-waste in 2019, making it one of the largest e-waste producers in Southeast Asia. However, local-level information on household e-waste generation, collection pathways, and management behavior remains limited, particularly outside metropolitan areas (Forti et al., 2020).

Although Indonesia has introduced regulations related to hazardous waste management and recently enacted Minister of Environment and Forestry Regulation No. 9 of 2024 concerning waste containing hazardous and toxic substances, the implementation of e-waste management remains limited in Indonesia. Formal collection and recycling systems remain underdeveloped, while informal collectors continue to dominate the e-waste value chain. Previous studies have reported that most e-waste generated in Indonesia is either stored by households, sold to informal collectors, mixed with municipal waste, or disposed of without proper treatment (Ayuni et al., 2016; Hilary et al., 2020; Kabul et al., 2024).

Methodologically, e-waste quantification research is heterogeneous. Rimantho et al. (2019) applied material flow analysis (MFA) to assess e-waste flows in Jakarta; Santoso et al. (2019) used a population balance model to estimate e-waste generation at the national scale; and Kastanaki and Giannis (2021) employed a dynamic approach to estimate future flows of obsolete laptops. These approaches differ in spatial scale, temporal treatment, and data requirements. Stock-based MFA is transparent and suitable for local inventory development, but its estimates are sensitive to assumptions about product weight, service life, and retirement timing. Population-balance and dynamic models are better suited for temporal projection; however, they do not explain why households store, resell, donate, or release obsolete products to collection channels. Consequently, physical estimates of potential e-waste generation should not be interpreted as equivalent to the quantity that becomes immediately accessible to collection and recycling systems.

A second research stream focuses on household awareness, attitudes, intentions, and recycling behavior. Previous studies have shown that knowledge and positive environmental attitudes influence e-waste management, while Puzzo and Prati (2024) found that recycling intentions and behaviors are associated with several psychological factors. However, behavioral studies usually provide limited information on the quantity and types of e-waste affected by household decisions. In contrast, material-flow studies can estimate e-waste stocks and potential generation but cannot explain why households with similar electronic stocks choose different disposal pathways. This separation creates an important gap between estimating the amount of e-waste that may be generated and understanding whether, when, and through which pathway households release it.

The third research stream concerns the governance of formal, informal, and community-based collection systems. Informal collectors often provide convenient door-to-door services and immediate economic value, whereas formal systems offer better control over downstream treatments. Community-based facilities, including waste banks and TPS3R, can also support participation and local collection (Rachman et al., 2021; Anam and Siwiendrayanti, 2023; Annashr et al., 2024). However, findings from general solid waste management cannot be directly applied to e-waste because obsolete electronics retain resale value, may contain hazardous components, and require specific reverse logistics arrangements. Circular Economy studies emphasize value retention through reuse, repair, refurbishment, recycling, and resource recovery (Marinello and Gamberini, 2021; Satori et al., 2024). Nevertheless, effective local implementation requires evidence linking available e-waste stocks, household decisions, and institutional pathways through which these materials move.

Taken together, these strands reveal a scientific problem that is broader than the absence of data for a particular locality. Material-flow studies primarily answer how much e-waste may arise; behavioral studies explain factors associated with household actions; and governance studies examine collection and recovery arrangements. These dimensions are rarely integrated at the district scale, where household decisions, community facilities, informal collectors, and local governments interact directly. Bangil District provides a relevant setting for examining this interface because empirical information on electronic device stocks, household e-waste generation, management pathways, and behavioral readiness is limited, while waste banks, TPS3R facilities, and informal collectors already form part of the local waste management landscape. The unresolved question is therefore not only how much e-waste may be generated, but why potentially recoverable materials remain stored, move through informal channels, enter formal recovery, or leak into municipal waste streams.

Accordingly, this study aimed to estimate household e-waste generation using a stock-based MFA approach, map household management pathways, assess knowledge, attitudes, and practices, and interpret these results using stakeholder evidence in the Bangil District, Pasuruan Regency. The novelty of this study lies not merely in applying MFA and KAP within the same investigation but in linking stock-derived potential e-waste generation, household disposal pathways, behavioral conditions, and local recovery institutions within one district-level diagnostic framework. This integration enables the identification of a material–behavioral mismatch that cannot be detected by material-flow or behavioral analysis alone: a locality may contain substantial recoverable stock and environmentally favorable attitudes while still achieving limited formal collection because accessible institutional pathways are absent or unattractive.

2. Methods

2.1 Theoretical and Conceptual Framework

The framework treats MFA, KAP, and the Circular Economy as complementary analytical layers rather than interchangeable methods. MFA represents the biophysical layer by estimating the quantity and composition of electronic stocks that potentially become waste. KAP provides a behavioral diagnostic layer by examining knowledge, evaluative attitudes, and reported practices. The circular economy provides a system-level perspective for distinguishing value-retention pathways such as reuse, repair, refurbishment, and recycling from hibernating stock and material leakage. Within this framework, local e-waste circularity is conceptualized as the alignment among material availability, behavioral readiness, and institutional opportunity

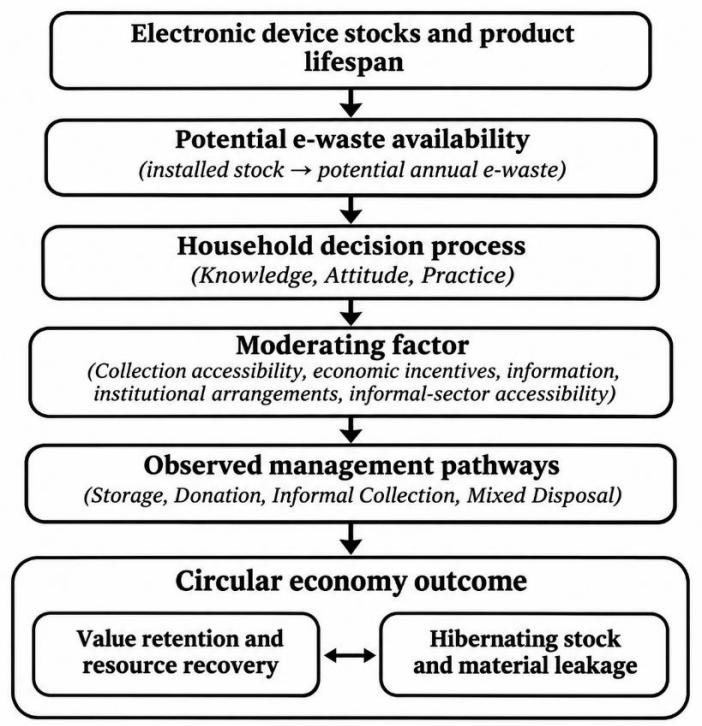


Figure 1. Theoretical and conceptual framework in this study

2.2 Study Area

This study was conducted in the Bangil District, Pasuruan Regency, East Java, Indonesia. The Bangil District is located at approximately 7°35′52″ S and 112°47′04″ E. It is the administrative center of Pasuruan Regency and is characterized by residential areas, commercial activities, educational facilities, and government offices, which contribute to the use of electrical equipment.

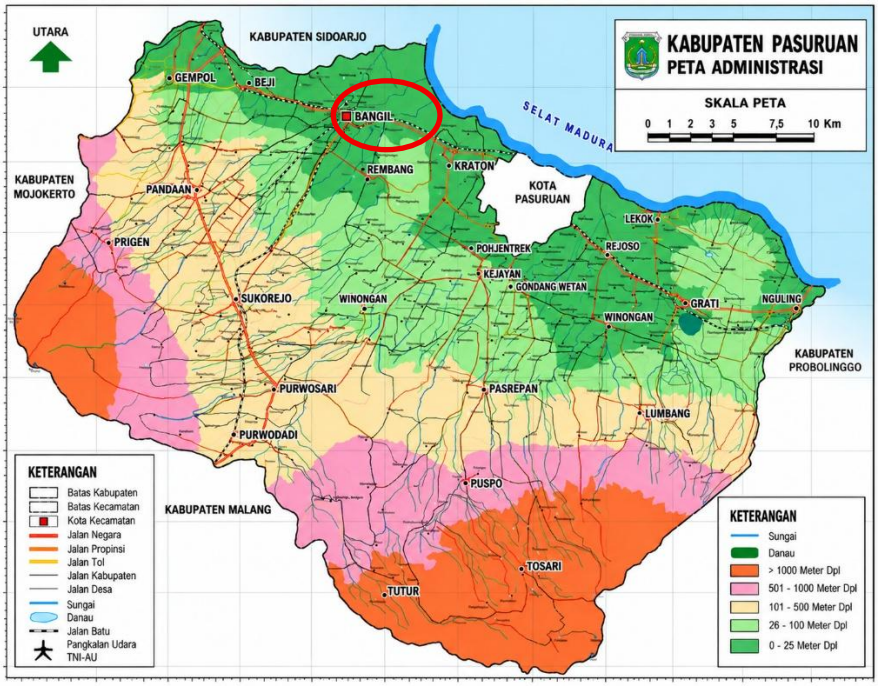


Figure 2. Location of the study area in Bangil District, Pasuruan Regency, East Java, Indonesia
Source: Authors' elaboration based on Badan Informasi Geospasial (BIG) administrative spatial data.

2.3 Data Collection and Sampling

This study employed a sequential explanatory mixed-methods approach, combining quantitative and qualitative analyses. Quantitative data were collected to estimate household e-waste generation and assess public knowledge, attitudes, and practices (KAP) regarding e-waste management. Qualitative data obtained through stakeholder interviews were subsequently used to explain and support the quantitative findings.

Primary data were collected through household surveys, semi-structured interviews, and field observations. Secondary data were obtained from government reports, statistical publications, regulations, and relevant literature. The household questionnaire consisted of four sections: respondent characteristics, ownership of electronic devices, household E-waste generation, and E-waste management practices. Public awareness was evaluated using the knowledge–attitude–practice (KAP) framework.

The target population comprised all households in Bangil District, totalling approximately 21,376 households. The minimum sample size was determined using Cochran's formula with a 95% confidence level and a 10% margin of error. The calculation resulted in a minimum sample requirement of 96 households. Although the minimum sample size calculated with a 10% margin of error was 96 households, this study increased it to 200. This larger sample reduced the effective margin of error to approximately 6.9% at a 95% confidence level, thereby improving the precision of household-level estimates. Respondents were selected using systematic random sampling. The minimum sample size was calculated using Cochran's formula, as shown in Equation (1):

$$n_0 = \frac{Z^2 \times p(1-p)}{e^2} \quad (1)$$

In Equation (1), n_0 represents the minimum required sample size, (Z) denotes the z-value corresponding to the selected confidence level, (p) refers to the estimated population proportion, and (e) represents the margin of error. In this study, a 95% confidence level (Z = 1.96), an estimated population proportion of 0.5, and a 10% margin of error were used. The calculation resulted in a minimum sample requirement of 96 households. To improve statistical precision and ensure sufficient data for inferential analysis, the number of respondents was increased to 200 households. Respondents were selected using systematic random sampling.

The sampling frame consisted of 107 covering households in Bangil District. Based on a target population of 21,376 households, the final sample was 200 households. The sample was increased to improve the precision of household-level estimates. A random starting household between 1 and 200 was selected using purposive sampling, after which every 200th household in the sampling frame was approached for participation. Eligible respondents were adult household members familiar with the ownership, use, replacement, and disposal of household electronic devices. If a selected household was unavailable, ineligible, or declined participation, the sampling moved to other available households to obtain data. Non-response was handled by replacement.

In addition to the household survey, qualitative data were collected through purposive sampling of 10 stakeholders, comprising three representatives of local government agencies, one TPS3R operator, three waste-bank staff, and five informal e-waste collectors. Participants were selected because of their direct involvement in household waste collection, community-based waste management, or the local e-waste value chain. These stakeholders were selected based on their involvement in waste management activities and their relevance to local e-waste management practices

2.4 E-Waste Generation Estimation and KAP Assessment

Household e-waste generation was estimated using a Material Flow Analysis (MFA) approach adapted from Chung et al. (2011) and Rimantho et al. (2019). The estimation considered the number of electronic devices owned by households, average device weight, and average service life. Annual e-waste generation was calculated using Equation (2) (Chung et al., 2011; Rimantho et al. 2019):

$$E = \sum \frac{W_i \times N_i}{L_i} \quad (2)$$

where E is the annual e-waste generation (kg year^{-1}), W_i is the average weight of electronic device type i (kg), N_i is the number of devices owned, and L_i is the average lifespan of the device (years). Per-capita e-waste generation was calculated by dividing the total estimated annual e-waste generation by the total population represented by surveyed households.

We assessed public awareness of e-waste management using the Knowledge–Attitude–Practice (KAP) framework. The questionnaire included five indicators for each dimension (knowledge, attitude, and practice) measured on a five-point Likert scale. The obtained scores were converted into percentages and subsequently classified into five categories: very low (0–20%), low (21–40%), moderate (41–60%), high (61–80%), and very high (81–100%) (Hassooni et al., 2024).

Before the main survey, the questionnaire was pilot tested on 30 respondents with characteristics similar to the target population. Construct validity was evaluated using Pearson 's product moment correlation by comparing the corrected item–total correlation values with the critical r-value of 0.361 (n = 30; α = 0.05). All questionnaire items exceeded the required threshold and were therefore considered valid. Reliability was assessed using Cronbach's alpha coefficient. The results indicated that all constructs demonstrated satisfactory internal consistency, with Cronbach's alpha values ranging from 0.809 to 0.946, exceeding the minimum acceptable threshold of 0.70. A summary of the validity and reliability test results is presented in Table 1.

Table 1. Summary of validity and reliability test results

Variable	Number of Items	Corrected Item–Total Correlation	Validity	Cronbach's Alpha	Reliability
Knowledge	5	0,785 – 0,921	All item valid	0,946	Excellent
Attitude	5	0,768 – 0,903	All item valid	0,942	Excellent
Practice	5	0,495 – 0,668	All item valid	0,809	Good

Source: Authors' analysis using IBM SPSS Statistics 26 (2026).

2.5 Data Analysis

Quantitative data were analyzed using Microsoft Excel and IBM SPSS Statistics version 26. Descriptive statistics were used to summarize the respondents' characteristics, ownership of electronic devices, e-waste generation, and KAP levels. Chi-square tests were performed to examine the associations between the socioeconomic characteristics and KAP variables. Statistical procedures were selected according to the measurement characteristics of the variables. The KAP dimensions were derived from five-point Likert-type items and therefore retained an ordinal component in the analysis. Spearman's rank correlation coefficient (rs) was used to assess the relationships among knowledge, attitude, because this non-parametric method does not require normally distributed interval-scale variables and is appropriate for evaluating monotonic relationships involving ordinal data.

Chi-square tests of independence were used to examine associations between categorical socioeconomic characteristics and categorized KAP outcomes. The independence of observations and expected cell frequencies were considered when interpreting the Chi-square results. Statistical significance was established at $p<0.05$, while the magnitude of the correlation coefficients was also considered to distinguish statistical significance from the practical strength of the relationships.

Additionally, multivariate analysis was considered to examine the independent contribution of socioeconomic and behavioral variables to household e-waste management practices. Given the ordered nature of the practice categories, ordinal logistic regression was an appropriate approach, with practice as the dependent variable and knowledge, attitude, education, age, and income as explanatory variables.

Where applied, model assumptions, multicollinearity, goodness-of-fit, adjusted odds ratios, and 95% confidence intervals should be evaluated before interpreting the mode

Qualitative interview data were transcribed and analyzed thematically. The findings were categorized into themes related to existing e-waste management practices, institutional roles, barriers, and opportunities for improving e-waste management in the Bangil District. The integration of quantitative and qualitative findings was subsequently used to formulate recommendations for local waste management.

3. Result and Discussion

3.1 Respondent Characteristics

The respondents were distributed across all villages and urban wards in the Bangil District, providing a representative overview of household characteristics in the study area. Female respondents accounted for 62.5% of the sample, while males accounted for 37.5%. Most respondents were within the productive age groups, particularly 41–50 years (30.0%) and over 50 years (29.0%), indicating that the majority were actively involved in household decision-making, including the purchase and replacement of electronic devices. Regarding educational attainment, most respondents had completed senior high school (47.5%), followed by bachelor's degree holders (29.5%).

In terms of occupation, self-employed workers and traders constituted the largest group (28.5%), followed by unemployed respondents (17.0%). Most households (69.0%) had monthly incomes below the regional minimum wage (< IDR 5 million per month), indicating that most respondents belonged to low- to middle-income groups. Despite these economic conditions, ownership of electronic devices was common across all income categories, suggesting a substantial potential for household e-waste generation. The average household size was approximately four persons per household. The socioeconomic characteristics of the respondents are listed in Table 2.

Table 2. Socioeconomic characteristics of respondents

Variable	Category	n	%
Gender	Male	75	37.5
	Female	125	62.5
Age	<20 years	4	2.0
	21–30 years	42	21.0
	31–40 years	36	18.0
	41–50 years	60	30.0
	>50 years	58	29.0
Education	Elementary School	11	5.5
	Junior High School	34	17.0
	Senior High School	95	47.5
	Bachelor's Degree	59	29.5
	Postgraduate Degree	1	0.5
Occupation	Government Employee	26	13.0
	Private Employee	26	13.0
	Self-employed/Trader	57	28.5
	Laborer	25	12.5
	Unemployed	34	17.0
	Others	32	16.0
Monthly Income	< IDR 5 million	138	69.0
	IDR 5 million	15	7.5
	> IDR 5 million	21	10.5
	No income	26	13.0

Source: Field Survey (2026).

3.2 Ownership of Electronic Device

The survey results showed that the ownership of electronic devices among households in Bangil District was relatively high. A total of 15 types of electronic devices were identified during the survey, including smartphones, televisions, single-door refrigerators, two-door refrigerators, one-tub washing machines, two-tub washing machines, laptops, computers, air conditioners, rice cookers, printers, electric fans, audio equipment, water dispensers, and LED lamps. The extensive use of these gadgets reflects households' growing reliance on electronic devices for entertainment, domestic tasks, communication, and information access.

Among all devices, LED lamps were the most frequently owned electronic products, with 1,609 units recorded from 200 households. Smartphones ranked second with 586 units, followed by electric fans (578 units), rice cookers (201 units), LED/LCD televisions (172 units), and laptops/computers (139 units). The high ownership of smartphones indicates the growing role of digital communication technologies in daily life, whereas the large number of household appliances reflects increasing living standards and access to electrical equipment.

The ownership pattern shows that the number of electronic devices owned by households does not necessarily correspond to the potential e-waste generation. LED lamps and smartphones were among the most commonly owned devices; however, their contribution to the estimated e-waste mass was relatively low because of their small unit weight. In contrast, washing machines and refrigerators were owned by fewer households but contributed considerably to the estimated e-waste mass because of their larger weight and replacement characteristics. This indicates that the potential generation of e-waste is influenced not only by the number of devices in use but also by the weight and the service life of each device.

Nevertheless, the potential significance of e-waste cannot be assessed from mass alone. Different types of electronic devices have different material compositions and may contain hazardous substances as well as materials with potential economic value for recovery. Therefore, a device with a relatively low weight may still require attention when it reaches the end of its useful life because of the materials contained in it. In this study, the estimation focuses on the potential mass of e-waste based on household electronic stock, unit weight, and service life. The estimated mass should therefore be interpreted as an indication of the potential quantity of e-waste generated rather than as a complete measure of its environmental burden. Further assessment of the material composition and hazardous characteristics would be needed to determine the potential environmental and resource-recovery implications of each device category.

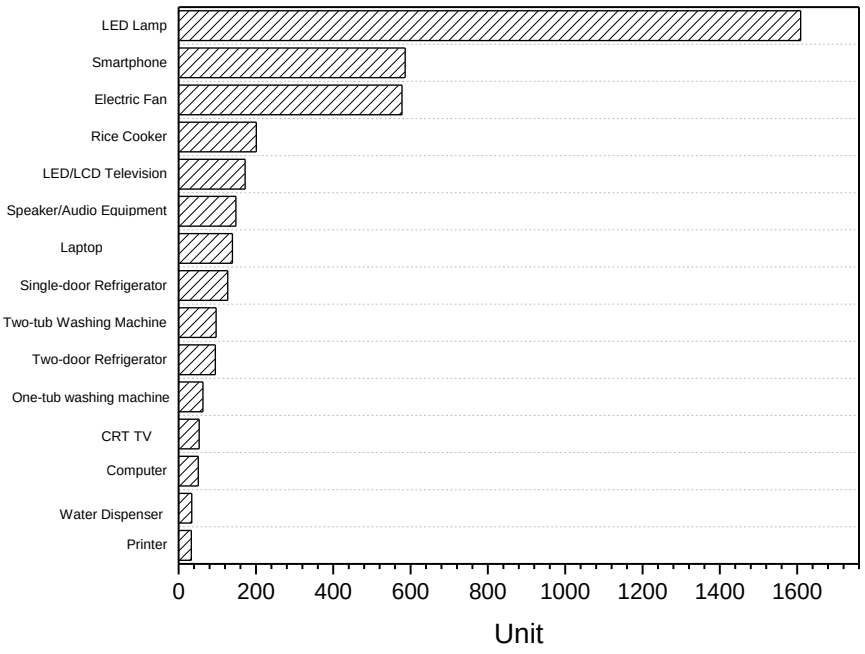


Figure 3. Ownership of electronic devices among surveyed households in Bangil District
Source: Field Survey (2026).

This pattern has important implications for local waste collection planning. Small electronic devices, such as smartphones and lamps, may require convenient drop-off points and awareness campaigns because they are easily stored, forgotten, or disposed of with household waste. Conversely, bulky appliances, such as washing machines and refrigerators, require different reverse-logistics arrangements, including scheduled collection, collector-based pickup, and coordination with repair shops or second-hand markets. Therefore, household e-waste management strategies should be differentiated according to the device category, rather than applying a single collection model for all types of electronic waste.

3.3 Household E-Waste Generation

Household e-waste generation was estimated using the material flow analysis (MFA) approach based on the number of electronic devices owned, average device weight, and average service life. The survey covered 200 households, comprising 754 household members based on the number of household members reported by each respondent. The total potential e-waste generation associated with these surveyed households was estimated at 3,727.98 kg year^{-1}. Based on the total number of household members recorded in the survey, the estimated e-waste generation was 4.94 kg capita^{-1} year^{-1} (Table 3). The value of 4.94 kg capita^{-1} year^{-1} was calculated using the unrounded estimated e-waste generation before rounding to two decimal places. The estimated 3,727.98 kg year^{-1} represents the potential e-waste generation associated with the 200 surveyed households and should not be interpreted as the actual total e-waste generation of Bangil District. The estimated generation rate obtained in this study is comparable to previous studies conducted in Indonesia and other developing countries, which reported increasing household e-waste generation due to growing ownership of electronic devices and shorter product lifespans (Rimantho et al., 2019; Santoso et al., 2019; Parajuly et al., 2019).

The estimated value represents the potential e-waste generation derived from the stock of electronic devices owned and used by the surveyed households. In the stock-driven approach, the existing stock of each device category is related to its average service life to estimate the amount of equipment that may reach the end of its useful life within a given year. Thus, the estimated annual e-waste generation

reflects the potential quantity of devices leaving the in-use stock based on their ownership and lifespan characteristics. This approach assumes that the observed household electronic stock and the average service life of each device are representative of the conditions during the estimation period. The resulting value provides an estimate of the potential annual e-waste flow rather than the actual quantity collected or entering the waste management system. Differences may occur because devices may remain unused or stored in households, be reused or transferred to other users, or be sold through informal channels instead of immediately entering the waste management system.

The average device weights used in the MFA calculation were obtained from previous studies and technical product specifications. The weights of televisions, refrigerators, washing machines, and air conditioners were adopted from Rimantho et al. (2019), while laptop weights were obtained from Kastanaki and Giannis (2021). For devices not covered by these references, representative weights were derived from the technical specifications of commonly marketed products. The use of these weight values provides an estimate of the potential e-waste mass based on the characteristics of the electronic devices owned by the surveyed households. However, the estimated mass should be interpreted considering the sources and representativeness of the weight data used in the calculation.

The survey findings further show that household e-waste management in Bangil District is characterized by a strong role of informal collection, with collectors being the main channel used by households to manage discarded electronic equipment. The survey also identified the continued storage of unused electronic devices in the households. These findings indicate that household e-waste management is not determined solely by the number of electronic equipment owned but also involves the way households manage devices after they are no longer used. Factors such as access to collection services may further influence these decisions, as reported in previous studies (insert citation).

Table 3. Estimated household E-Waste generation in the Bangil District

Indicator	Value
Total potential e-waste generation	3,727.98 kg year^{-1}
Surveyed households	200 households
Surveyed population	754 persons
Per-capita e-waste generation	4.94 kg capita^{-1} year^{-1}

Source: Authors' calculation based on Field Survey data (2026).

Figure 4 presents the contribution of each electronic device type to the estimated annual e-waste generation. Large household appliances contributed substantially to the estimated potential e-waste mass owing to their relatively high unit weights. In contrast, smaller electronic devices contributed less to the total estimated e-waste mass despite their relatively high ownership rates. The sum of the device-specific values presented in Figure 3 is 3,727.97 kg year^{-1}, compared with the total potential e-waste generation of 3,727.98 kg year^{-1} reported in Table 3. The slight difference of 0.01 kg year^{-1} is attributable to the rounding of the individual device-specific values presented in Figure 3, whereas the total value in Table 3 was calculated using unrounded values.

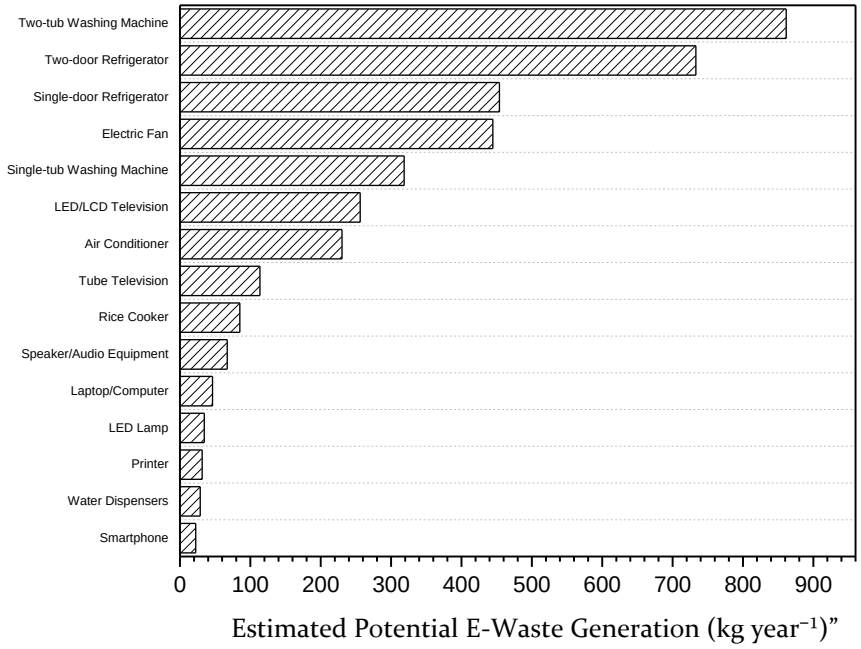


Figure 4. Contribution of electronic devices to estimated potential annual e-waste generation in Bangil District

Source: Authors' calculation based on Field Survey data (2026).

Figure 4 presents the contribution of each electronic device category to the estimated potential annual e-waste generation among the surveyed households in the Bangil District. The estimated generation rate was calculated using the number of devices, representative unit weight, and average service life, as presented in the MFA calculation table (Table X). In this calculation, the material stock of each device category was obtained by multiplying the number of devices owned by their representative unit weight (W × N), while the potential annual e-waste generation was estimated by dividing the material stock by the average service life (L).

The results showed that two-tub washing machines contributed the largest share of the estimated potential annual e-waste generation, accounting for 861.51 kg year^{-1}, followed by two-door (733.18 kg year^{-1}) and single-door refrigerators (454.06 kg year^{-1}). The relatively high contribution of two-tub washing machines was associated with their relatively high unit weight of 67.50 kg and a material stock of 6,547.50 kg from 97 units, combined with an average service life of 7.6 years. In contrast, smartphones were among the most frequently owned devices, with 586 units recorded in the households surveyed. However, their low unit weight of 0.18 kg resulted in a material stock of only 105.48 kg and an estimated potential e-waste generation of 22.44 kg year^{-1}, based on an average service life of 4.7 years. These findings indicate that the potential generation of household e-waste is not determined by ownership frequency alone but also by the weight and service life of electronic devices.

The sum of the rounded device-specific values presented in Figure 3 was 3,727.97 kg year^{-1}, while the total potential e-waste generation reported in Table 3 was 3,727.98 kg year^{-1}. The difference of 0.01 kg year^{-1} is attributable to the rounding of the individual device-specific values presented in Figure 3, whereas the total value reported in Table 3 was calculated using the unrounded values.

The estimated potential e-waste generation among the surveyed households was 3,727.98 kg year^{-1}. Based on the 754 household members included in the survey, the corresponding estimated per-capita generation was 4.94 kg capita^{-1} year^{-1}. This value is slightly higher than the 4.04 kg capita^{-1} year^{-1} reported by Rimantho et al. (2019) for DKI Jakarta. However, this comparison should be interpreted

considering the differences in study location, device ownership patterns, and the characteristics of the data used for e-waste estimation.

When the per-capita estimate was applied to the total population of Bangil District, the potential household e-waste generation was estimated to be approximately 422 tonnes y^{-1}. This value represents an extrapolation based on the surveyed households and the population of Bangil District, rather than a direct measurement of e-waste entering the waste management system. Therefore, the estimated value should be interpreted as the potential annual e-waste generation associated with household electronic stock and its service-life characteristics. The actual amount entering formal or informal waste management pathways may differ because electronic devices may be stored, reused, transferred to other users, or sold to collectors.

Table 4. Parameters and estimated potential annual e-waste generation of household electronic devices

Electronic Device	Unit weight, W (kg)	Number of devices, N	Average service life, L (year)	Material stock, W × N (kg)	Potential annual e-waste generation, (W × N)/L (kg $year^{-1}$)
Smartphone	0.2	586	4.7	105.48	22.44
LED/LCD television	9.7	172	6.5	1664.96	256.15
CRT television	22.9	53	10.7	1215.82	113.63
Single-door refrigerator	31.8	127	8.9	4041.14	454.06
Two-door refrigerator	65.6	95	8.5	6232.00	733.18
Single-tub washing machine	34.4	63	6.8	2165.94	318.52
Two-tub washing machine	67.5	97	7.6	6547.50	861.51
Laptop/Computer	2.2	139	6.7	309.97	46.26
Air conditioner	31.2	51	6.9	1589.16	230.31
Rice cooker	2.5	201	5.9	502.50	85.17
Printer	7.0	33	7.3	231.00	31.64
Electric fan	4.0	578	5.2	2312.00	444.62
Speaker/Audio/Radio	3.0	148	6.6	444.00	67.27
Water dispenser	6.0	34	7.1	204.00	28.73
LED lamp	0.1	1609	3.5	120.68	34.48
Total	—	—	—	—	**3727.98**

Source: *Authors' calculation based on Field Survey data (2026), Rimantho et al. (2019), Kastanaki and Giannis (2021), and supporting literature and technical product specifications*

3.4 Household E-Waste Management Pathways

Understanding household e-waste management pathways is important for identifying how electronic devices are handled after they are no longer actively used by consumers. Figure 5 presents the e-waste management practices identified through the household survey and their potential connections with local collection, recovery, and recycling pathways in the Bangil District.

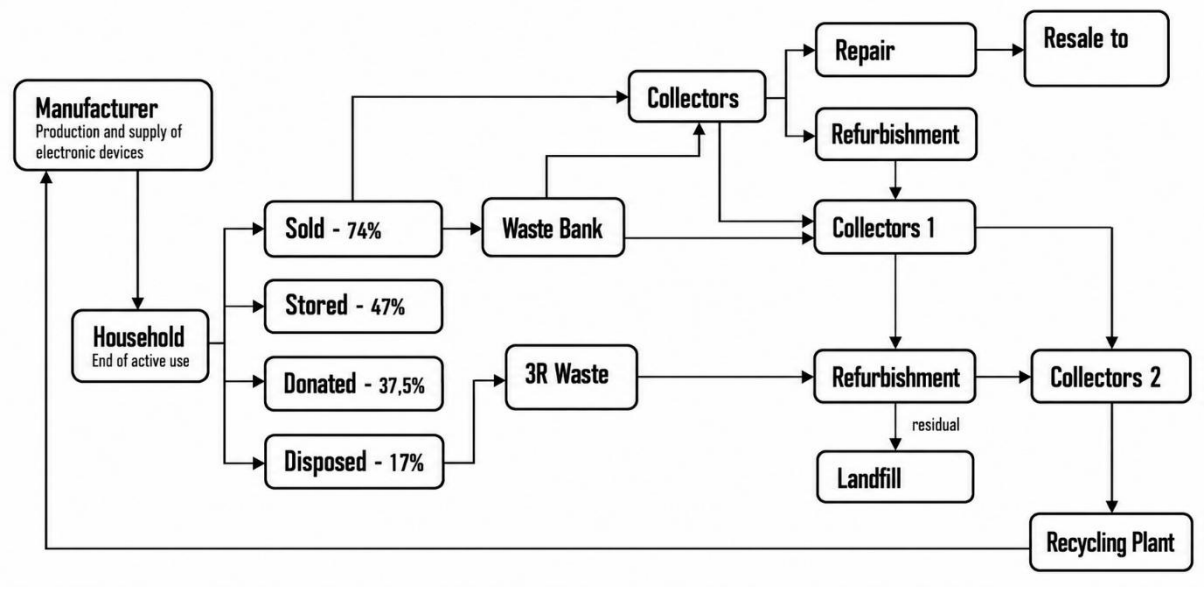


Figure 5. Observed household e-waste management practices and potential management pathways in *Bangil District*

Source: Authors' compilation based on Field Survey (2026).
Note: Percentages represent multiple response data and are therefore not mutually exclusive. The observed household practices are distinguished from the potential management pathways presented in the conceptual flow.

The results indicate that informal collection plays an important role in household e-waste management. Based on the multiple-response survey, 74.0% of respondents reported selling obsolete electronic devices to collectors, making this the most frequently reported management practice. In addition, 37.5% of respondents reported donating electronic devices to relatives or neighbors, particularly when the devices were still functional. These practices indicate that economic value, opportunities for continued use, and access to collectors may influence household decisions regarding unused electronic devices.

The storage of unused electronic devices was also commonly reported, with 47.0% of respondents indicating that they kept unused devices at home. This finding indicates that a considerable proportion of electronic devices remain outside established waste management pathways after they are no longer actively used. These stored devices may represent a potential hibernating stock because they remain within households and may subsequently enter reuse, resale, recycling, or disposal pathways. However, the survey only measured the practice of storing unused devices and did not determine their intended future destination. Therefore, the 47.0% storage rate should be interpreted as an indication of potential hibernating stock rather than a direct measurement of hibernating stock.

Improper disposal was reported by 17.0% of respondents, who indicated that electronic devices were disposed of together with household waste, while 11.0% reported delivering e-waste to formal recycling facilities. The relatively lower use of formal recycling channels compared with informal collection indicates that formal e-waste management is less frequently accessed by households. Because respondents were allowed to report more than one management practice, these percentages are not mutually exclusive and should not be summed to represent a single e-waste flow distribution.

As shown in Figure 5, the observed household practices are connected to several potential downstream management pathways. The household survey directly identified selling, storing, donating, disposing of e-waste with household waste, and delivering e-waste to formal recycling facilities. The figure also presents potential pathways involving waste banks, 3R waste centers (TPS3R), repair and refurbishment, collectors, dismantling, and recycling facilities. These pathways are presented to illustrate

possible connections within the local e-waste management system and should not be interpreted as quantitatively measured flows from household surveys. The prominent role of collectors suggests that informal actors currently provide an important channel for moving unused electronic devices out of households and potentially toward reuse, material recovery, or further processing in the WEEE flow.

Overall, household e-waste management in Bangil District is characterized by the frequent use of informal collection and household storage, while formal recycling is less frequently reported. These findings highlight the need to improve accessible collection pathways and strengthen coordination among households, community-based facilities, informal collectors and formal recycling or treatment facilities. Strengthening waste banks and TPS3R facilities as potential local collection points could provide an opportunity to improve e-waste collection and facilitate its subsequent transfer to appropriate recovery or treatment pathways. Similar findings were highlighted by Satori et al. (2024), who emphasized the importance of understanding material flows and strengthening collection and recovery systems to support circular economy implementation.

3.5 Knowledge, Attitude, and Practice (KAP) Assessment

The Knowledge–Attitude–Practice (KAP) framework was used to assess household knowledge, attitudes, and practices regarding the management of e-waste. Each dimension consisted of five questionnaire items, resulting in a total of 15 items. All items were assessed using a five-point Likert scale ranging from 1–5, with equal weighting. The percentage score for each dimension was calculated by comparing the observed score with the maximum possible score and multiplying the result by 100. The resulting scores were classified into low, moderate, and high categories based on the criteria presented in Appendix G. The detailed scoring procedure and interpretation of the five-point Likert scale are provided in Appendix H.

Table 5. Knowledge, attitude, and practice (KAP scores)

Dimension	Score (%)	Category
Knowledge	60.48	Moderate
Attitude	78.85	High
Practice	50.66	Moderate

Source: Authors' calculation based on field survey data (2026).

The results showed that respondents had a moderate level of knowledge (60.48%), high level of attitude (78.85%), and moderate level of practice (50.66%). The 28.19 percentage point difference between attitude and practice scores indicates an attitude–practice gap, suggesting that positive attitudes toward e-waste management were not fully reflected in reported household practices.

To further examine the variation within each KAP dimension, the five questionnaire items for knowledge, attitude, and practice were separately assessed. The item-level results are presented in Tables 6–8, respectively.

Table 6. Item-level knowledge assessment of household E-Waste management

Item	Knowledge Indicator	Score (%)	Category
A	Awareness that damaged electronic devices are classified as e-waste	59	Moderate
B	Awareness that e-waste may contain hazardous substances (B_3)	56	Moderate
C	Awareness that e-waste can cause environmental pollution	63	High
D	Awareness that e-waste can pose risks to human health	62	High
E	Awareness that e-waste requires special treatment for safe disposal	63	High

Item	Knowledge Indicator	Score (%)	Category
Average		**60**	**Moderate**

Note: Item-level percentages are presented as rounded values; therefore, the average of the displayed values may differ slightly from the overall KAP score calculated using the unrounded individual scores.
Source: *Authors' calculation based on Field Survey data (2026).*

The item-level results show that knowledge varied across the five aspects assessed. The lowest score was observed for awareness that e-waste may contain hazardous substances (56%), followed by awareness that damaged electronic devices are classified as e-waste (59%). In contrast, awareness of the environmental impacts and the need for special treatment of e-waste obtained higher scores (62–63%). These results indicate that respondents were more aware of the environmental and health implications of e-waste than of its classification and hazardous characteristics.

Table 7. Item-level attitude assessment toward household E-Waste management

Item	Knowledge Indicator	Score (%)	Category
K	Agreement that e-waste should be properly managed	77	High
L	Agreement that e-waste should not be disposed of together with household waste	79	High
M	Agreement that households have a responsibility to manage the e-waste they generate	77	High
N	Agreement with the provision of e-waste collection facilities at appropriate locations	77	High
O	Agreement that proper e-waste management can reduce environmental pollution	80	High
Average		**78**	**High**

Source: *Authors' calculation based on Field Survey data (2026).*

The attitude scores were consistently high across all five items, ranging from 77%–80%. The highest score was observed for the statement that proper e-waste management can reduce environmental pollution (80%), while the other items ranged from 77%–79%. This consistent pattern indicates that respondents generally expressed positive attitudes toward responsible household waste management.

Table 8. Item-level practice assessment of household E-Waste management

Item	Knowledge Indicator	Score (%)	Category
V	Separating unused electronic devices from household waste	54	Moderate
W	Temporarily storing e-waste until an appropriate collection point is available	59	Moderate
X	Delivering e-waste to collection points such as waste banks, collectors, or other appropriate parties	57	Moderate
Y	Participating in e-waste collection programs in the surrounding environment	38	Low
Z	Seeking information on proper e-waste management	46	Moderate
Average		**51**	**Moderate**

Source: *Authors' calculation based on Field Survey data (2026).*

The practice scores showed greater variation, ranging from 38%–59%. The lowest score was observed for participation in e-waste collection programs (38%), which was classified as low, followed by seeking information on proper e-waste management (46%). In contrast, temporarily storing e-waste until an appropriate collection point was available obtained the highest score (59%). These findings indicate

that participation in organized collection activities and efforts to obtain information on proper e-waste management remain relatively weak among the surveyed households.

Overall, the KAP results indicate moderate knowledge, high attitudes, and moderate practices regarding household e-waste management. The 28.19% difference between the attitude and practice scores demonstrates a clear attitude–practice gap. This finding is consistent with the household e-waste management practices identified in the survey, in which 74.0% of respondents reported selling unused or discarded electronic devices to collectors, 47.0% reported storing unused devices at home, and 17.0% reported disposing of e-waste together with household waste, while only 11.0% reported using formal recycling facilities.

The combination of positive attitudes and moderate practices indicates that positive perceptions do not necessarily translate into appropriate e-waste management practices. The frequent use of collectors and continued household storage suggests that households may rely on management options that are accessible or provide economic value. However, these factors were not directly tested as causal determinants in the present study. Therefore, the KAP findings should be interpreted as indicating an association between respondents' attitudes and reported management practices, rather than a direct causal relationship.

These findings highlight the importance of supporting positive attitudes toward practical and accessible e-waste management options. Strengthening collection points and improving linkages among households, community-based facilities, collectors, and formal recycling or treatment facilities may help facilitate the transition from positive attitudes to more appropriate waste management practices.

3.6 Factors Affecting E-Waste Management Practices

Chi-square and Spearman's rank correlation tests were conducted to examine the relationships between socioeconomic characteristics and KAP dimensions. The Chi-square test was used to assess associations between categorical socioeconomic characteristics and categorized KAP scores, while Spearman's rank correlation was applied to assess the direction and strength of monotonic relationships among KAP scores. Prior to the Chi-square analysis, KAP scores were classified into low, moderate, and high categories based on the criteria presented in Appendix H. A p-value < 0.05 was considered statistically significant.

Table 9. Result of Chi-Square and Spearman correlation analyses

Variable Relationship	Statistical Value	df	p-value	Interpretation
Education – Knowledge	$\chi^2 = 18.434$	4	0.001	Significant
Education – Attitude	$\chi^2 = 13.315$	4	0.01	Significant
Education – Practice	$\chi^2 = 7.316$	4	0.12	Not Significant
Income – Knowledge	$\chi^2 = 12.034$	6	0.061	Not Significant
Income – Attitude	$\chi^2 = 3.899$	6	0.69	Not Significant
Income – Practice	$\chi^2 = 6.342$	6	0.386	Not Significant
Age – Knowledge	$\chi^2 = 10.824$	6	0.029	Significant
Age – Attitude	$\chi^2 = 1.230$	6	0.748	Not Significant
Age – Practice	$\chi^2 = 7.214$	6	0.071	Not Significant
Knowledge – Attitude	rs = 0.369	-	<0.001	Significant
Knowledge – Practice	rs = 0.343	-	<0.001	Significant
Attitude – Practice	rs = 0.323	-	<0.001	Significant

Source: Authors' analysis using IBM SPSS Statistics 26 (2026).

Education was significantly associated with knowledge ($\chi^2 = 18.434$, df = 4, p = 0.001) and attitude ($\chi^2 = 13.315$, df = [df], p = 0.010), but not with practice ($\chi^2 = 7.316$, df = [df], p = 0.120). Age was significantly

associated with knowledge (χ^2 = 10.824, df = [df], p = 0.029), whereas no significant association was found between age and attitude or practice. Income was not significantly associated with any KAP dimensions (p > 0.05).

Spearman's rank correlation showed significant positive relationships between knowledge and attitude (r_s = 0.369, p < 0.001), knowledge and practice (r_s = 0.343, p < 0.001), and attitude and practice (r_s = 0.323, p < 0.001). The correlation coefficients indicate weak-to-moderate associations, suggesting that the KAP dimensions are related but do not fully explain the household e-waste management practices. The non-significant association between education and practice, together with the high attitude but moderate practice scores, further supports the attitude–practice gap identified in this study.

Chi-square and Spearman's rank correlation tests were performed using IBM SPSS Statistics 26. The Chi-square test was used to examine associations between categorical socioeconomic characteristics and categorized KAP dimensions, while Spearman's rank correlation was used to assess the direction and strength of monotonic relationships among KAP scores. KAP scores were categorized into low, moderate, and high levels prior to the Chi-square analysis. A p-value < 0.05 was considered statistically significant.

3.7 Comparison of Previous E-Waste Studies and Main Findings Relevant to the Study

To position the present findings within the broader literature, Table X compares the methodological focus, key findings, and limitations of relevant material-flow, behavioral, and community-based e-waste studies with the contribution of this research.

Table 10. Critical comparison of previous e-waste studies and the contribution of the present study

Study	Scope	Key quantitative evidence	Main finding relevant to this study
Rimantho et al. (2019)	MFA; household and informal-sector e-waste in DKI Jakarta	We surveyed 400 households and 54 informal-sector actors and estimated the e-waste generation at 7,713.42 kg year^{-1}, equivalent to approximately 4.04 kg capita^{-1} year^{-1}. (UNDIP Publisher)	Reported substantial e-waste generation and an important role of informal recycling pathways
Santoso et al. (2019)	Population Balance Model; national e-waste forecasting in Indonesia	PBM incorporated sales, stocks, and product lifespans for four product groups. E-waste is projected to grow by an average of 14.91% year^{-1} and reach approximately 49.63 million units or 487,416 tonnes by 2028. (Universitas Indonesia)	Projected increasing e-waste generation associated with electronic consumption
Puzzo and Prati (2024)	Meta-analysis of psychological determinants of e-waste recycling	We synthesized 36 studies, 37 independent samples, and 18,410 participants. Recycling intention → behavior, and attitudes, convenience, and perceived policy effectiveness → intention showed very large effect sizes. (Cris)	Demonstrated that e-waste recycling behavior is associated with multiple psychological factors rather than awareness alone
Rachman et al. (2021)	Community participation in a village waste-bank system	Of the 1,988 households, only 448 participated in the waste bank (≈22.5%). Among 182 surveyed households, 51.4% were not members, but 94.4% of those non-members	Demonstrated the potential role of community-based systems in improving

Study	Scope	Key quantitative evidence	Main finding relevant to this study
		expressed a willingness to join. (Scholar Hub)	waste-management participation
Anam and Siwiendrayanti (2023)	Community-based waste-bank assessment, Tinjomoyo	A total of 143 respondents were surveyed. The waste bank handled 3,946 kg of inorganic waste in 2022, which was approximately 8.6% of all waste handled by waste banks in Semarang. Of the respondents, 87.4% reported improved household waste-handling behavior, 71.3% perceived reduced waste accumulation, and 71.3% perceived a cleaner environment. (ResearchGate)	Highlighted the contribution of waste banks to local waste-management participation
Annashr et al. (2024)	Cross-sectional determinants of waste-bank participation	Included 102 households. Significant determinants included education (OR=2.889; p=0.049), knowledge (OR=6.333; p<0.001), socialization (OR=4.146; p=0.012), and external support (OR=14.074; p<0.001 in bivariate analysis). In the multivariate model, external support was the strongest determinant (OR=8.636).	Identified factors associated with participation in community-based waste-management systems
Marinello and Gamberini (2021)	Systematic review of multi-criteria approaches for WEEE management	We reviewed 44 studies on WEEE decision-support approaches. AHP was the most frequently applied MCDM method, often combined with VIKOR, Delphi, and TOPSIS; criteria included environmental, economic, social, technical, and legal dimensions.	Emphasized the complexity of WEEE management and the importance of integrated management strategies
Satori et al. (2024)	MFA + economic analysis + Circular Economy; recycling center	The existing system managed only 34% of the total waste, with 4% reused and approximately IDR 97.9 million year^{-1}. The proposed system increased the managed waste to 60% and estimated the economic potential of approximately IDR 1.08 billion year^{-1}.	Demonstrated the importance of material-flow understanding for resource recovery and Circular Economy implementation
Present study	Stock-based MFA + pathway mapping + KAP + stakeholder evidence; Bangil District	200 households; potential e-waste 3,727.98 kg year^{-1} (4.94 kg capita^{-1} year^{-1}). Among them, 74% sold obsolete devices to informal collectors, 47% stored unused devices, and only 11% used formal recycling. The KAP scores were 60.48% for knowledge, 78.85% for attitude, and 50.66% for practice.	Identifies substantial potential e-waste together with an attitude–practice gap, household storage, and strong informal-sector dependence

Overall, previous studies provide important but largely separate insights into e-waste generation, household behavior, and collection governance. This study extends this literature by integrating these dimensions at the district scale, allowing potential material availability to be interpreted together with behavioral readiness and institutional pathways for circular recovery. The comparison in Table 6 demonstrates that the present findings both support and extend previous research. The estimated potential e-waste generation in Bangil (4.94 kg capita^{-1} year^{-1}) is moderately higher than the 4.04 kg capita^{-1} year^{-1} reported by Rimantho et al. (2019) for Jakarta. However, this difference should not be interpreted solely as a geographical difference because stock-based MFA estimates are sensitive to product categories, device weights, service-life assumptions, and survey periods. At the national scale, Santoso et al. (2019) projected e-waste growth of approximately 14.91% year^{-1}, demonstrating the increasing physical magnitude of the problem but providing limited information on how households release obsolete products into recovery systems. The present study complements these approaches by showing that potential generation and actual accessibility to collection systems are not equivalent.

3.8 Practical Implications and Future Perspectives

This study focuses on household-generated e-waste in Bangil District and excludes commercial, institutional, and industrial sources. The district also has specific socioeconomic characteristics, community-based waste facilities, and informal-sector relationships; therefore, the numerical findings should not be generalized directly to other regions. Future studies should incorporate longitudinal material-flow monitoring, direct measurement of discarded products, multivariate behavioral modelling, and comparative studies across districts to assess the robustness and transferability of the proposed framework. Several limitations in this study are illustrated in Figure 5.

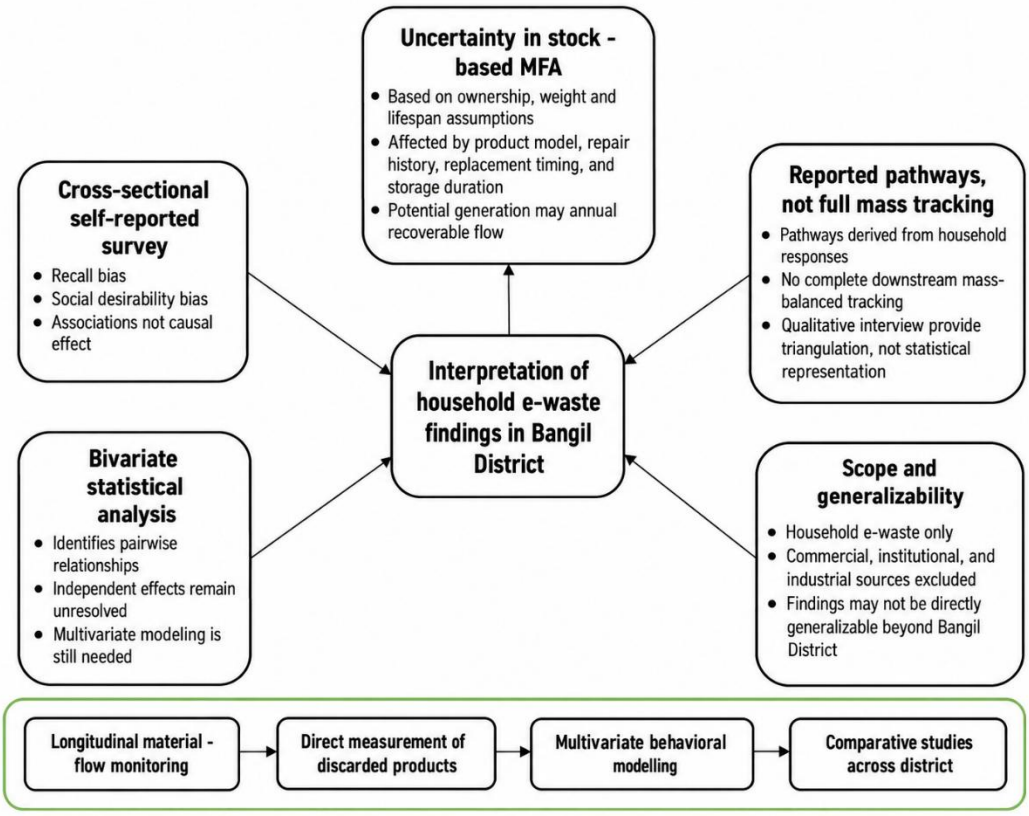


Figure 6. Study limitations and implications for future studies

The findings of this study have important implications for the development of household e-waste management systems in the Bangil District. The estimated e-waste generation rate of 4.94 kg capita^{-1} year^{-1} indicates a considerable future burden on local waste management systems, particularly as the

ownership of electronic devices continues to increase. In addition, the dominance of large household appliances, such as washing machines and refrigerators, highlights the need for dedicated collection and transportation mechanisms that can handle bulky e-waste.

The flow pathway analysis revealed that informal collectors currently play a central role in household e-waste management. Most respondents preferred selling obsolete electronic devices to collectors because of collectors' accessibility and the residual economic value of these products. Although this informal system contributes to material recovery and reuse, the limited involvement of formal recycling facilities indicates the need for stronger integration between the informal and formal sectors to improve collection efficiency and environmental performance.

The KAP assessment further identified an attitude–practice gap among the respondents. Although public attitudes toward e-waste management are generally positive, actual management practices remain limited. This finding suggests that awareness alone is insufficient to encourage proper electronic waste management behavior. The availability of accessible collection services, clear disposal information, and economic incentives may be equally important in influencing household participation in waste separation.

Based on these findings, community-based collection systems may provide a practical approach to improving household e-waste management in the Bangil District. Existing waste banks and 3R waste centers (TPS3R) can be utilized as temporary collection points for household e-waste before transfer to collectors or recycling facilities. This approach would strengthen local collection networks while minimizing the need for new infrastructure investments. Community-based collection systems, including waste banks, have been widely recognized as effective mechanisms for increasing participation in waste management programs and improving local collection performance (Rachman et al., 2021; Annashr et al., 2024). In addition to serving as collection points, waste banks can function as educational platforms that encourage environmentally responsible behavior and facilitate community engagement in e-waste management activities

The proposed approach is consistent with previous studies emphasizing the role of community-based waste management systems in increasing public participation and improving collection performance. Waste banks can serve not only as temporary collection points but also as educational platforms that encourage environmentally responsible behavior. Furthermore, incentive-based mechanisms, such as reward schemes, savings programs, and buy-back systems, may increase household willingness to participate in e-waste collection activities, particularly in areas where formal recycling infrastructure remains limited.

Overall, effective e-waste management in Bangil District requires a combination of public awareness programs, accessible collection services, institutional collaboration, and integration of informal collection networks into formal recycling systems. The integration of formal and informal sectors has been highlighted as an important factor in improving the effectiveness and sustainability of e-waste management systems, particularly in developing countries where informal actors dominate collection activities (Marinello and Gamberini, 2021). These measures can improve collection rates, reduce improper disposal practices, and support the recovery of valuable materials from household electronic waste. Therefore, district-level e-waste management should not stop at collection but should be designed as the first step of a resource recovery chain that supports safer recycling, reduced environmental leakage, and circular material use (Ni'am et al., 2019; Ni'am et al., 2020a; Ni'am et al., 2020b).

4. Conclusions

This study estimated household e-waste generation, mapped management pathways, assessed household knowledge, attitudes, and practices, and interpreted the findings within the local institutional context of Bangil District. The stock-based MFA estimated potential household e-waste generation at approximately 4.94 kg capita^{-1} year^{-1}, while pathway and KAP analyses revealed a strong dependence on

informal collection, considerable household storage, limited formal recycling, and a clear gap between favorable environmental attitudes and actual management practices. These empirical findings indicate a material–behavioral mismatch, in which potentially recoverable electronic materials and positive behavioral readiness coexist with insufficient institutional opportunities for formal recovery. The main scientific and methodological contribution of this study is the integration of stock-based MFA, household pathway mapping, KAP assessment, and stakeholder evidence within a district-level diagnostic framework linking material availability, behavioral readiness, and institutional opportunities. This integration extends conventional e-waste assessment beyond estimating material quantities or examining behavior separately by explaining why potentially recoverable materials may remain stored or move through informal rather than formal recovery pathways in the Global South. From a Circular Economy and policy perspective, the findings indicate that improving household e-waste management requires more than awareness campaigns. District-level strategies should strengthen accessible collection services, utilize waste banks and TPS3R as local aggregation points, and improve the coordination between informal collectors and formal recycling systems. Future research should test the framework in other districts, incorporate longitudinal monitoring of actual e-waste flows, and apply multivariate analysis to better identify the determinants of household E-WM behavior.

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CRediT Author Statement

Rizqi Meuthia Widyansingsih: Conceptualization, Methodology, Investigation, Data Curation, Formal Analysis, Writing – Original Draft.
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Ethics Statement

This study involved voluntary participation from household respondents and stakeholders in Bangil District, Pasuruan Regency. All participants were informed about the purpose of the study prior to data collection and provided their consent to participate. The anonymity and confidentiality of the respondents were maintained throughout the research process, and all collected data were used solely for academic purposes.

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