Feasibility of the 9Rs Circular Economy Framework for Household Waste Management in High-Rise Residential Buildings in Bangkok

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ABSTRACT

Rapid urbanization has intensified household waste management challenges within high-rise residential buildings. The application of advanced circular economy frameworks at the building unit-level remains limited. This study investigated the feasibility of applying the 9Rs circular economy framework to household waste management in high-rise residential buildings in Bangkok, with a focus on buildings operating at approximately 300 residential units. Waste generation and composition profiles were collected from residential buildings in the Watthana and Khlong Toei districts using the WACS guideline. The results indicated a mean waste generation rate of 0.91 ± 0.19 kg/unit/day, with a moderate CV reflecting inter-building variability attributable to differences in occupancy behavior and household consumption patterns. Characterization analysis showed that general waste constitutes the largest proportion, followed by organic, recyclable, and hazardous waste at 40.8%, 33.6%, 22.8%, and 2.8%, respectively. At a detailed subcategory level was classified into 23 subcategories spanning composition was dominated by food waste, stained paper, single-use plastics, and recyclable plastics at 32.21%, 13.53%, 9.64%, and 9.24%, respectively. Which collectively constituting approximately 65% of total waste generated. Systematic mapping of the 23 waste subcategories against the 9Rs framework demonstrated that more than 90% of identified fractions possess at least one viable circular economy pathway. However, the aggregate flow is heavily skewed toward low-order recovery strategies, particularly R9 (Recover) due to high organic moisture and material contamination, followed by R7 (Repurpose), R3 (Reuse) and R8 (Recycle), reflected the structural limitations imposed by insufficient source separation and indicated that while waste generation rates are relatively uniform, individual consumption behaviors and lifestyle patterns vary significantly. The study concluded that transitioning to a circular economy building-scale is partially and conditionally feasible due to mixture of household waste. The findings provide the design of building-scale circular waste management strategies with source separation infrastructure for maximizing the recovery of high-potential resources into recovery process.

Keywords: 9Rs-circular economy/ Household waste/ Waste management/ High-rise residential buildings

1. INTRODUCTION

High-rise residential buildings have emerged as a dominant urban housing typology in rapidly growing Asian megacities, including Bangkok, where condominium development has accelerated substantially over the past two decades [1,2]. Buildings of this type, typically operating at scales of several hundred residential units, generate substantial and continuous household waste streams characterized by high spatial concentration, shared waste infrastructure, and limited on-site treatment capacity [3,4]. Unlike single-family dwellings, high-rise condominiums concentrate waste generation within a defined physical boundary governed by building management systems, making them a distinct and underexplored context for circular economy implementation. Despite their significance, the waste generation profiles, compositional characteristics, and recovery potential of waste streams produced at the building unit-level remain poorly documented, particularly for buildings operating at the 300-unit scale, which represents a prevalent and policy-relevant occupancy range in Bangkok's residential market [2,5]. A critical gap therefore exists, while studies on municipal solid waste in Bangkok have provided aggregate compositional profiles, they do not resolve the specific waste generation rates and material composition patterns attributable to individual buildings at a defined unit-level occupancy. Equally important is the question of inter-building variability, specifically whether buildings of comparable scale but different resident profiles exhibit meaningfully distinct waste characteristics, a

distinction that carries direct implications for the transferability of circular waste management interventions across similar building types [1,4].

The circular economy (CE) has emerged as a widely endorsed paradigm for decoupling resource consumption from waste generation through prioritizing prevention, reuse, and recovery over linear end-of-pipe disposal [6,7,8]. Among the various frameworks operationalizing CE principles, the 9Rs hierarchy offers the most granular structure for waste management decision-making is called circularity level, extending from high-order prevention strategies (Refuse, Rethink, Reduce) through mid-order material retention strategies (Reuse, Repair, Refurbish, Remanufacture, Repurpose) to low-order material recovery options (Recycle, Recover) [9,10,11]. The applicability of each R-strategy to household waste, however, is fundamentally contingent upon the material composition of that waste stream without empirical characterization of waste composition at the building scale, systematic 9Rs mapping remains speculative. In a post-consumption household waste context, where products have already passed through use and entered the waste stream, the feasible range of R-strategies is constrained primarily to mid-to-lower order interventions, making the compositional profile the key determinant of circular recovery potential [12,13,14]. Yet existing literature on CE implementation in the built environment tends to focus on municipal systems, industrial symbiosis, or green building certification frameworks, with limited attention to the residential building as a discrete operational unit of waste management [1,12]. High-rise residential buildings present a governance and behavioral context that is distinct from both individual households and municipal systems that waste-related decisions are mediated by building management regulations, shared infrastructure design, and collective resident behavior, rather than being determined solely by individual choice or city-level policy [1,4,15]. This governance specificity means that CE strategies feasible in municipal or low-density residential contexts may not be directly transferable to high-rise settings, and that building-specific empirical evidence is necessary to formulate realistic implementation pathways.

Against this backdrop, this study empirically investigates the feasibility of applying the 9Rs circular economy framework to household waste management in high-rise residential buildings in Bangkok, with a focus on buildings operating at approximately 300 residential units. The study is guided by three research objectives (1) to characterize household waste generation rates and compositional profiles across high-rise residential buildings operating at approximately 300 residential units in Bangkok, (2) to map the identified 23 waste subcategories against the 9Rs circular economy framework in order to assess the recovery feasibility of each waste fraction within a post-consumption household waste context, and (3) to evaluate the degree of inter-building variation in waste generation and composition among sampled buildings of comparable unit-level scale, with implications for the generalizability of circular waste management strategies across similar residential contexts. These objectives are addressed through field-based waste characterization across five representative residential buildings using the Waste Analysis and Characterization Study (WACS) guideline [16,17], followed by systematic 9Rs framework mapping.

2. METHODOLOGY

This study employed a quantitative research methodology combined with field surveys and interviews with stakeholders to obtain comprehensive data on both the quantity and behavior of waste management.

2.1 Study area and sample group

Data collection was conducted in the sampled residential buildings in the Watthana and Khlong Toei districts, Bangkok areas with high population density and rapid economic growth. These buildings were selected to represent at a level close to 300 units of current residents that were 5 representatives of occupied unit-level, which the number of residents at this level, serving as the average occupancy rate for residential buildings, will reflect household waste generation patterns as shown in Table 1.

Table 1. The characteristic of unit-level residents in sampled residential buildings

Residential building	Occupied unit-levels
B1	369
B2	293
B3	370
B4	308
B5	316
Average	331

2.2 Data collection and preparation

Waste sampling was conducted continuously for four days during in September, a sufficient period for waste analysis and characterization (WACS) according to JICA [16,17] and Pollution Control Department (PCD) guidelines [5]. Waste collected from each floors collection point is sent to a central waste collection point for total weighing. Then, the quartering method is used to randomly sample a weight from 25% (Approximately 74 kg) of the average waste weight of 294 kg from each building for detailed sorting.

2.3 In-depth waste classification

Household waste is classified into 4 main categories, including organic waste, general waste, recyclable waste, and hazardous waste. These are further subdivided into 23 subcategories to align with the 9Rs framework and Thai's Pollution Control Department (PCD) guidelines [5]. This detailed classification allows for the precise identification of the recovery potential of each type of material.

2.4 Data analysis

The data were analyzed using descriptive statistics, including the mean and standard deviation (SD). Additionally, collected data were analyzed using a comparative analysis and an analytical framework that mapped existing practices against each R-strategy [6,10,18], as followed by Table 2.

Table 2. Comparison of the priorities of the 9Rs strategies in the circular economy [11,13,14]

Circularity level	R-Strategy	Definitions and practical meanings
High-level	R0: Refuse	Reject the use of unnecessary products or designs that eliminate the need for those materials.
	R1: Rethink	Rethinking product usage to make it more intensive, such as through sharing.
	R2: Reduce	Reducing the efficiency of resource use in production or consumption processes.
Mid-level	R3: Reuse	Reusing usable products for their original function.[8]
	R4: Repair	Repairing damaged products to restore them to their original working condition.
	R5: Refurbish	The improvement or restoration of older products to make them more modern and functional.
	R6: Remanufacture	Reusing discarded product components to manufacture new products with the same function.
	R7: Repurpose	The process of using a product or component in a new function that is different from its original purpose.
Low-level	R8: Recycle	The process of transforming waste materials into secondary raw materials of the same or lower quality.
	R9: Recover	Waste-to-Energy (Waste incineration for energy recovery)[8]

3. RESULTS AND DISCUSSION

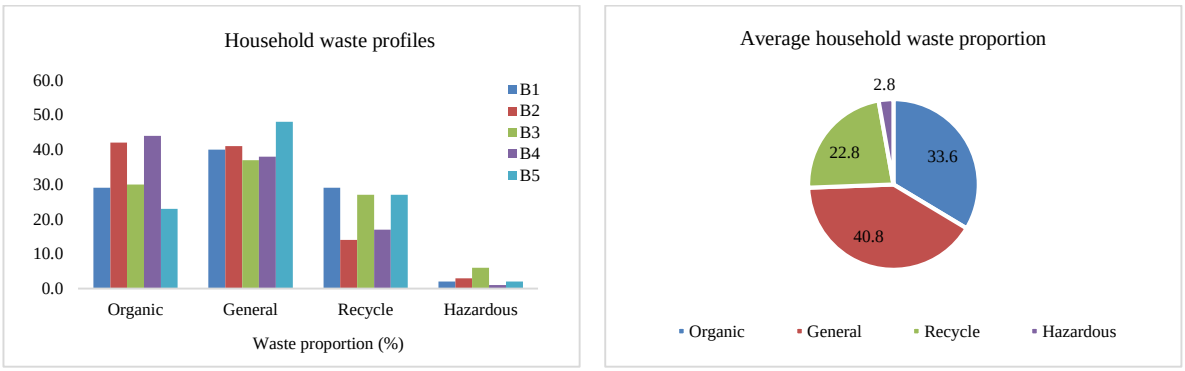
3.1 Characteristics of waste generation and proportional profiles

The waste generation from the sampled high-rise residential buildings as shown in Table 3, revealed an average total waste generation of 294.0 ± 40.49 kg/day, with an average daily waste generated rate of 0.91 ± 0.19 kg/unit/day. The quantity and household waste generated rate were compared across groups, with the highest waste volume recorded at B5 and B2 accounted for 352.4 and 319.8 kg/day, while B4 and

B3 were around the average waste generated accounted for 285.5 and 280.8 kg/day. Additionally, B1 had the least waste generated accounted for 231.8 kg/day, respectively. These were reflected in the total CV of 13.77%, which statistically confirms that the total waste generated varies moderately between buildings depending on the number of residents and the physical scale of the building. These variations are primarily attributable to differences in building scale, number of residential units, and actual occupancy rates, all of which directly influence daily waste accumulation [19]. Considering the waste generation rates per occupied unit, and disregarding absolute building scale, it was found that B5 and B2 had 1.14 and 1.09 kg/unit/day, which still hold the highest point for generating the most waste per unit, which is significantly higher than the overall average accounted for 0.91 kg/unit/day. While B1 had the lowest waste generation rate at 0.63 kg/unit/day, while the overall CV of 20.88% indicated that the consumption and waste generation behaviors of the population in each building show a moderate level of variation and are not fully clustered together.

Table 3. Household waste generation and proportional profiles

Residential buildings	Waste generated (kg/day)	Waste generated rate (kg/unit/day)	Household waste generated							
			Organic		General		Recycle		Hazardous	
			kg/day	%	kg/day	%	kg/day	%	kg/day	%
B1	231.8	0.63	67.2	29.0	92.7	40.0	67.2	29.0	4.6	2.0
B2	319.8	1.09	134.3	42.0	131.1	41.0	44.8	14.0	9.6	3.0
B3	280.8	0.76	84.2	30.0	103.9	37.0	75.8	27.0	16.8	6.0
B4	285.5	0.90	125.6	44.0	108.5	38.0	48.5	17.0	2.9	1.0
B5	352.4	1.14	81.1	23.0	169.2	48.0	95.2	27.0	7.0	2.0
Average	294.0	0.91	98.5	33.6	121.1	40.8	66.3	22.8	8.2	2.8
S.D.	40.49	0.19	26.47	8.06	27.10	3.87	18.46	6.08	4.89	1.72
CV (%)	13.77	20.88	26.87	23.99	22.38	9.49	27.84	26.67	59.63	61.43



A B

Figure 1. The characteristic of household waste generated (A) and Average percentage of household waste proportional profiles (B)

In terms of waste proportional profiles as shown in Figure 1 and Table 3, household waste was categorized into four main types including organic, general, recyclable, and hazardous waste. General waste was the largest percentage proportion accounted for 40.8 % of total waste proportion, followed by organic, recyclable, and hazardous accounted for 33.6%, 22.8% and 2.8%, respectively. These waste proportions corresponded to average household waste by weight, accounted for 98.5±26.47, 121.1±27.10, 66.3±18.46, and 8.2±4.89 kg/day, respectively. This indicated that relationship between consumption behavior and unit-level of building, which sampled building groups with similar unit-level across buildings. The trend is generally in the same direction about general waste that showed the least difference between buildings [12,17,19]. All residential buildings had a general proportion of approximately 37-48%, regardless of group, residents tend to dispose of general waste in similar proportions.

For building groups with moderate difference, there was considerable variation of organic waste with B4 and B2 were 44.0 and 42% accounted for almost half of all waste generated, while B5 was 23.0% that had the lowest proportion. This reflected differences in cooking lifestyle and patterns. Furthermore, the relatively high proportions of organic and general waste reflect the consumption patterns of urban residential building residents [1], particularly behaviors associated with ready-to-eat meals and food delivery ordering patterns across the buildings. Additionally, recyclable waste in all buildings clustered together at approximately 27%. However, B2 and B4 accounted for 14.0 and 17.0% fell below the group, this indicated that the recycling management systems or awareness in separating recyclable waste were different and may need more promotion than other buildings. Finally, hazardous waste was groups with extremely difference that showed the greatest statistical variation among buildings. B3 had a hazardous waste proportion as high as 6.0% or 16.8 kg/day, which was double the overall average hazardous waste proportion at 2.8%, while B4 has only 1.0% or 0.6 kg/day, respectively. This indicated that the population structure or activities in daily life pattern or infrequent disposal of hazardous waste leads to accumulation, which causes the weight of hazardous waste to fluctuate per disposal [4,20].

Considering the statistical differences using the coefficient of variation (CV%) of waste types, it was found that the disposal behavior of general waste among residents in all buildings was the most consistent and similar, with the lowest CV at only 9.49%. Conversely, the quantity and proportion of hazardous waste showed the greatest difference and distribution, with a high CV of 61.43%. B3 had the highest proportion of hazardous waste accounted for 6.0%. This reflected the need for appropriate waste management measures to prioritize controlling hazardous waste in specific areas and improving the recycling capacity of buildings to align with the circular economy concept. These findings highlight the importance of implementing effective source separation systems, particularly a considerable potential for material recovery throughout entire of post-consumption stage, to improve household waste management efficiency through circular economy in high-rise residential settings [21].

3.2 Household waste compositional profiles

The compositional analysis of household waste generated in residential buildings with an average of 331 units per building. It was conducted through waste sampling across five buildings (B1 to B5). Each building yielded randomly sample a weight from 25% of the average waste weight of 294 kg, which was subsequently classified into 23 waste subcategories, as presented in Table 4 and Figure 2. It was found that the household waste composition contained the highest percentage of food waste, which accounted for 32.21% or approximately 8 kg/day of total waste composition. This finding is consistent with the dietary consumption patterns typically observed among urban residential building residents with the associated standard deviation (SD = 2.24), indicated a moderate level of inter-building variability, which may be attributed to differences in household structures, including variations in family structure and in-unit cooking behavior among residents. In additional, examined at the unit-level, these findings presented in the significant influence of household activity patterns in daily life and consumption behaviors of high-density unit-level in residential buildings context [1,12].

Subsequently, stained paper represented the second highest proportion, accounted for 13.53% of total waste, with a mean of 3.38 kg and a relatively low level of inter-building variability (SD = 0.51). This consistency reflected consumption pattern of food packaging and disposable product consumption among residents, including tissue paper, food wrapping materials, and packaging associated with food delivery which contained moisture. Correspondingly, single-use plastics and recyclable plastics exhibited comparable proportions of 9.64% and 9.24%, respectively, collectively comprising nearly 19% of total waste generated. These findings highlight the persistent distribution of plastic packaging in the daily consumption behaviors of residents. Additionally, plastic bags accounted for 4.99% (SD = 0.56), which indicated that household-level plastic bag usage remains substantial.

Table 4. Comparison of household waste composition in the sampled buildings

No.	Household waste composition	B1	B2	B3	B4	B5	Mean	Percentage (%)	SD
1	Food waste	20.29	30.14	21.64	15.55	30.77	23.68	32.21	6.59
2	Garden waste	0.00	0.00	0.08	0.87	1.37	0.46	0.63	0.62
3	Pet waste	0.00	0.33	0.81	3.65	0.00	0.96	1.31	1.54
4	Recyclable paper	5.20	1.81	3.13	4.77	1.52	3.29	4.47	1.68
5	Stained paper	10.91	11.81	8.07	8.91	10.02	9.94	13.53	1.50
6	Wood	0.32	0.71	0.38	0.67	0.00	0.42	0.57	0.29
7	Fabrics	2.36	1.54	0.80	1.23	1.47	1.48	2.01	0.57
8	Rubber and Leather	1.59	0.48	0.08	0.48	0.00	0.53	0.72	0.64
9	Diapers	1.01	3.14	5.02	4.91	1.64	3.15	4.28	1.83
10	Single-use Plastics	8.73	3.06	7.75	6.13	9.77	7.09	9.64	2.62
11	Plastic bags	4.27	5.47	1.00	4.13	3.46	3.67	4.99	1.65
12	Recyclable plastics	10.10	4.63	6.42	7.35	5.46	6.79	9.24	2.11
13	Multi-layer Plastics	1.25	2.68	1.93	1.99	1.98	1.97	2.68	0.51
14	Durable plastics	0.00	0.17	1.49	1.31	0.50	0.69	0.94	0.67
15	Foam	0.00	0.90	0.38	0.35	0.00	0.33	0.44	0.37
16	Metals	1.27	1.24	1.26	1.76	0.35	1.17	1.59	0.51
17	Glass	4.40	2.52	7.61	4.46	4.45	4.69	6.38	1.83
18	Hazardous waste	0.00	0.77	0.89	0.22	0.75	0.53	0.72	0.39
19	Damaged electronics	1.23	0.65	0.03	0.80	0.00	0.54	0.74	0.53
20	Infectious waste	0.34	0.80	3.87	0.55	0.00	1.11	1.51	1.57
21	Stone and Ceramics	0.00	0.22	0.30	1.09	0.00	0.32	0.44	0.45
22	Bones and Shells	0.22	0.33	0.30	0.81	0.00	0.33	0.45	0.30
23	Other	0.00	0.10	0.27	1.52	0.00	0.38	0.51	0.65

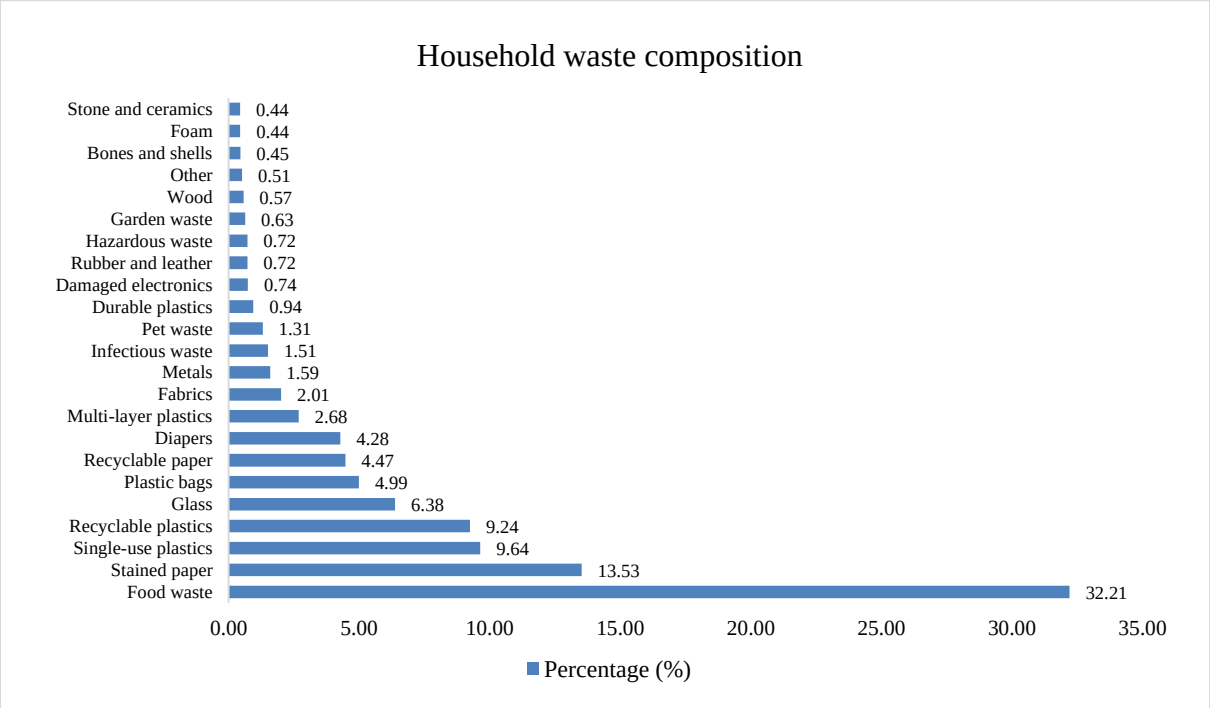


Figure 2. Household waste compositional profiles

Glass averaged 6.38% with the highest value observed in building B3 accounted for 2.59 kg. An inter-building variability may be associated with differences in the resident age profile and beverage consumption habits. Diapers constituted 4.28% of total waste (SD = 0.62), with notably higher quantities presented in B2 and B4, suggested a relatively greater proportion of households with infants or elderly residents in those buildings. This finding carried practical implications for the planning of waste segregation systems, particularly for waste streams requiring specialized handling or categorized as infectious waste. Notably, waste categories with a low proportion but high environmental implications, including hazardous waste, infectious waste, and damaged electronics were 0.72%, 1.51%, and 0.74%, respectively. Despite their minor shares, these categories required management and disposal systems that strictly adhere to safety standards, which these materials into general waste stream may pose considerable risks to public health and environmental risks, particularly within high-density residential building contexts [22].

Overall, the unit-level compositional analysis of waste generated in residential buildings with approximately 300 residential unit-levels demonstrated that organic waste, especially food waste and packaging waste such as various categories of paper and plastics, collectively accounted for more than 65% of total waste generated. This finding suggested that promoting source separation alongside enhancing in-building packaging recycling systems, represented by a critical strategy for effectively reducing the waste volume directed disposal facilities into landfill [23].

3.3 Household waste composition and applicable 9Rs circular economy framework mapping

The application of the 9Rs circular economy framework to the household waste compositional profile generated in the sampled residential buildings revealable a resource recovery and waste valorization opportunities, as detailed in Table 5, identified 23 waste categories, each subsequently mapped to applicable 9Rs circular economy pathway. The findings indicated that the majority of household waste fractions were amenable to at least one circular pathway, thereby underscoring the feasibility of transitioning from a conventional linear waste management model toward a more resource-efficient, circular approach at the building unit-levels.

Food waste represented the largest composition at 32.21%, which is associated with multiple recovery strategies (R3, R7, R9) such as composting, anaerobic digestion (AD) and biogas production. Additionally, garden waste and bones and shells had 0.63 and 0.45%, similarly support composting and soil amendment pathways (R3, R7), while pet waste had 1.31% which is directed toward AD or controlled waste-to-energy (WtE) conversion (R9). Stained paper represented the largest composition accounted for 13.53% of paper and packaging fractions, despite its contamination which remained amenable to refuse-derived fuel (RDF) or WtE (R7, R9), followed by recyclable paper had 4.47% sortable through reuse, recycling, and RDF pathways (R3, R8, R9). The convergence of stained and recyclable paper fractions, collectively accounting for approximately 18% of total waste, highlights the importance of source separation at the point of generation to preserve material quality and maximize circular value. However, wood and fabrics had 0.57 and 2.01%, respectively. These were similarly directed toward lower-order recovery options including biomass fuel and RDF (R9), or repurposing into rags and insulation materials.

In context of plastic fractions were found the combined any plastic waste stream, including single-use plastics, recyclable plastics, plastic bags, multi-layer plastics, durable plastics, and foam accounted for 9.64%, 9.24%, 4.99%, 2.68%, 0.94%, and 0.44%, respectively. These were collective constitutes approximately 28% of total waste, represented the single most significant material group after food waste. Recyclable plastics were positioned highest within the circularity hierarchy, supporting refurbishment, remanufacturing, and mechanical recycling processes including cleaning, sorting, grinding, and remelting into secondary raw materials (R5, R6, R8, R9). In contrast, single-use plastics and plastic bags were largely confined to RDF or WtE pathways (R8, R9) due to the technical and economic limitations of their recyclability [11,24,25]. Multi-layer plastics presented particular challenges, as their composite structure constrains recovery options to specialized recycling or low-

grade applications such as construction materials (R8, R9). These findings were consistent with the low recyclability of mixed and multi-material plastic packaging in municipal solid waste streams [17].

Additionally, glass, metals, durable plastics, rubber and leather, and stone and ceramics, which it accounted for 6.38%, 1.59%, 0.94%, 0.72%, and 0.44%, respectively. These groups were categorized to the inorganic and durable fractions that supported reuse, refurbishment, and recycling (R3, R5, R8). However, non-recyclable glass may be downcycled into construction aggregates or specialty glass products such as Pyrex and mirror composites. Metals offered high-value circular potential through refurbishment, remanufacturing, and closed-loop recycling (R5, R6, R8) that reflected in the well-established economic viability of metal recovery. For durable plastics can be reprocessed by melting and reshaping into new products (R3 to R6, R8), while foam, primarily expanded polystyrene (EPS), can be recycled through grinding, densification, or melting to generate new materials or RDF (R5, R6, R8, R9). Rubber and leather were directed toward repair, refurbishment, or energy recovery by co-processing in cement kilns (R4, R5, R9). Stone and ceramics were supported by upcycling as construction aggregates and surface materials (R3, R7, R8). Household waste streams required a specialized management such as diapers, hazardous waste, infectious waste, and E-waste were 4.28%, 0.72%, 1.51%, and 0.74%, respectively. These were classified as a hygiene waste stream, which are currently limited to WtE treatment (R9) due to biological contamination, underscored the need for dedicated collection infrastructure and necessitates high-temperature incineration to prevent biological risk. These fractions collectively represent critical gaps in existing residential household waste management systems, as improper co-disposal with general refuse poses significant risks.

Overall, the 9Rs mapping demonstrated that more than 90% of the household waste fractions identified in this study possess at least one viable circular economy pathway. However, the effective realization of these pathways was contingent upon the implementation of robust source separation at point sources, behavioral resident engagement, and the establishment of appropriate downstream processing infrastructure [12]. The dominance of organic and packaging waste fractions was collectively exceeding 65% of total waste, suggested that priority investment in organic waste valorization and plastic packaging recovery systems would yield the greatest systemic impact in reducing the volume of residual waste directed to disposal facilities [15,26,27]. These findings provided an empirical basis for the formulation of building unit-levels circular waste management strategies tailored to the specific compositional characteristics of high-density residential buildings [1,21].

Table 5. Household waste composition and applicable 9Rs-framework mapping [6,9,10,14]

Composition	Percentage (%)	Applicable 9Rs	Circular pathway
Food waste	32.21	R3, R7, R9	Animal feed, composting, anaerobic digestion (AD), biogas and soil amendment.
Garden waste	0.63	R3, R7, R9	Mulch, composting and biomass energy recovery.
Pet waste	1.31	R9	AD or controlled waste to energy (WtE).
Recyclable paper	4.47	R3, R8, R9	Wrapping, pulping or refuse derived fuel (RDF) if contaminated.
Stained paper	13.53	R7, R9	Crafts, RDF or WtE.
Wood	0.57	R9	Biomass fuel.
Fabrics	2.01	R3, R7, R9	Rags, insulation or RDF.
Rubber and leather	0.72	R4, R5, R9	Repair, refurbish or energy recovery through co-processing in cement kilns.
Diapers	4.28	R9	WtE.
Single-use plastics	9.64	R8, R9	RDF or WtE.
Plastic bags	4.99	R3, R8, R9	Liners, PE/LDPE (bubble) to recyclable plastic pallets, bags or gasoline, and RDF/WtE if contaminated.
Recyclable plastics	9.24	R5, R6, R8, R9	Refurbish, remanufacture, recycle through the process of cleaning, sorting, grinding, and remelting to form new products and RDF if degraded.

Composition	Percentage (%)	Applicable 9Rs	Circular pathway
Multi-layer plastics	2.68	R8, R9	Specialized recycling, green road or construction materials for upcycling and RDF/WtE (Low recyclability).
Durable plastics	0.94	R3, R4, R5, R6, R8	Such as PP and HDPE are mostly recyclable by melting and reshaping and it requires a specific process, which is often used to create durable new plastic products as well.
Foam	0.44	R5, R6, R8, R9	As expanded polystyrene (EPS) can be recycled almost 100% by grinding, densifier or melting to create new products and RDF.
Metals	1.59	R5, R6, R8	Refurbish, remanufacture and recycle with high-value recycling.
Glass	6.38	R3, R5, R8	Reuse containers, refurbish and recycling. Non-recyclable or difficult to recycle glass can be crushed to make a mixture for construction materials such as eat-resistant glass (Pyrex), mirror, ceramic and light bulb.
Hazardous waste	0.72	R8, R9	These materials are amenable to recycling, particularly those classified as metals, plastics, or certain chemical substances, but it must undergo specialized safe handling and management processes and thermal treatment under controlled conditions.
E-waste	0.74	R4, R5, R6, R8	These materials are recyclable and should be processed through proper recycling channels, given that they contain both precious metals including gold, silver, and copper. Such materials should be directed to designated drop-off collection points such as dry cell batteries and damaged electrical waste.
Infectious waste	1.51	R9	High-temperature incineration (Thermal treatment).
Stone and ceramics	0.44	R3, R7, R8	As construction aggregate for upcycling, solid surface and construction materials (Low recyclability).
Bones and shells	0.45	R3, R7	Upcycling, composting, soil amendment or RDF.
Other	0.51	R3, R7, R8, R9	Sorting, recycling depending on material type and RDF.

3.4 Synthesized household waste management into integrated 9Rs circular economy implementation

This study employs a mapping approach to assess alignment between existing household waste management practices in high-rise residential building and the 9Rs framework. The analysis focuses on feasibility of the extent to which each R-strategy can be realistically implemented under prevailing behavioral, infrastructural, and governance conditions rather than performance outcomes [11,25]. Mapping logic including lower-order strategies (Refuse, Rethink, Reduce) through behavior-driven with highly feasible at household level that require awareness and minimal institutional support [23]. Mid-order strategies (Reuse, Repair, Refurbish, Repurpose) require shared facilities constrained by space, management policies, and lifestyle patterns and higher-order strategies (Remanufacture, Recover) about adjust system-dependent as largely beyond condominium management control [1,2,12].

From system-level synthesis of the data presented that certain the integration of compositional analysis and 9Rs framework mapping, recovery efficiency estimation that provided a comprehensive evidence base for the formulation of a building unit-level circular waste management strategy tailored to the specific characteristics of moderate-density residential buildings with approximately 300 residential units. At this occupancy scale, the daily household waste generation and material composition patterns identified in this study translate into a predictable and quantifiable resource stream that, if systematically managed, presents substantial opportunities for circular value creation within and beyond the building boundary [24].

4. CONCLUSIONS

This study demonstrated that the application of the 9Rs circular economy framework to household waste management in high-rise residential buildings in Bangkok at a 300 unit-scale occupancy is currently partially and conditionally feasible. The empirical evidence indicated that while over 90% of the household waste fractions generated possess at least one technically viable circular

economy pathway. The total waste stream is heavily dominated by low-order-recovery fractions, specifically food waste (32.21%) and stained paper (13.53%), which collectively skew the aggregate system flow toward R9 (Recover/Waste-to-Energy). Conversely, high-value, high-order-recovery materials like metals and recyclable plastics represented modest volumetric shares, despite holding superior closed-loop circular potential. While the waste generation rate mean stands at 0.91 kg/unit/day, the high coefficient of variation (CV) in proportional subcategories like hazardous waste (61.43%) and organic waste (23.99%) highlights highly diverse consumer behaviors and household lifestyle patterns within the same building scale. This can be confirmed that a 300 unit-scale is highly sensitive and effective at reflecting localized demographic variations and lifestyle behaviors. The primary structural and behavioral barriers preventing a full circular transition stem from the current lack of source-separation infrastructure and localized material contamination. Without robust separation at the point of generation, high-value recyclables rapidly lose their product integrity, dropping down the 9Rs hierarchy into general refuse destined for landfills or low-grade incineration. Future research should seek to validate the proposed recovery efficiency estimates against empirical data from pilot-scale implementations of building-level circular waste management systems, and to assess the socioeconomic feasibility of different intervention strategies across building types of varying scale and socio-demographic composition.

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