Municipal Solid Waste Characteristics: Recycling Potential and Waste Diversion Rate in Bali Province, Indonesia

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Municipal solid waste characteristics: recycling potential and waste diversion rate in Bali Province, Indonesia

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Abstract

This research was conducted to evaluate waste management in Bali Province through the waste recycling potential and waste diversion rate. These values describe how much waste can be recycled and diverted from landfills. Based on observations and data analysis, Bali's total waste amounts to 2,253,542.03 kg d^{-1} or equivalent to 822,542.84 tonnes yr^{-1} from 9 (nine) cities/regencies with a population of 4,183,072 in 2019. Bali Province's waste at the source is dominated by organic waste with 65% wet weight (ww) of the total waste generated, consisting of food waste and wood/leaf waste. It is also dominated by plastic waste with 15.70% ww and paper waste with 8.92% ww. The material flow analysis results in 53.02% ww of waste, or equivalent to 436,137.41 tonnes yr^{-1}, which ended up in the landfill. Meanwhile, 13.36% ww or equivalent to 109,896.80 tonnes yr^{-1} is sold outside Bali, while 26.94% or equivalent to 221,583.37 tonnes yr^{-1} is unmanaged. Waste reduction by recycling in Bali's landfill only reaches 20.38% of its potential; in comparison, the waste that can be diverted from landfills only reached 11.79% ww of the total generated waste. The reality is still very far from the 2025 government target of 30% reduction waste target and its diversion rate potential of 77.35% ww of the total waste generation.

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1. Introduction

Bali Province (henceforth referred to as Bali) consists of 9 (nine) cities/regencies: Denpasar City as the capital city of Bali Province, Badung Regency, Karangasem Regency, Jembrana Regency, Bangli Regency, Buleleng Regency, Klungkung Regency, Tabanan Regency, and Gianyar Regency. Bali is located at 08°03’40” – 08°50’48” South Latitude and 114°25’53” – 115°42’40” East Longitude with an area of 5,636.66 km^2 consisting of Buleleng Regency with 1,365.88 km^2 (24.23%) from the total area of the province, followed by Jembrana Regency with 841.80 km^2 (14.93%), Karangasem Regency with 839,54 km^2 (14.89%), and Tabanan Regency with 839.33 km^2 (14.89%) by Statistical Bureau of Bali Province as shown in Figure 1 [1].

Bali is a global tourism area in Indonesia. The increase in tourism activities also increases waste generation in Bali. While waste management in Bali still relies on landfills, which leads to the landfill’s shorter lifespan as reported by Widyarsana et al. [3]. The Bali government has attempted to manage waste generated by the community as reported by Regional Research and Development Planning Agency of Bali Province [4]. Currently, the main stakeholder that manages solid waste in Bali is the government, but the management is done collaboratively by the community and private sector in some locations. Bali’s waste management system is limited to managing waste in urban areas, while waste management in rural areas still uses conventional methods such as dumping and open burning as reported by Rechberger [5]. This research was conducted to evaluate Bali’s waste management system through the waste recycling potential and waste diversion rate values. These 2 (two) values describe how much waste can be recycled in the landfill and how much waste can be diverted from landfills by reducing the waste using the Reduce, Reuse, Recycle (3R) hierarchy. The result will then be evaluated by comparing the value against the government’s targeted waste reduction from Law No. 18 of 2008, Government Regulation No. 81 of 2012, as well as the targets set in Presidential

Regulation No. 97 of 2017 with a waste reduction target of 30% solid waste generation in 2025 and waste handling by 70% of waste generation. By knowing these values, waste recycling activities in Bali can be increased, considering that Bali is one of the tourism centers in Indonesia, waste management and waste reduction activities are very important to maintain environmental quality and aesthetic for tourism purposes. In addition, increasing waste reduction by recycling is also a step forward towards sustainable development and a change from a linear economy to a circular economy that provides economic benefits for recycling actors and all parties involved.

2. Materials and methods

2.1 Waste Characteristics

The waste characteristic in this study consist of waste generation and waste compositions. Waste generation and composition were investigated in 9 (nine) cities/regencies in Bali, where the waste generation and its management system is obtained through primary data collection. Primary data collection is done through observations, interviews with related governmental agencies such as the Environment and Sanitation Agency and the Bali Regional Government, followed by interviews with relevant formal and informal sectors in mid to late 2019. Interviews were also conducted with the residents of each city/regency in Bali. Interviews with the local community were conducted with 400 respondents using a questionnaire. This interview was done to collect information about waste management at the source and waste management at several waste reduction facilities such as Waste Banks, 3R Transfer Depos, Transfer Depos, Intermediate Informal Collectors, and Waste End Collectors in 9 (nine) cities/regencies in Bali. Direct waste sampling was the last method and was conducted with 200 households using the stratified random sampling method, followed by waste sampling in 162 non-household samples consisting of educational facilities, health facilities, tourism objects, offices, public temples, private temples, and business areas in Bali. Direct sampling was conducted to study waste generation and waste composition in Bali, and the information will be used to assess the waste flow in every waste management facility in Bali. These direct sampling procedures were done following the sampling procedures regulated in SNI 19-3964-1995 regarding Collection and Measurement Methods of Urban Waste Generation and Composition.

The waste characteristic was analyzed using proximate analysis and ultimate analysis. The proximate and ultimate analysis and heating value of municipal solid waste are fundamental parameters for incineration, pyrolysis, and gasification as reported by Zhou et al. [6]. The proximate analysis consists of water content and volatile content of waste analysis, while the ultimate analysis consists of calorific value, C-Organic value, and Nitrogen content analysis. Once the waste characteristics are found, they can be used to determine the waste's processing potential. The methods used for each parameter are shown in Table 1.

2.2 Material Flow Analysis

Calculations of the waste generation and the total waste in Bali's waste management facilities were analyzed for the Material Flow. The Material Flow Analysis in this research is explained in tonnes yr^{-1}, where all the stock is presumed to leave every waste management facility by the end of the year. The flow of the waste coming in and out of Bali's waste facility will also be explained in the Material Flow Analysis diagram.

$$WG = WR \; x \; P \; x \; 0.365 \qquad \text{Eq. (1)}$$

Where:

WG = Waste generation (tonnes yr^{-1})

WR = Waste generation rate (kg $capita^{-1}$ day^{-1})

P = Number of population (people)

$$TW = WF \; x \; N \qquad \text{Eq. (2)}$$

Where:

TW = Total waste generated (tonnes yr^{-1})

WF = Waste in facility (tonnes yr^{-1})

N = Number of facility

2.3 Waste Recycling Potential and Waste Diversion Rate

Waste diversion rate explains the amount of waste that is diverted from landfills. The diversion rate considers potentially diverted waste using the 3R's of the recycling hierarchy, which are Reduce, Reuse, and Recycle. Currently, cities use their waste diversion rate to measure their waste management system as reported by Zaman and Lehmann [7]. Waste Diversion Rate is different from Waste Recycling Potential. Recycling potential only considers the amount of waste that is recycled, while Waste Diversion Rate considers all the waste undisposed into the landfill due to the 3R activities, including waste reduction and reuse of the waste. Waste Diversion Rate can be calculated using the following equation.

$$WDR = \frac{WD}{WD+TW} \; x \; 100\% \qquad \text{Eq. (3)}$$

Where:

WDR = Waste Diversion Rate (%)

WD = Waste diverted from the landfill (tonnes yr^{-1})

TW = Total waste generated (tonnes yr^{-1})

Meanwhile, Waste Recycling Potential will be calculated for each waste component found in the landfill. To calculate the Waste Recycling Potential, the recovery rate value of each waste is required. The recovery rate can determine how much of the waste component can be recycled, as shown in the following equation.

$$WRP = \frac{RW}{TW} \; x \; 100\% \qquad \text{Eq. (4)}$$

Where:

WRP = Waste Recycling Potential (%)

RW = Recyclable waste (tonnes yr^{-1})

TW = Total waste generated (tonnes yr^{-1})

3. Results and discussion

3.1 Waste Generation

The total population in 9 (nine) cities/regencies in Bali reached 4,183,072 people in 2019. The sampling results show that the total waste generation rate in 9 (nine) cities/regencies is 0.54 kg $capita^{-1}$ day^{-1}, bringing the total waste generated in Bali to 2,253,542.03 kg day^{-1} or equivalent to 822,542.84 tonnes yr^{-1}. More detailed information on Bali's total waste generation is shown in Table 2 and Figure 2 below.

Based on each city/regency's minimum wage in Bali in 2020 by Statistical Bureau of Bali Province [1], the 9 (nine) cities/regencies in Bali are divided into 3 (three) economic categories, namely high-income community, medium-income community, and low-income community. Based on the largest to the smallest minimum wage: the high-income communities are from Badung Regency, Denpasar City, and Gianyar Regency. The medium-income communities are from Tabanan Regency, Jembarana Regency, and Karangasem Regency, while the low-income communities are from Buleleng Regency, Klungkung Regency, and Bangli Regency. Based on these categories, the waste generation comparison can be seen in Figure 3.

The analysis shows that the low-income community's waste is greater than the waste generated from the middle-income community, contradicting the theory that states the largest waste generation will be generated from people with a high economic level. In this situation, high-income communities generate the largest waste as it is also the area with the largest population in Bali, with the population 2 (two) times above Bali's average population. However, differences occur in the medium-income communities and low-income communities. This is possibly due to people who have higher economic levels tend not to do their activities at home, but in other places, generally at work or other public places. Thus, although having a similar population, the low-income community's waste is more than the medium income community.

3.2 Waste Characteristics

Characteristics of waste are analyzed using proximate analysis and ultimate analysis. The waste is tested for water content, volatile content, calorific value, organic carbon, and nitrogen. The waste characteristics are tested using the waste from Gianyar Regency, Tabanan Regency, Badung Regency, and Denpasar City. The waste came from household and non-household waste. The analysis results of the mixed waste are shown in Table 3.

Bali's high-water content value indicates the large contributions of organic waste, including food waste and leaf waste produced by the community. Moisture content is a physical characteristic of waste that shows the humidity level. In this condition, the water content reached 59.20% wet weight (ww). Good water content usually ranges between 50-60%, with the optimum value for composting activities being 55% as reported by Damanhuri and Padmi [8].

Volatile levels indicate the effectiveness of waste reduction using the combustion method stated in percentage. The volatile content in Bali's waste reached 67.86% dry weight (dw) for household and non-household waste. This indicates that the waste in Bali can be processed using the combustion method.

Calorific value could be used to determine the waste's potential energy if it were to have thermal processing technology applied. The Lower Heating Value (LHV) includes the heat of water evaporation. This LHV value is more realistically used as a heating value to evaluate the waste's energy potential because it contains a lot of water. LHV values factors in the required energy to evaporate water content as reported by Damanhuri and Padmi [8]. Bali's waste calorific value is 11.86 MJ kg^{-1}. The minimum criteria for LHV Value to ensure that waste is suitable for the thermal process is 5.02 MJ kg^{-1}. The heating value contained in Bali's waste has met the minimum criteria to be processed using an incinerator. However, because of the high value of water content, the thermal method may be unnecessary because the higher the water content, the more energy is needed to achieve a suitable temperature for thermal processing.

C/N ratio is an essential factor in waste treatment by composting. The value of the C/N ratio depends on the content of the waste. A good C/N ratio for composting material ranges from 25-30. If the C/N ratio values are too high, it will reduce the microorganism's biological activity, whereas the low C/N ratio values will increase nitrogen emissions as ammonia as reported by Work Unit for the Development of a Residential Environmental Sanitation System [9]. The value of C/N ratio of organic waste in Bali is 79.03.

3.3 Waste Composition in Landfill

This research analyzes waste composition based on Bali's landfill to analyze each waste component's recycling potential. Waste composition can be affected by the income of the community, due to the generated waste per capita is increasing along with the increasing of the economic state of the community. It also affect the waste composition and characteristics. Denpasar City generated the biggest waste with 32.86% ww or equivalent to 740,545 tonnes yr^{-1}, followed by Badung Regency, which generated 17.36% ww or equivalent to 391,240 tonnes yr^{-1}. Denpasar City produces the most waste due to its population, which is far above Bali's average population; furthermore, it is the capital of Bali, where it is the center of government and community activities. On the other hand, Badung Regency is considered the wealthiest regency in Bali as reported by Patera et al. [10] as it has some of Bali's best resorts, restaurants, bars, clubs, and designer stores. Badung Regency is also the home of Bali's most renowned beaches, such as Kuta Beach and Seminyak. This is what makes Denpasar City and Badung Regency the greatest waste contributor in Bali. Bali's waste is dominated by household waste with 71.58% followed by non-household waste with 28.42%; this follows the theory which states that people's lifestyle in developing countries decisively characterizes the waste composition's percentage, where organic waste stream and overburden over 50% of the total generated municipal solid waste as reported by Sharma and Sharma [11] and shown in Figure 4.

The sampling results show that household waste dominates Bali's waste generation except for the high-income community. The high-income communities that can cause this usually have a consumptive behavior, as shown in the resulting waste composition. Wastes tend to be diverse and likely produce plastic and packages waste due to a higher level of instant food consumption, making the non-household waste generation greater than the household waste generation. The waste composition at the source based on the sampling is shown in Figure 5**.**

Figure 5 shows that Bali's waste at the source is dominated by food waste with 65% ww of the total waste generated, consisting of 45,30% ww of food waste and 19,70% ww of wood and leaf waste. It is also dominated by plastic waste by 15.70% ww and paper waste by 8.92% ww. Waste from the communities will then be transported to several waste management facilities until it is finally disposed of into the landfill. The waste in the landfill consists of food waste, wood and leaf waste, plastic waste, paper waste, metal waste, rubber waste, cloth, and textile waste, glass, and hazardous waste. A detailed waste composition in the landfill based on the sampling process can be seen in Figure 6.

Figure 6 shows that Bali's waste in landfill is dominated by organic waste with 62.64% ww of the total waste in the landfill, consisting of 27.13% ww of food waste and 35.51% ww of wood and leaf waste. It is also dominated by paper waste by 13.95% ww and plastic waste by 10.50% ww. This waste composition proves that the waste in developing countries is dominated by household waste with over 50% of the total waste as reported by Sharma and Sharma [11].

The waste composition and waste characteristics data can be grouped into 5 (five) criteria: putrescible waste, organic waste, biodegradable waste, combustible waste, and recyclable waste. Furthermore, waste characteristics and composition identified that 78.40% ww of waste at the landfill and 75.95% ww of waste at the source could be potentially processed through a biological method, followed by 88.90% ww of waste at the landfill an 91.65% ww of waste at the source could be processed by thermal method, and 26.99% ww of waste at the landfill and 28.75% ww of waste at the source can potentially be recycled. In addition, 62.64% ww of waste at the landfill and 65% ww of waste at the source are categorized as organic, and 27.13% ww of waste at the landfill and 45.30% ww of waste at the source are categorized as putrescible waste or easily decomposed waste. This waste is easily decomposed by microorganisms, thus needing faster management, including collection, transportation, and processing.

3.4 Material Flow Analysis

Direct observation and interviews with related government agencies identified that 9 (nine) cities/regencies across Bali have 26.28% ww of waste, or equivalent to 216,160.59 tonnes yr^{-1} directly transported to the landfill from the source. In comparison, 34.19% ww of waste from the source is transported to Transfer Depo. The waste was then transported to 3 (three) different waste management facilities: Informal Sector, Waste Crews, and Landfill. 53.02% ww of waste or equivalent to 436.137,41 tonnes yr^{-1} ended up in the landfill. This waste came from Transfer Depo and the source. 3R Transfer Depo also disposed of their waste processing residue into the landfill by 20,079.89 tonnes yr^{-1}.

The waste from the source was also transported to the Waste Banks, 1st Intermediate Informal Collectors, and 3R Transfer Depo with 4.52% ww, 3.78% ww, and 4.29% ww, respectively. All of the waste in these facilities will then be managed and utilized. The rest of the waste is then transported to the Intermediate Informal Collectors. All wastes from this facility will be sold outside Bali to be recycled or reused by 13.36% ww or equivalent to

109,896.80 tonnes yr^{-1}. Some waste management facilities produced residues from their waste processing and had the residues disposed into the landfill while the rest was dumped into the environment as unmanaged waste. The 20.26% unmanaged waste from the source brings the total unmanaged waste disposed into the environment to 26.94%, equivalent to 221,583.37 tonnes yr^{-1}. The amount of unmanaged waste from the source and waste management facilities were still very high and could be detrimental to the environment and the surrounding ecosystem. So, a better and more integrated waste management system could be one solution to solve this problem. The detailed waste flow in Bali is shown in Figure 7.

3.5 Waste Recycling Potential

The waste recycling potential analysis was carried out to determine the total amount of recyclable waste in Bali Province compared to the actual waste recycled in Bali stated in the material flow. Waste recycling potential analysis is calculated by considering each type of waste's recovery factor based on the waste composition, as shown in Figure 5. These recovery rates value is used to calculate the quantity of waste that can be recycled. The recycling potential of each waste is analyzed in more detail in the following explanation. Based on the landfill's waste composition, some recovery rates value of the waste is shown in Table 4.

Figure 5 shows that organic waste consists of food waste with 45.30% ww or equivalent to 372,611.91 tonnes yr^{-1}, and wood/leaf waste dominated the disposed waste in the landfill with 19.70% ww or equivalent to 162,040.94 tonnes yr^{-1} respectively. Food waste is generated every day and is often heavy and wet as reported by Zhang et al. [16], thus dominating the source and landfill. Meanwhile, wood/leaf waste dominated the source and landfill due to the Balinese habits of giving offerings in flowers, leaf, or food in their daily worship rituals as reported by Widyarsana and Salmaa [17]. Organic waste must be handled immediately due to its putridness and disturbing odor to the surrounding community. Based on Table 4, the recovery factor of organic waste is 80%. Thus, recyclable organic waste amounted to 52% ww or 427,722.28

tonnes yr^{-1}. Thus, making 13% ww of the organic waste considered as non-recyclable waste with 106,930.57 tonnes yr^{-1}.

Based on Figure 5, plastic waste was the second-largest disposed waste at the source in the amount of 15.70% ww or equivalent to 129,139.23 tonnes yr^{-1}. Plastic waste poses a great challenge to the environment. Most developing countries have large amounts of polyethylene bag, which has little recycling capacity and could cause environmental damage as reported by Sharma and Sharma [11]. So it is essential to control the amount of plastic waste generated. Based on Table 4, the recovery factor of plastic waste is 53.10%. So, recyclable plastic waste is equal to 8.34% ww or 68,572.93 tonnes yr^{-1}. Thus, making 7.36% ww of the waste considered as non-recyclable waste with 60,566.30 tonnes yr^{-1}.

Based on Figure 5, Paper waste was the third-largest disposed waste at the source with 8.92% ww or equivalent to 73,370.82 tonnes yr^{-1}. Bali is one of Indonesia's largest tourist destinations, which results in the community and incoming tourists having a consumptive behavior as many tourist attractions and restaurants used paper as their alternative for food and beverage packaging. In addition, the many tourist attractions, hotels, and resorts also resulted in many business brochures being discarded, causing paper waste to dominate one of the waste in at the source and landfills. Based on Table 4, the recovery factor of paper waste is 40%. Thus, the amount of paper waste considered as recyclable waste is equal to 3.57% ww or 29,348.33 tonnes yr^{-1}. Thus, making 5.35% ww of the waste considered non-recyclable waste as much as 44,022.49 tonnes yr^{-1}.

Figure 5 also shows that 0,90% ww or equivalent to 7,402.89 tonnes yr^{-1} of metal waste was generated at the source. Metals have the greatest recycling potential among other waste, with 98%, as shown in Table 4. This potential is due to metal's ability to retain quality despite being recycled many times. Its long life period causes metal recycling to be very profitable as it is the ideal candidate for a circular economy, which will provide many benefits for the environmental and socio-economic aspects as reported by Europian Recycling Industries' Confederation [18]. The amount of metal waste considered as recyclable waste in Bali is equal to 0.88% ww or 7,254.83 tonnes yr^{-1}. Thus, making 0.02% ww of the waste considered as non-recyclable waste, or 148.06 tonnes yr^{-1}.

Based on Figure 5, 0.75% ww or 6,169.07 tonnes yr^{-1} of rubber and 1.20% ww or 9,870.51 tonnes yr^{-1} of glass were generated at the source. Based on Table 4, rubber has the lowest recovery factor, with only 10.90%, while the glass recovery rate is relatively high, reaching 57.50%. So, the amount of rubber waste considered as recyclable waste is equal to 0.08% ww or as much as 672.43 tonnes yr^{-1}. Thus, making 0.67% ww of the rubber waste considered non-recyclable waste or 5,496.64 tonnes yr^{-1}, as shown in Figure 12. As for glass waste, 0.69% ww or 5,675.55 tonnes yr^{-1} can be recycled, while the other 0.51% ww of waste is non-recyclable, equivalent to 4,194.97 tonnes yr^{-1}.

Previous explanations show that source's recyclable waste is organic waste consisting of food and leaf waste, plastic waste, paper waste, metal waste, rubber waste, and glass waste. Calculations found that the recyclable waste is 539,246.34 tonnes yr^{-1} or equivalent to 65.56% ww of the total waste generated at the source. A more detailed percentage of each recyclable waste is shown in Figure 8.

Direct observation and material flow analysis identified that the generated waste at the source is equal to 822,542.84 tonnes yr^{-1}. There are 3 facilities that recycled waste in Bali, which are 1st Intermediate Informal Collectors, Intermediate Informal Collectors, and End Collectors, which totaled to 11.60% ww of waste or equivalent to 95,399.00 tonnes yr^{-1} waste recycled. From the source, 26.28% ww of waste or 216,160.59 tonnes yr^{-1} of waste is directly transported to the landfill. Despite waste already placed in the last disposal facility, waste reduction efforts are still made by the informal sectors, namely the scavengers. Usually, around 484 scavengers collected the waste deemed to have economic value as reported by Widyarsana et al. [19], with the waste reaching 1.76% ww or equivalent to 14,497.80 tonnes yr^{-1}. The collected valuable waste was later sold to the 1st Intermediate Informal Collectors, which some waste sold outside of Bali or recycled in the facility, making Bali's waste recycling potential amounts to 13.36% ww of waste or equivalent to 109,896.80 tonnes yr^{-1}.

Calculations show that the total recyclable waste in Bali's landfill is equal to 539,246.34 tonnes yr^{-1} or 65.56% ww of the total waste at the source. This means that the waste reduction by recycling only reached 20.38% of its potential; thus, much work needs to be done, and the system must be improved to ensure recycled wastes increase before being dumped into the landfill. Even more so with the waste reduction target under Law No. 18 of 2008, Government Regulation No. 81 of 2012, as well as the 30% waste reduction in 2025 and 70% handling of waste set in Presidential Regulation No. 97 of 2017. Moreover, all waste in the landfill will usually be managed by open dumping as reported by Widyarsana et al. [19], which is still far from the environmental standards. With the improvement of waste recycling at the landfill, many parties' will obtain economic benefits; furthermore, landfill waste reduction and the improvement of the dumping system in the landfill will have environmental benefits.

3.6 Waste Diversion Rate

Waste diversion rate explains the amount of waste that is diverted from landfills. The diversion rate considers what can be diverted using the 3R's of the recycling hierarchy: Reduce, Reuse, and Recycle. Direct observations and material flow analysis in Figure 6 show some of the waste reduction activities in the 3R hierarchy in Bali's waste management facilities.

Transfer Depo received 34.19% ww of waste or 281,204.58 tonnes yr^{-1} from the source, while Waste Banks received 4.52% ww of waste equivalent to 37,188.03 tonnes yr^{-1} and 3R Transfer Depo received 4.29% ww of waste or 35.273,60 tonnes yr^{-1}. In the landfill, 1.76% ww of waste, or equivalent to 14,497.80 tonnes yr^{-1}, were collected by the Informal Sectors then sold to the 1st Intermediate Informal Collectors. The intermediate informal collector also received 8.12% ww of waste from the Transfer Depo, which will then be sold to the Intermediate Informal Collectors while all wastes in the Waste Banks and 0.43% ww of waste from 3R Transfer Depo were also sold to the Intermediate Informal Collectors to be recycled and sold outside Bali as a new and clean product.

All the waste from Informal Sectors will then be sold outside Bali. Some of the waste was sold through Formal Sectors or End Collectors, and some were directly sold outside Bali. There are ten end-collectors (formal sector) identified in Bali. The waste is dominated by plastic shipped to East Java Province, such as Banyuwangi City and Surabaya City, as a clean plastic as reported by Widyarsana et al. [19]. The sold waste is categorized as managed waste, and diverted waste from the landfill amounts to 13.36% ww or 109,896.80 tonnes yr^{-1}. Currently, Bali's actual waste diversion rate right now is equal to 11.79% or 96,997.80 tonnes yr^{-1}. If we consider the waste recycling potential in Bali's landfill amounting to 65.56% ww or as much as 539,246.34 tonnes yr^{-1}, then the potential waste diversion rate in Bali can reach 77.35% ww or equivalent to 636,224.14 tonnes yr^{-1}.

Currently, 26.94% ww of waste, equivalent to 221,583.37 tonnes yr^{-1}, is unmanaged and disposed of into the environment. Globally, the waste management sector is under increasing pressure to improve its environmental performance as reported by Thushari et al. [20]. Considering Bali's waste is dominated by household waste with a relatively high recovery rate, reaching 80%, the actual number of waste that can be diverted from landfills is still relatively small because it only reached 11.79% ww of the total waste generated. Distributed questionnaires to Bali residents shows a large gap between the waste diversion and waste recycling potential and the actual conditions: around 26% ww of the waste is still disposed of into vacant lots, 4.9% ww is disposed of into the water bodies, and 7.8% ww of waste is buried in open land done by the community at the waste source as reported by Widyarsana et al. [19].

It is necessary to increase recycling activities in Bali's waste management facility to reach the potential waste diversion rate to 77.35% ww of the total waste generation. Waste reduction activities are the most likely activity to be carried out; it also involved many parties, including the community and waste management facilities in Bali, because it benefits both the socio-economic and environmental sector.

4. Conclusion

The total population in 9 (nine) cities/regencies in Bali reached 4,183,072 people in 2019. Sampling results show that the total waste generation rate in 9 (nine) cities/regencies is 0.54 kg capita^{-1} day^{-1}. Bali's waste generation totalled to 2,253,542.03 kg day^{-1} or equivalent to 822,542.84 tonnes yr^{-1}. Based on the waste characteristics and composition, 78.40% ww of waste at the landfill and 75.95% ww of waste at the source could be potentially processed through a biological method, followed by 88.90% ww of waste at the landfill an 91.65% ww of waste at the source could be processed by thermal method, and 26.99% ww of waste at the landfill and 28.75% ww of waste at the source can potentially be recycled. The waste reduction by recycling in Bali only reached 20.38% ww or 109,896.80 tonnes yr^{-1} of its 65.56% ww or 539,246.34 tonnes yr^{-1} potential; the actual waste diversion rate in Bali is currently equal to 11.79%. If we consider the 65.56% ww of waste recycling potential or as much as 539,246.34 tonnes yr^{-1}, then the potential waste diversion rate can reach 77.35% ww or equivalent to 636,224.14 tonnes yr^{-1}. Currently, there are still 26.94% ww of unmanaged waste or equivalent to 221,583.37 tonnes yr^{-1} of and disposed of into the environment. It is necessary to increase recycling activities in Bali's waste management facility to reach the potential waste diversion rate of 77.35% ww of the total waste generation. Limited resources and local authorities' capacity, and poor implementation of targeted legislation usually challenge sustainable waste management practices in low and medium-income countries. Therefore, waste recycling is the right activity to reduce waste because many parties can do it. Waste recycling improvement can economically benefit many parties; furthermore, reduction of waste dumped in landfills and the improvement of the dumping system in the landfill will benefit the environment.

Declarations

Availability of data and materials

All data generated or analyzed during this study are available upon request.

Competing interest

The authors declare they have no competing interests.

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Authors' contributions

I Made Wahyu Widyarsana provided the data, processed the data, and wrote the draft. Suci Ameliya Tambunan fulfilled the analysis, processed the data, wrote the draft, and performed proofreading. Aurilia Ayuanda Mulyadi performed proofreading. All authors read and approved the final manuscript.

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Table 1 The methods of measuring the waste characteristics

No.	Parameter	Method
1	Water Content	ASTM D2216-98
2	Volatile Content	ASTM D2216-98
3	Calorific Value	Bomb calorimeter
4	C-organic	SMEWW-5220-B
5	NTK-Norg	SMEWW-4500-B

Table 2 Waste Generation in 9 (nine) cities/regencies in Bali

Cities/Regencies	Population in 2019 (people)	MSW Generation (kg cap^{-1} d^{-1})	Total Waste Generation (kg d^{-1})	Total Waste Generation (tonnes yr^{-1})
Jembarana	274,900.00	0.46	126,900.00	46,318.50
Karangasem	412,800.00	0.38	154,800.00	56,502.00
Bangli	225,100.00	0.37	83,287.00	30,399.76
Klungkung	231,462.00	0.38	88,689.03	32,371.50
Buleleng	653,600.00	0.47	310,281.00	113,252.57
Gianyar	503,900.00	0.36	180,400.00	65,846.00
Tabanan	441.000.00	0.40	177,400.00	64,751.00
Denpasar	914,300.00	0.81	740,545.00	270,298.93
Badung	526,010.00	0.74	391,240.00	142,802.60
Total	4,183,072.00	0.54	2,253,542.03	822,542.84

Table 3 Characteristics of waste in Bali

No.	Parameter	Unit	Analysis Result
1	Water Content	% ww	59.20
2	Volatile Content	% dw	67.86
3	Calorific Value (HHV)	MJ kg^{-1}	21.32
	Calorific Value (LHV)	MJ kg^{-1}	11.86
4	Organic C	% dw	50.37
5	NTK	% dw	1.06

Table 4 Waste recovery rates

Waste Component	Recovery Factor
Organic Waste	80% [12]
Plastic Waste	53.1% [13]
Glass Waste	57.5% [13]
Rubber / Leather Waste	10.9% [13]
Paper Waste	40% [14]
Metal Waste / Scrap Metal	98% [15]

Figure 1 Bali administration map [2]

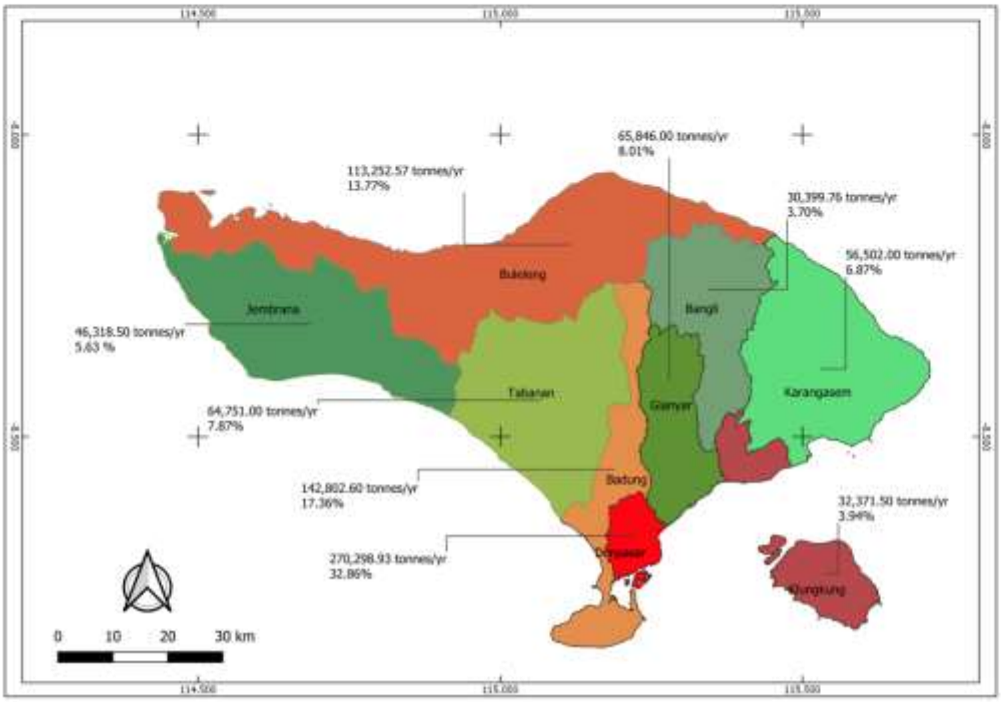

Figure 2. Waste generation in every city/regency in Bali

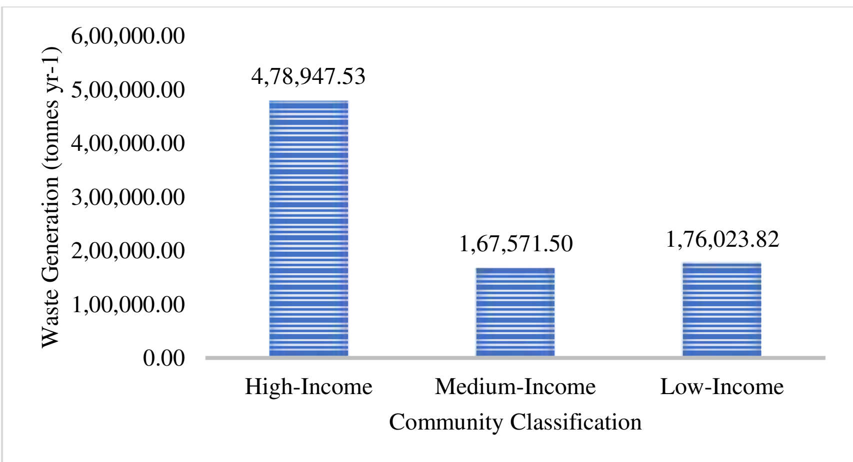

Figure 3. Waste generation based on economic classification

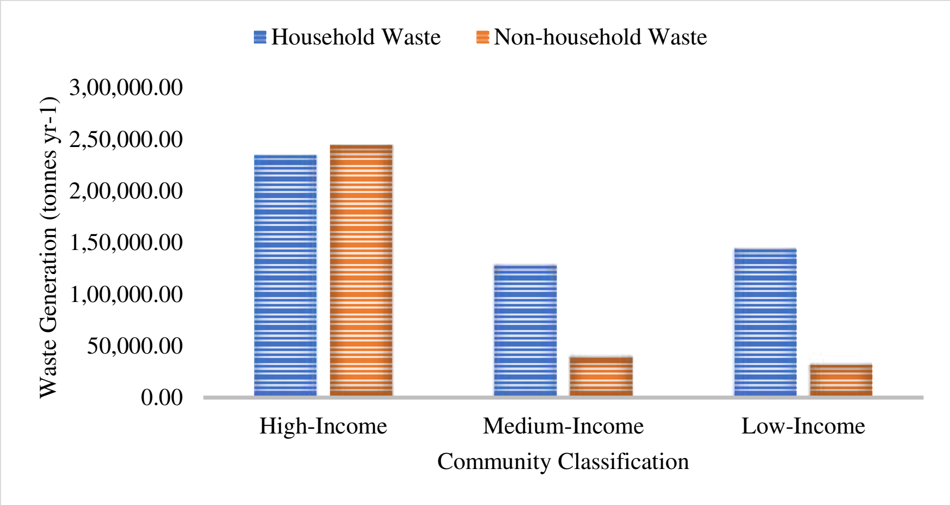

Figure 4. Household and non-household waste generation based on community classification

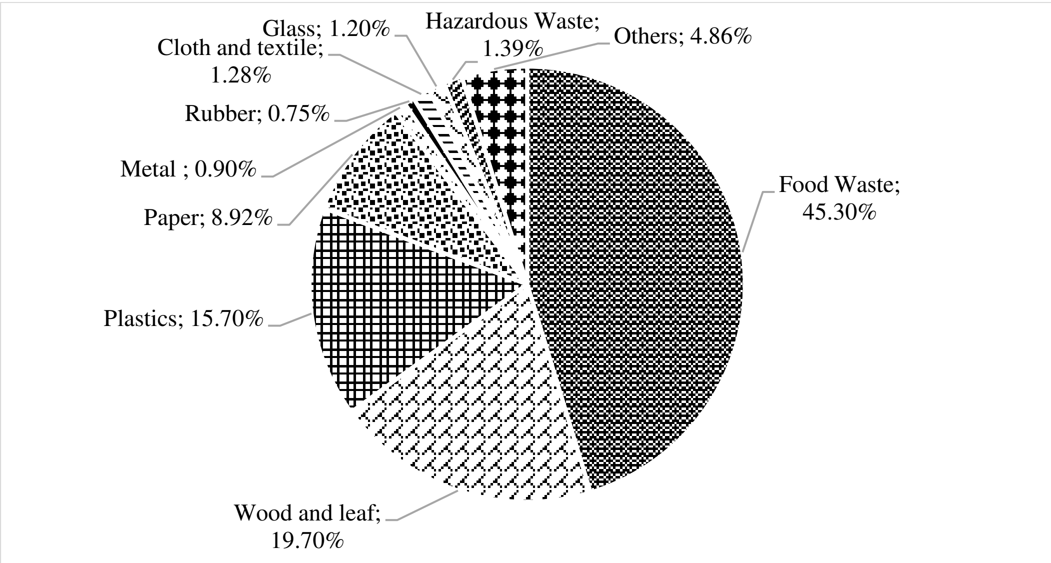

Figure 5 Waste composition at the source

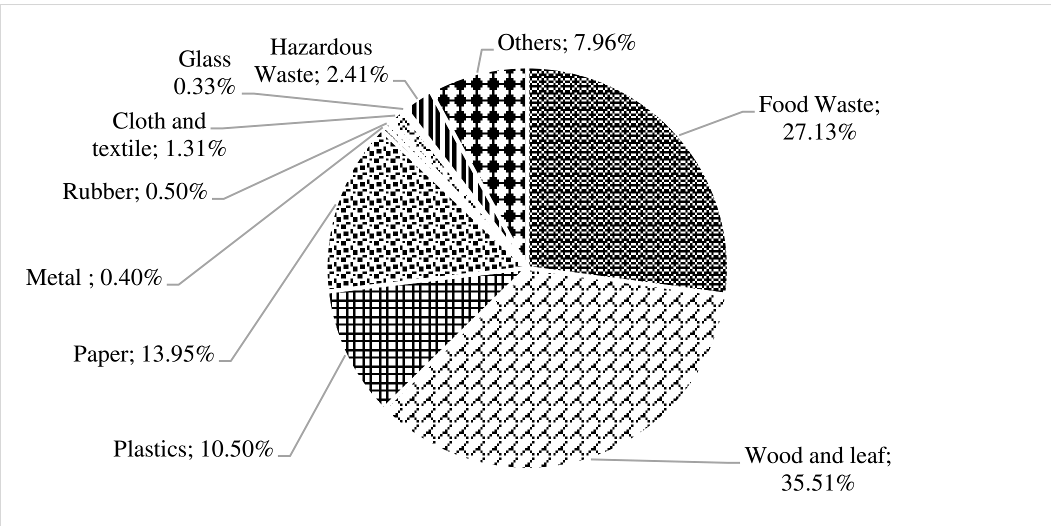

Figure 6. Waste composition in landfill

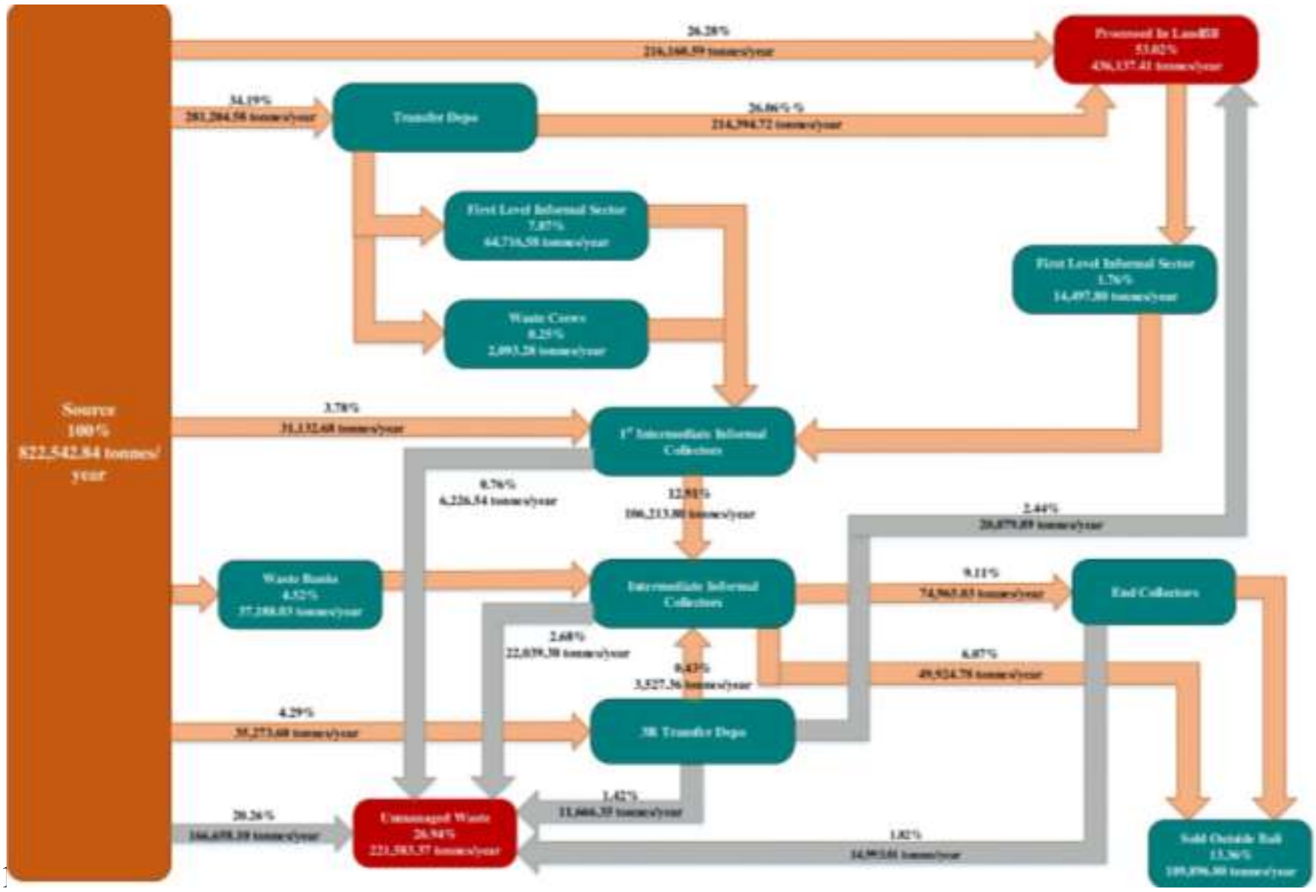

Figure 7. Material flow analysis in Bali

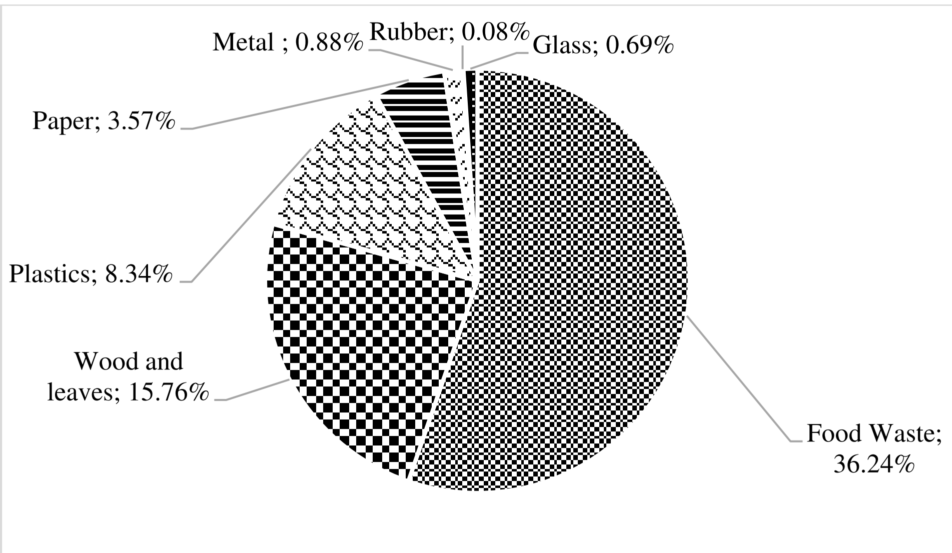

Figure 8. Waste recycling potential in Bali Province

Figures

Figure 1

Bali administration map [2] Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

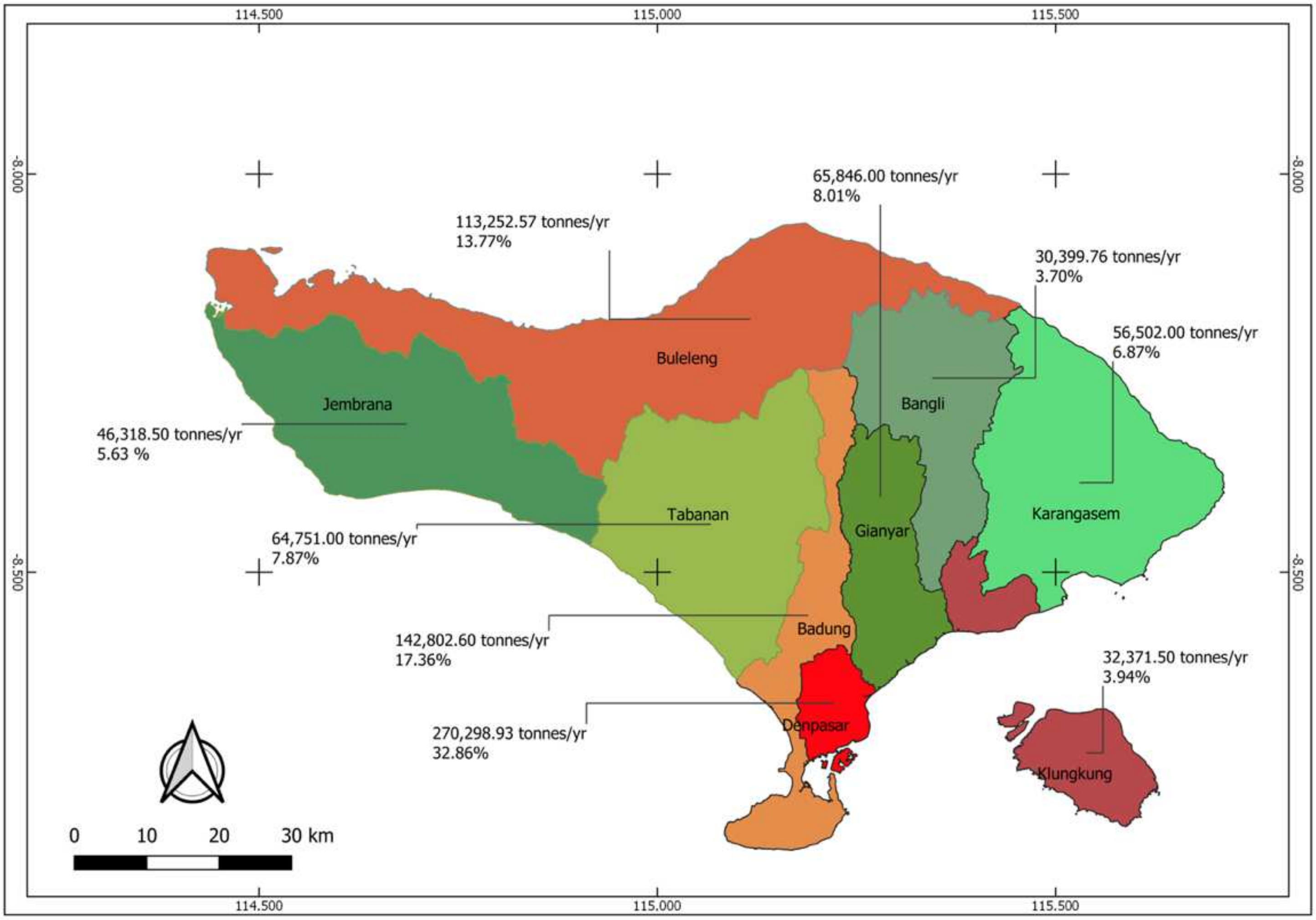

Figure 2

Waste generation in every city/regency in Bali Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

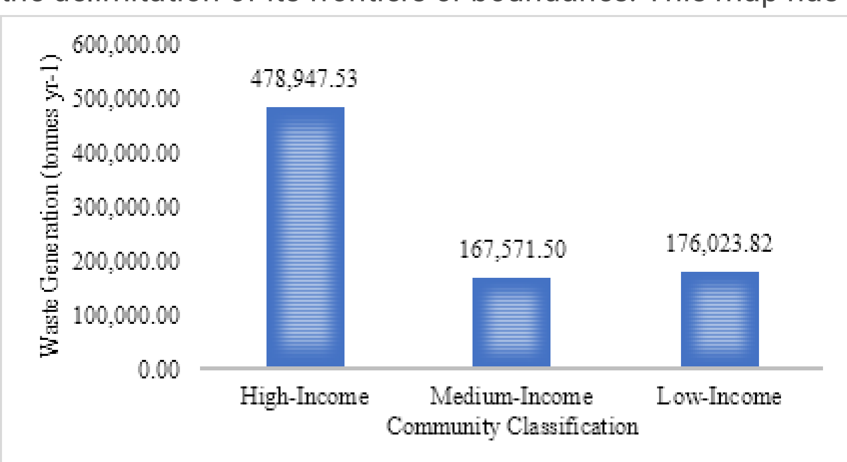

Figure 3

Waste generation based on economic classification

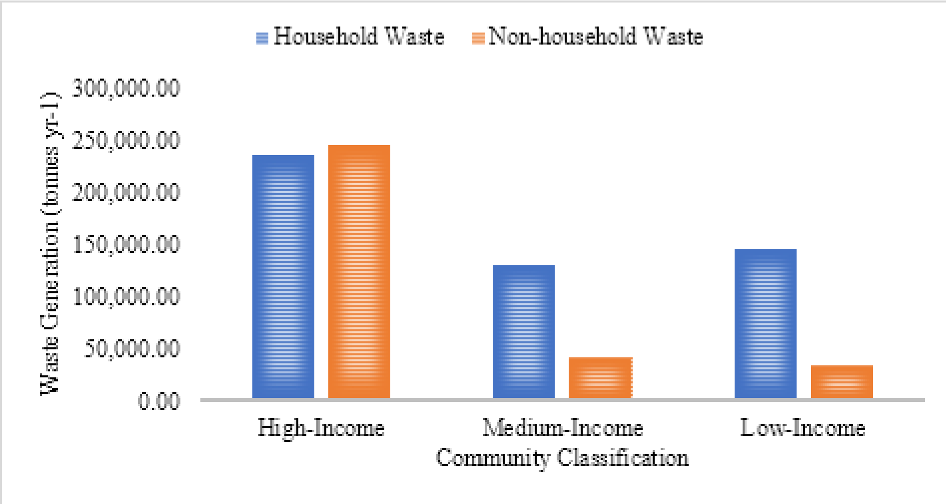

Figure 4

Household and non-household waste generation based on community classification

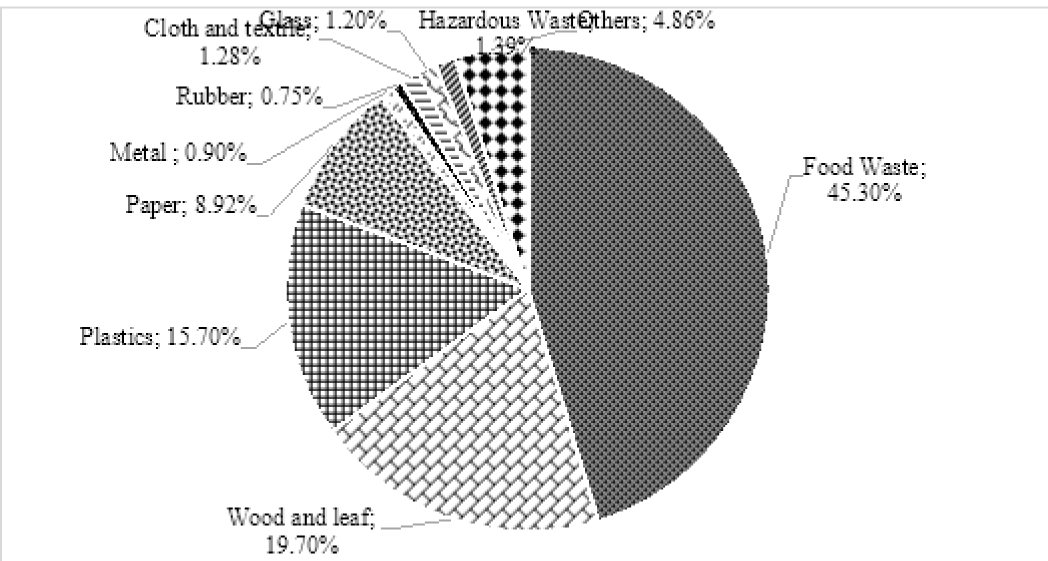

Figure 5

Waste composition at the source

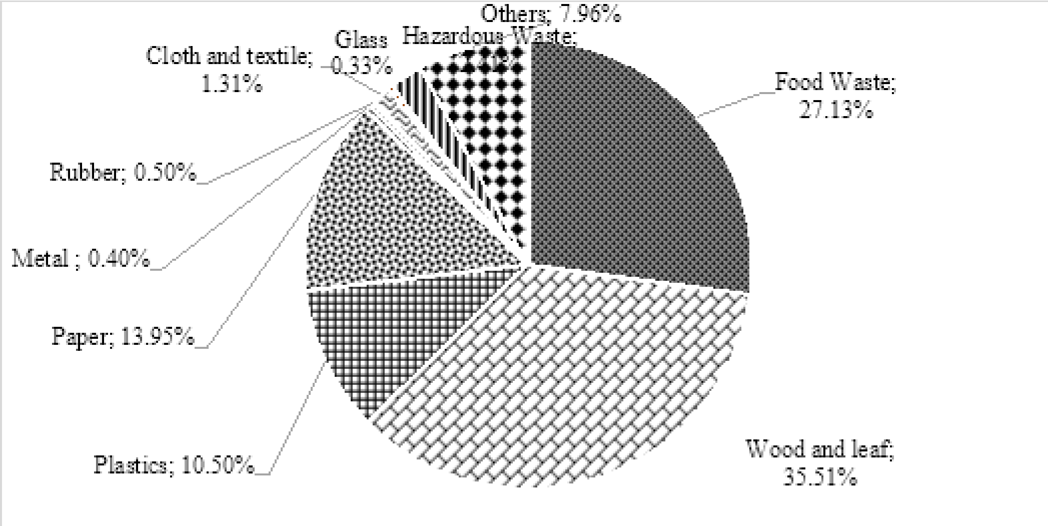

Figure 6

Waste composition in landfill

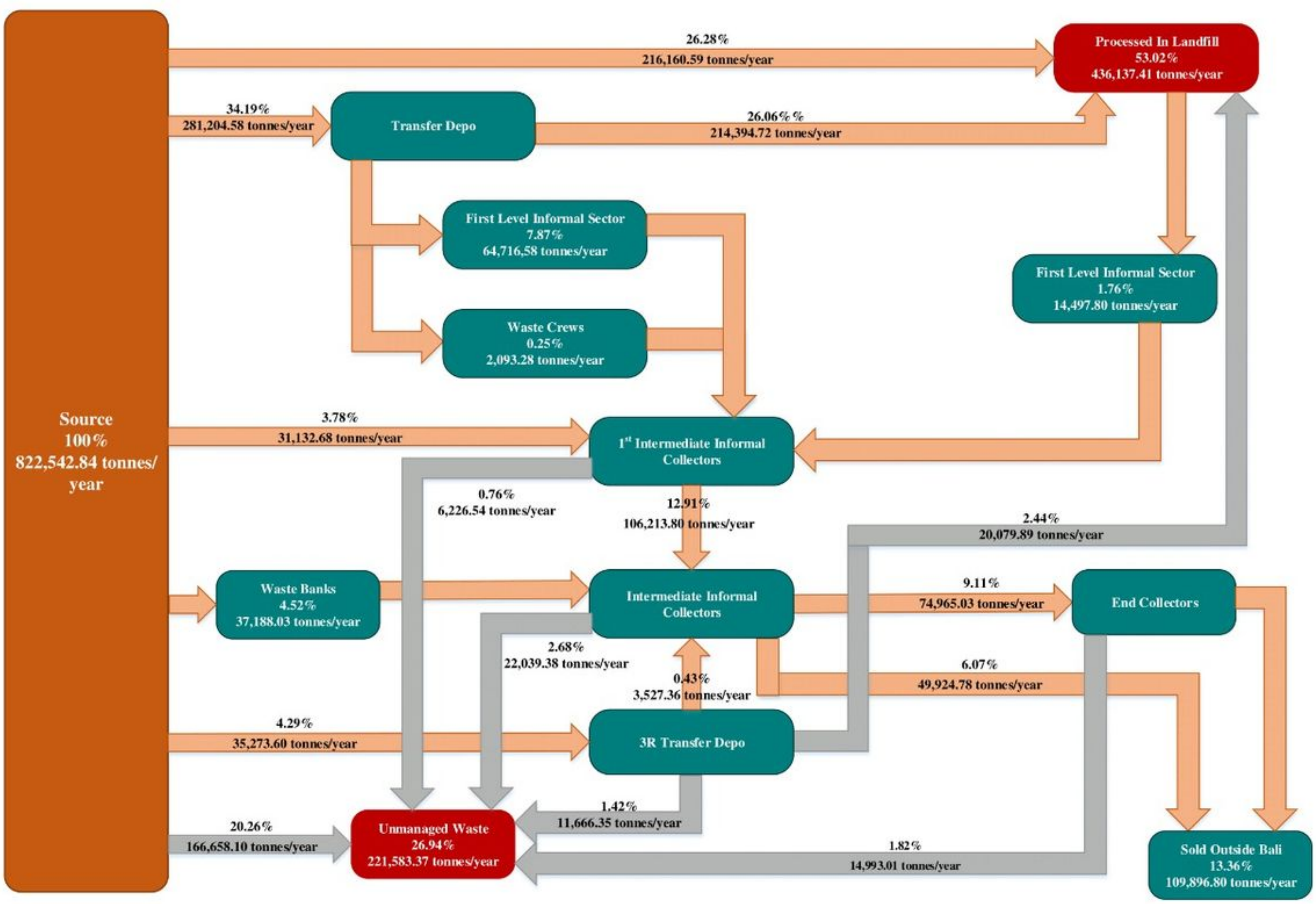

Figure 7

Material flow analysis in Bali

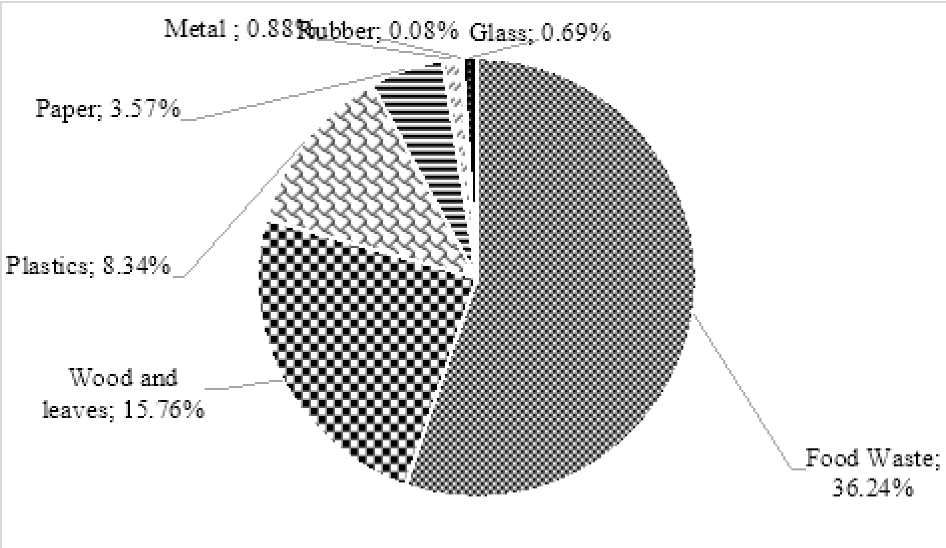

Figure 8

Waste recycling potential in Bali Province