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Assessment of Household Solid Waste Composition and Characterization for Sustainable Waste Management in Ba Ria–Vung Tau Province, Vietnam

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Abstract: Classifying household solid waste into specific categories was a foundational step for effective waste management, enabling tailored strategies for each waste type. The household solid waste in Ba Ria–Vung Tau Province was classified into three main categories: (i) food waste, (ii) reusable and recyclable waste, and (iii) inorganic and hazardous waste—each requires distinct handling, processing, and disposal methods to optimize resource use and minimize environmental impact. The physical properties of solid waste have been characterized based on the density of waste, moisture content, and calorific value. The components of household solid waste in Ba Ria–Vung Tau Province recorded urban areas, rural areas, and islands in the percentage by dry weight. According to the surveyed results in 2021 – 2022, the household solid waste generated in Ba Ria–Vung Tau Province was 1,288,180 kg/day. Of which, the quantity of solid waste generated in urban areas was highest with 860,740 kg/day, next in rural areas at 418,600 kg/day, and the district of Con Dao Island at 8,840 kg/day. The values of the various parameters were recorded: density (292.5 – 349.1 kg/m3), moisture content (54.3 – 61.2 %), and calorific value (6.37 – 9.28 MJ/kg). The high calorific value of waste indicates that it contains a significant amount of energy that could be harnessed. According to statistics, the amount of household solid waste generated in this province by 2030 will be more than 2,458,000 kg/day. This study is the baseline for a sustainable waste management system with a focus on source separation.

Keywords: *Assessment, Characterization, Classification, Composition, Household solid waste*

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1. Introduction

Household or municipal solid wastes were typically generated from various sources linked to different human activities, including residential areas, commercial establishments, institutions, and public spaces. Several studies reported that the municipal solid waste that was generated in developing countries was mainly from households (55 – 80%), followed by the market or commercial areas (10 – 30%) (Nguyen & Phan, 2022). The rest included various quantities generated from industries, streets, institutions and many others (Miezah et al., 2015; Hussein & Mansour, 2018). In general, solid waste from such sources is highly heterogeneous in nature and has variable physical and chemical characteristics depending on their original sources. Their composition was garden waste, food waste, plastics, wood, metals, papers, rubbers, leather, batteries, inert materials, textiles, paint containers, demolition and construction materials as well as many others that would be difficult to classify (Ngo et al., 2021). Knowledge of the waste generation rate, the type of waste generated, the generation rate by income level, and the type of waste generated per income level, as well as the generation rate during weekdays and weekends, could be useful in planning for solid waste management system (Hussein & Mansour, 2018). Understanding the physical and chemical composition of waste helps determine its energy value and supports the design and implementation of effective waste treatment solutions (Nguyen & Phan, 2022).

Solid waste management poses significant challenges worldwide, especially in Southeast Asia, due to rapid urbanization and population growth (Tseng et al., 2021). Implementing integrated Solid Waste Management (ISWM) and circular economy principles is necessary for effective solid waste management, prioritizing waste prevention, recycling, and environmentally sound disposal practices (Gir, 2021; Subedi, Pandey, & Khanal, 2023). According to Regional Waste Management in Asia (Kojima, 2020), the Philippines enacted the Ecological Solid Waste Management Act of 2000 (RA 9003) to promote waste segregation at source, recycling, and reduction. However, the country continues to struggle with challenges related to collection efficiency and the prevalence of open dumpsites, indicating the need for stronger enforcement and community involvement. In 2018, Thailand generated approximately 27.8 million tons of municipal solid waste, of which 34.4% were reused or recycled, 39.1% were properly managed, and 26.5% were improperly disposed of. Indonesia’s waste management system is under significant strain from rapid urbanization and population growth. Although the country has implemented various policies and programs to improve waste management practices, challenges persist in achieving sustainable and effective solutions (Suprapto, 2022). In 2022, Vietnam generated approximately 26.1 million tons of municipal solid waste, ranking third among Southeast Asian (SEA) countries in waste generation. This municipal solid waste accounted for 49.5% of the country's total waste generation (Bartels, 2024). Most of this waste is managed through landfills, with limited recycling and reuse efforts (Tseng et al., 2021). Waste characteristics are crucial in designing efficient, cost-effective, and environmentally friendly waste management systems (Hussein & Mansour, 2018; Mir et al., 2021).

By 2021, a resource utilization model for sustainable solid waste management had been established in Vietnam. A concurrent survey highlighted that national waste management policies were not applied uniformly across all localities in Vietnam. Cities and provinces responded by adopting different approaches to improve the effectiveness of these policies (Ngo et al., 2021). According to the Ministry of Natural Resources and Environment, Vietnam generated approximately 68,000 tons of household solid waste daily, with the household solid waste generated in Ho Chi Minh City and Hanoi accounting for nearly one third of the total national generation (MONRE, 2022). Specifically, Ho Chi Minh City produced around 9,500 tons of household solid waste daily, with an annual growth rate of 6 - 10% in waste volume. The daily household solid waste generation in Hanoi was about 7,000 tons (MONRE, 2022). This rapid increase places substantial pressure on the current waste management system, necessitating effective waste sorting, collection, treatment, and recycling solutions to protect the environment and public health.

A study conducted in Ba Ria–Vung Tau Province provides detailed insights into local waste characteristics and management strategies, focusing on (1) understanding household waste composition, (2) analyzing waste generation patterns, (3) assessing recycling potential, and (4) forecasting waste quantities through 2030. These targeted efforts offer data-driven guidance for more effective waste management practices, supporting the transition toward sustainable waste systems in Vietnam.

2. Materials and methods

2.1. Study area

Ba Ria–Vung Tau is a coastal province in southern Vietnam, known for its strategic economic position and natural beauty. As part of the Southern Key Economic Region, the most dynamic and economically vibrant area in Vietnam, the province contributes significantly to the national economy with an impressive average growth rate of around 7% per year (Figure 1). Ba Ria–Vung Tau spans approximately 1,989.56 km2 and is home to about 1,167,938 people. With an average density of 589 people/km2, this province has a relatively high population concentration, particularly in its urban and coastal regions (Ba Ria–Vung Tau Statistics Office et al., 2021; Lina et al., 2021). However, this development comes with the significant challenge of managing the increasing volume of solid waste generated by residents, tourists, and businesses. Effective solid waste management is crucial to sustaining economic growth and ensuring environmental health. In June and July 2022, a comprehensive solid waste sampling campaign was conducted in Ba Ria–Vung Tau to identify suitable waste management and control strategies. The parameters of solid waste characteristics could not be completed in the field, so an in-depth analysis of these waste characteristics was designated to be completed in the laboratory at the Environmental Technology Center (ENTEC).

Figure 1: Map of Ba Ria–Vung Tau Province

2.2. Classification of household solid waste

Solid waste consists of organic and inorganic waste, which includes a mix of heterogeneous waste from urban and rural communities and a more homogeneous accumulation from specific activities. This has been classified based on the source and type of solid waste; these included domestic/residential, agricultural, institutional, and commercial waste (Hussein & Mansour, 2018; Pheakdey et al., 2022). In this study, the classification of household solid waste in Ba Ria–Vung Tau adhered to the TCVN 9461:2012 (ASTM D5231-92) standard, which categorized the waste into several groups: biodegradable waste (food waste); recyclable waste (plastic, glass, metal, fabric, rubber, paper); and, inorganic substances (soil, sand, debris,...) and hazardous wastes (batteries, accumulators, light bulbs,...).

Solvin's (1960) formula was used to determine the number of survey households needed for classification in Equation 1 with a specified level of 90% accuracy (Ba Ria–Vung Tau Statistics Office, 2021). In this study, household solid waste samples were collected from 1,120 households. Among these, 43.7% of the samples were collected from urban areas, 50.0% from rural areas, and 6.3% from island regions.

$$n = \frac{\mathrm{N}}{1 + \mathrm{N}(e^2)} \qquad (1)$$

In which: n: the number of survey households (sample size); N: the total of survey households in each ward, town or commune; e: the standard error (e = 0,1), typically set to 0.1 (which corresponds to 10% margin of error or 90% accuracy).

The sampling strategy for household solid waste was carefully designed for a comprehensive analysis, with the following key steps: (1) Solid waste samples were collected daily at 7:30 am, over 7-day period; (2) Each sample combined waste from 10 households, creating a mixed sample weighting between 30 – 50 kg; (3) Nylon bags were used to store the solid waste sample securely; (4) Each mixed sample was classified, weighed, and analyzed on-site to determine the composition and distribution of waste types; and, (5) A 2 kg subset of each sample was collected separately for laboratory testing to analyze moisture content and calorific value.

2.3. Characterization of household solid waste

This analysis involved key parameters such as density, moisture content, and calorific value, which were collected and analyzed in the laboratory to provide precise and actionable data.

Density of wastes (kg/m3)

In this study, the density of solid waste (DW) was determined using Equation 2:

$$\mathrm{DW} = \frac{W_2 - W_1}{V_1} \qquad (2)$$

In which: W1: weight of solid waste in the container before setting (kg); W2: weight of solid waste in the container after setting (kg); V1: volume of container (m3).

Moisture content (%)

The dry-weight method was used to measure household solid waste's moisture content (MC), which was essential for accurate calorific value (CV) assessment and understanding the waste's characteristics for management and treatment. This research used the dry-weight method of measurement. The calculation followed the TCVN 9461:2012/ ASTM D5231-92 standard using Equation 3:

$$\mathrm{MC} = \frac{H_s - H_t}{Hs}\ x\ 100 \qquad (3)$$

In which: MC: moisture content of household solid waste (%); Ht: weight of household solid waste before drying, kg; Hs: weight of household solid waste after drying, kg.

Calorific value (kJ/kg)

The CV of household solid waste was a crucial parameter for assessing its potential for energy recovery. The testing followed the standard TCVN 200:2011/ ISO 1928: 2009 (Solid mineral fuels – Determination of gross calorific value by the bomb calorimetric method and calculation of net calorific value).

2.4. Forecasting the solid waste quantity

The volume of generated solid waste was calculated according to Equation 4:

$$M_i^{SH} = N_i \times k^{SH} \qquad (4)$$

MiSH is the volume of solid waste of the ith year (kg); Ni is the population of the ith year (people); and kSH is the waste generation coefficient (kg/person).

To project the population for future years up to 2030, a sequence of equations (5, 6, & 7) were used:

$$N_{i+1}^* = N_i + \mathrm{r}^*\Delta\mathrm{t}^*\mathrm{N}_i \qquad (5)$$

$$N_{i+1/2} = \frac{N_{i+1}^* + N_i}{2} \qquad (6)$$

$$N_{i+1} = N_i + \mathrm{r}^*\mathrm{N}_{i+1/2}{}^*\Delta\mathrm{t} \qquad (7)$$

In which: N^*_{i+1}: preliminary estimate of the population for the $(i+1)^{th}$ year; N_i: population of the i^{th} year; r: average growth rate of population; Δt: time increment; $N_{i+1/2}$: Average population between the i^{-th} and $(i+1)^{-th}$ years; Ni+1: Final estimate of the population for the $(i+1)^{-th}$ year.

2.5. Data analysis

The metrics of solid waste analysis (weight, density of wastes, moisture content, calorific value) were tested for their potential as parameters in the assessment of household solid waste management by regressing values two times in 2021 and 2022. The obtained data were subject to statistical analysis to test the analysis of variance (ANOVA) and the Pearson correlation among all the parameters using R-statistical software. Significant or highly significant positive or negative correlations were assumed when the p-calculated value was < 0.05, respectively.

3. Results and discussion

3.1. Household solid waste generation

According to the research results in Ba Ria–Vung Tau from 2021 – 2022, the total household solid waste generated per day this province was 1,288,180 kg. In which, the amount of solid waste generated in urban areas was highest with 860,740 kg/day, next rural areas 418,600 kg/day, and the district of Con Dao Island 8,840 kg/day (Table 1). Divide the total solid waste generated by the total population to find the average amount per person per day: average solid waste per person per day = 1,288,180 kg / 1,167,938 people ≈ 1.10 kg/capita/day. The result indicated that the average solid waste generation rate in Ba Ria–Vung Tau was higher than in several other cities, including Medan, Indonesia (0.22 kg/person/day), Hanoi, Vietnam (0.63 kg/person/day), and Irbid, Jordan (0.90 kg/person/day) (Khair et al., 2019; Ngo et al, 2021; Alwedyal, 2021). The elevated waste generation in Ba Ria–Vung Tau could be attributed to its status as a coastal tourism city, where high seafood consumption and other food-related activities contributed to the increased waste production (Ba Ria–Vung Tau Investment, Trade and Tourism Promotion Center, 2022). The tourism-driven increase in consumption likely lead to higher volumes of waste, particularly in food-related packaging and disposables, which were common in such locations. Though the urban area accounted for 58.5 percent, 683,129 people of the province's population, urban areas generated to 66.8%, 860,740 kg/day, of the province's household solid waste (Figure 2).

Table 1: The quantity of household solid waste generated in Ba Ria–Vung Tau, period from 2021 – 2022

Population (people; %)						Solid waste quantity (kg/day; %)					
Uban area		Rural area		Islands		Uban area		Rural area		Islands	
683,129	58.5	475,689	40.7	9,120	0.8	860,740	66.8	418,600	32.5	8,840	0.7

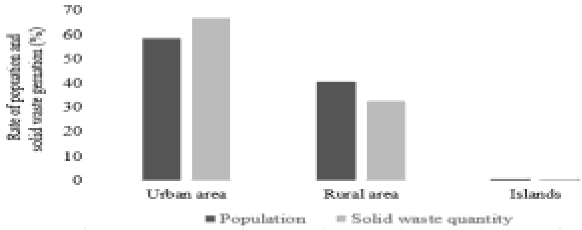

Figure 2: The rate of proportion and solid waste generation in Ba Ria–Vung Tau

3.2. Characterization of household solid waste

Figure 3 illustrates the components of household solid waste in Ba Ria–Vung Tau, highlighting urban areas, rural areas, and islands in percentage by dry weight. Recyclable wastes were the largest contributors to total household solid waste, with contributions ranging from 52.9 – 53.6% in the urban and rural areas. The district of Con Dao Island had the highest contribution of household solid waste from food waste (90.5%). Verma et al. (2016) also showed that food waste was the most significant component to total the MSW in Ho Chi Minh City, 69,0%. Recyclable major components (plastic and papers) were 19,0%. The other components were identified with 12.0% (all calculated in wet weight). This information was essential for understanding the waste management challenges and opportunities in one of Vietnam's largest cities.

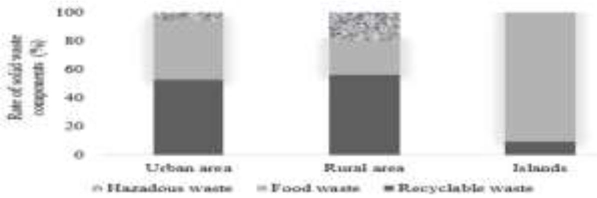

Figure 3: The rate of solid waste components in Ba Ria–Vung Tau

Density of wastes

The density of wastes varied with waste compaction, composition, and decomposition. The urban area waste yielded the highest density of 349.1 kg/m3. The waste collected from Con Dao islands yielded the lowest density of 292.5 kg/m3 (Table 2). This result agreed with Mugo et al. (2017) who noted the density of domestic/ residential waste of 307.6 kg/m3. However, the findings of Forouhar & Hristovski (2012) on municipal solid waste density in Kabul ranged from 361 to 465 kg/m3. This variation in waste density was crucial for waste management practices, including collection, storage, transportation, and the design of disposal facilities.

Table 2: Descriptive statistics on the density (kg/m3) of household solid waste in Ba Ria – Vung Tau

Survey areas	Descriptive statistics		
	Rank	Median	Mean ± SD
Urban area	323.8 –	349.1	353.6 ±

	384.0		20.9
Rural area	306.3 – 332.8	312.1	316.6 ± 10.5
Islands	291.0 – 293.1	292.5	292.3 ± 0.86

Moisture content

Moisture Content (MC) was different among the types of solid wastes. The MC was used to determine the quality of different types of waste as a fuel. Solid wastes from the urban area had the highest MC recorded at 61.2%. Solid wastes from the district of Con Dao Island contained the lowest MC recorded at 54.2%. (Table 3). The results also agreed with Chang et al. (2009), who reported that MC for solid waste from Taiwan ranged from 37.6 to 65.9% (Chang et al. 2009). While, the MC of household solid wastes recorded in Palapye, Botswana was higher, ranging from about 65.0 to 77.0 % (Dikole & Letshwenyo, 2020). So, the low MC of household solid waste in Ba Ria–Vung Tau would be attractive for recycling.

Table 3: Descriptive statistics on the MC (%) of household solid waste in Ba Ria–Vung Tau

Survey areas	Descriptive statistics		
	Rank	Median	Mean ± SD
Urban area	52.9 – 64.4	61.2	59.9 ± 4.34
Rural area	56.7 – 64.9	60.4	61.2 ± 2.92
Islands	53.8 – 55.9	54.3	54.6 ± 0.91

Calorific value

The calorific value (CV) depended on the moisture, carbon, and hydrogen contents of the waste and represented the amount of chemical energy in a given waste composition, as discussed by Bujak (2010) and Kathiravale et al. (2003). Municipal solid waste was an energy resource with sufficient energy/calorific value, making it a suitable substitute for fuel (Zaman, 2021).

Solid wastes from the district of Con Dao Island had the highest CV recorded at 9.28 MJ/kg, followed by urban solid waste, giving 6.63 MJ/kg. While rural solid waste yielded the lowest CV recorded at 6.37 MJ/kg. This result lowered with the findings by Omari (2015), who reported that the CV for municipal wastes from Arusha, Tanzania, gave 12.42 MJ/kg, and Khamala and Alex (2013), who published that the CV for municipal solid waste from Nairobi, Kenya, gave 12.48 MJ/kg. The results were higher than the findings by Das and Bhattacharyya (2013), who reported that the CV for municipal waste in Kolkata, India, was 5.03 MJ/kg in 2010. Zaman et al. (2021) improved the calorific factor of municipal solid waste through drying. The calorific values that were processed in the drying reactor and the control reactor were 55.3 % and 4.7 % higher than that of the unprocessed municipal solid waste, respectively.

Table 4: Descriptive statistics on the CV (MJ/kg) of household solid waste in Ba Ria–Vung Tau

Survey areas	Descriptive statistics		
	Rank	Median	Mean ± SD
Urban area	5.88 – 9.69	6.63	6.89 ± 1.29
Rural area	5.71 – 8.56	6.37	6.59 ± 0.95
Islands	9.17 – 9.49	9.28	9.29 ± 0.11

Higher CVs generally meant that waste could generate more energy when burned, which was important in areas where there was a focus on recovering energy from waste (Dadario et al, 2023). The high CV of solid wastes in Con Dao Island and urban areas suggested that it could be more suitable for energy recovery initiatives (such as incineration or biomass energy production). However, rural waste, characterized by a lower CV, presented challenges for energy recovery due to its lower energy density. To enhance the efficiency of waste-to-energy processes in rural areas, the waste could be sorted to remove low-calorific components, thus increasing its overall energy potential. Mixing rural waste with high-calorific materials would further boost its suitability for energy recovery.

3.3. Forecasting the quantity of solid waste

From data on solid waste emission coefficient and population, the quantity of household solid waste generated by 2030 will be forecasted in detail (Table 5). The total amount of household solid waste generated in Ba Ria–Vung Tau by 2030 is forecasted to be over 2,458,000 kg/day. Urban areas were projected to have the highest rate of waste generation, approximately 1.67 times higher than other areas. This drastically increasing trend could cause landfills, especially in crowded towns and sensitive ecological areas for socio-economic development such as Vung Tau, Ba Ria, Phu My, and Con Dao, to quickly reach their capacity limits. This information could assist the planning of infrastructure and policy development for decisions or strategies concerning the integrated solid waste management program. Another study used linear regression analysis to forecast the solid waste generation of Kathmandu Metropolitan City, Nepal, by undertaking past population data and solid waste generation (Khanal, 2023). Alqader and Hamad (2012) suggested that the composition of the generated waste was extremely variable due to seasonal, lifestyle, demographic, geographic, and legislation impacts. This variability made defining and measuring waste composition more difficult and, at the same time, more essential (ASTM, 2012). The results of forecasting the household solid waste quantity would support the integrated solid waste management in Ba Ria–Vung Tau. Pham et al. (2023) proposed a comprehensive roadmap to enhance the domestic solid waste management system for only Vung Tau City (one of eight districts/cities of Ba Ria–Vung Tau) from 2024 to 2033. The roadmap addressed various aspects of waste management, including waste reduction, collection, treatment, and disposal. In 2033, the amount of household solid waste in Vung Tau City recovered and recycled would increase five times compared to 2023.

Table 5: Forecasting the quantity (kg/day) of solid waste in Ba Ria–Vung Tau to 2030

Survey areas	Emission coefficient	Population (people)	Quantity of solid waste (kg/day)
Urban area	1.67	1,013,473	1,692,500
Rural area	1.31	562,931	737,440
Islands	1.39	20,296	28,200

4. Conclusion

The classification and characterization of household solid waste were crucial steps in designing an efficient, cost-effective, and environmentally compatible waste management system. The waste was classified into three main categories as food waste, recyclable waste, and inorganic and hazardous wastes. The wastes were characterized into DW, MC and CV, and values were obtained of 292.5 – 349.1 kg/m3, 54.3 – 61.2 %, and 6.37 – 9.28 MJ/kg respectively. Since the hazardous waste in the urban and rural areas contained debris or metal, they gave DW (over 300 kg/m3) and MC (over 60 %) was higher than this in the islands (lower 55 %). While, CV could not be fixed due to much variation in household solid waste composition. The biodrying process could be apply to increase CV, as it can increase the calorific value while reducing the water content of household solid waste, thus promoting the realization of waste to energy.

The assessment of household solid waste in Ba Ria–Vung Tau highlighted the urgent requirement for comprehensive and forward-thinking waste management planning. With daily waste generation projected to exceed 2,458,000 kg by 2030, especially in urban areas, the development of sustainable, scalable, and adaptable waste management solutions was essential to address this growing challenge. The insights from this assessment would be instrumental in advising the People's Committee of Ba Ria–Vung Tau and relevant agencies on implementing waste management practices that prioritize efficiency, environmental responsibility, and resilience. The strategies outlined for waste management in Ba Ria–Vung Tau are expected to involve several key initiatives: (i) community engagement and education; (ii) upgraded waste collection and transport infrastructure; (iii) enhanced waste segregation and recycling; and, (iv) investment in waste-to-energy technologies. Implementing province-wide waste classification initiatives establishes waste separation at the source as a sustainable, high-priority practice.

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