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Determination of Residual Municipal Solid Waste Composition from Rural and Urban Areas: A Step toward the Optimization of a Waste Management System for Efficient Material Recovery

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Abstract: Residual municipal solid waste (RMSW) is a rapidly expanding problem worldwide and a good waste management system could reduce concerns about its correct treatment. The purpose of this study was to characterize RMSW from urban and rural areas with the ultimate goal of estimating the recycling potential of the identified fractions and implementing waste collection and recovery methods according to the type of area that generates them. A direct sampling campaign of RMSW was performed. The results showed that the highest organic waste rate was found in the rural area (11.9%); urban-area-produced RMSW mainly constituted recyclable fractions such as plastic (26.3%), paper (21.8%), glass (3.5%) and metals (3.3%). The physical-chemical characteristics of RMSW showed levels of heavy metals below the detection threshold. The conditions necessary for composting could be met only for the organic fraction coming from rural areas as demonstrated by a pH value of 6.9 and a moisture content of 46.5%. These data will be extended to all the urban and rural areas to design appropriate disposal and/or recovery plants with profitable economic interventions that will lead to a reduction in costs in the planning of the integrated solid waste management.

Keywords: waste characterization; material recovery; waste management; residual municipal solid waste; urban and rural areas; recycling potential

Citation: Triassi, M.; De Simone, B.; Montuori, P.; Russo, I.; De Rosa, E.; Di Duca, F.; Crivaro, C.; Cerullo, V.; Pontillo, P.; Díez, S. Determination of Residual Municipal Solid Waste Composition from Rural and Urban Areas: A Step toward the Optimization of a Waste Management System for Efficient Material Recovery. *Sustainability* **2023**, *15*, 13378. https://doi.org/10.3390/su151813378

Academic Editor: Hosam Saleh

Received: 28 July 2023
Revised: 24 August 2023
Accepted: 5 September 2023
Published: 6 September 2023

1. Introduction

The generation of municipal solid waste (MSW) has increased along with population growth, urbanization, the improvement in living standards, human activity and economic development [1–5]. Dietary habits, level of commercial activity and seasons are just some of the variables that affect the amount and the generation rate of MSW [6,7]. Around 2.01 billion tons of MSW are produced globally every year, with at least 33% not being managed in an environmentally friendly way [8,9]. The statistic reported in Figure 1 shows the amount of municipal solid waste generated worldwide in 2016 with projections for 2030 and 2050: it is projected that in 2050, some 3.4 billion metric tons of municipal solid waste will be generated around the world [10,11].

Waste collection rates tend to be substantially higher for urban areas than for rural areas, because waste management is typically an urban service [11]. According to income level, the statistic in Figure 2 shows the global collection rate of municipal solid waste in rural and urban regions in 2016 [10,12].

In this year, the collection rate in rural areas in lower-middle-income regions was about 33%. As can be seen, waste collection rates in cities are more than twice as high as they are in rural regions in lower-middle-income nations.

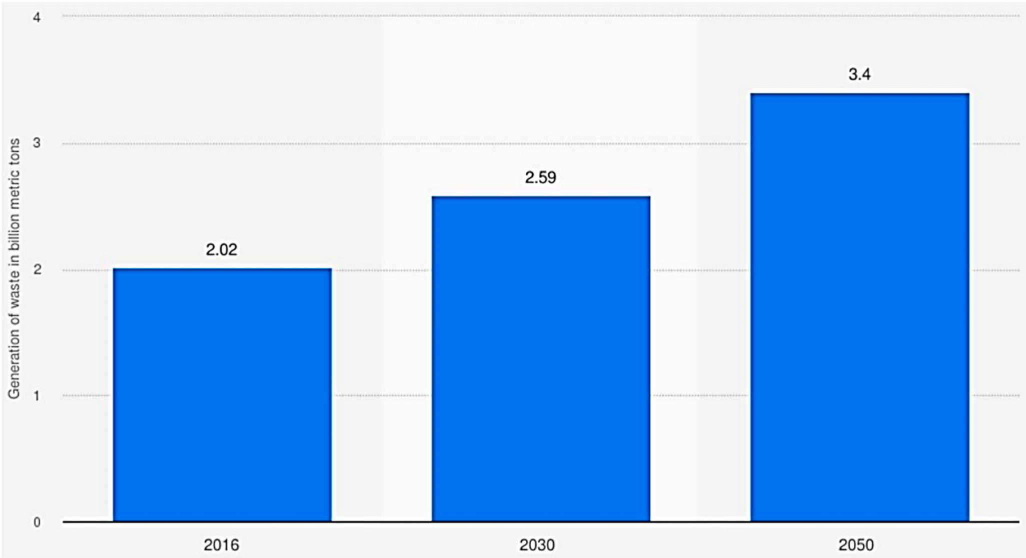

Figure 1. Projected generation of municipal solid waste worldwide from 2016 to 2050 (in billion metric tons) [10].

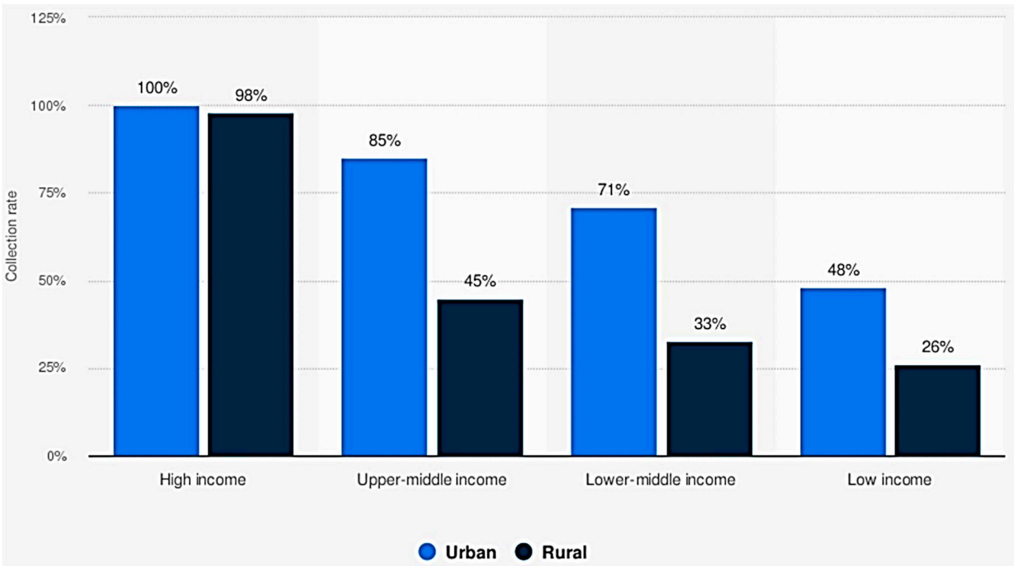

Figure 2. Rate of urban and rural municipal solid waste collection worldwide in 2016, by income level [10].

A growth in the volume of solid waste causes a number of issues with its transportation, storage and disposal, complicating the process of effective solid waste management [13]. In particular, residual municipal solid waste (RMSW), one of the main urban lifestyle by-products, is a fast-expanding problem worldwide. RMSW is the residual garbage consisting of a mixed range of materials of high heterogeneity, remaining after the separate collection of recyclable components (like plastic and paper) and other materials such as bulky waste, waste electrical and electronic equipment (WEEE) and household hazardous waste (HHW) [14]. RMSW production is rising faster than the global urbanization rate [8,15,16]. The collection and the disposal of RMSW are frequently unmanaged and unregulated in low- and middle-income nations [17,18]. Inadequate RMSW disposal or the lack of their management might lead to significant environmental issues posing adverse public health effects [7,18] and pollution problems in both developed and developing countries [19–21]. In many countries, waste offers a largely untapped supply of raw materials because resource recovery rates are still relatively low, despite the fact that recoverable materials make up the majority of the waste stream [18,22]. As a result of rising raw material prices, recycling offers a less expensive supply of primary resources for industry and serves as energy [17,23,24]. Moreover, through the composting process, microorganisms break down non-hazardous biodegradable garbage into organic chemicals that may be utilized as fertilizer [25–28]. Therefore, due to the global increase in RMSW that generated concern in the scientific field because of its fate as still unregulated and poorly managed in many countries, municipal solid waste management (MSWM) has attracted special attention in recent years all over the world [7,29,30]. Thanks to the introduction of numerous MSWM rules and regulations in recent decades that consider and discipline the entire life cycle of a product (from the producer to the consumption and the disposal), industrialized nations like the USA, Germany and Japan obtained substantial successes in waste management [29–31]. MSWM has significant economic potential, whose value is influenced by the effectiveness of waste management systems [5].

The implementation of an integrated management system of MSW for urban hygiene services involves the process of waste minimization at the point of generation, safe disposal and promotes the economic exploitation of waste as recoverable materials or as a source of energy, with both economic and environmental advantages [32,33]. In recent years, several studies have been conducted in which various stages of the waste management process of hazardous waste, such as electronic garbage [34] or waste arising from health facilities [35,36], have been implemented and optimized in order to encourage recovery or proper disposal. Waste minimization is a strategy to reduce waste, usually through source reduction but also by the recycling and reusing of materials [37,38]. Furthermore, RMSW cannot be directly reused by the society for its benefit, as some of it may be hazardous to human health: for example, various vegetables, fruits and cooked materials promote the growth of numerous groups of microbial flora, some of which can cause diseases [39,40]. Hence, the first step for developing a more efficient MSWM system that promotes recycling and reducing environmental impact associated with uncontrolled landfilling is establishing the composition of the wastes to identify the specific plan of recovery [30,41–43].

Because of the inherent complexity of most waste management issues, it is clear that traditional approaches based on rigorous algorithms and mechanistic models frequently fail to offer a sufficient solution, especially in circumstances where there is a scarcity of data [44,45]. For the present approaches to be successful, it is imperative to create efficient waste management systems using cutting-edge technologies [44]. Artificial Intelligence (AI) models provide a different, effective strategy that has attracted a lot of interest from scientists. AI has been a well-liked technology for forecasting MSW in recent years: the most widely used soft computing model for forecasting garbage generation is the artificial neural network (ANN) [46]. In reality, a number of AI models have been used in the literature for MSW forecasting and classification because accurate MSW forecasting is crucial for the creation of effective waste management systems and the optimization of current infrastructures [44,47]. AI-based MSWM systems are still mostly in the research and development (R&D) stage, despite the fact that research in this area is moving forward quickly. For the future design of reliable AI-based SWM applications, understanding the limitations of these techniques is essential. Among these limitations, we identified a lack of data as a significant barrier to the adoption of AI systems. Moreover, a large number of studies used AI models for solving only certain waste problems [45].

Despite an increasing concern about solid waste management on a global scale, rural areas in both industrialized and developing nations have received less attention and considerations than metropolitan ones [48]. Indeed, the composition of waste is very different between urban and rural settings, especially in consideration of the potential recovery [18,28]: according to Owamah et al. [49], there are typically fewer recyclable materials available because of the lesser use of paper and plastic in rural locations [49]. Moreover, as Massoud et al. have reported in their study, the composition of rural solid waste is made up mostly of the organic fraction [18]. The literature still lacks studies that report differences in the management and composition of residual solid waste in rural versus urban communities.

Thus, the present study aims to characterize RMSW as a measure for effective material recovery in two different areas, an urban area and a rural one. For this purpose, particularly, in both urban and rural areas, the study aims to (i) evaluate product categories and their components by population density and seasonal variations; (ii) estimate the recycling potentials of individuated fractions, explained as a possibility of converting waste materials into new and usable ones; and (iii) evaluate chemical and physical characteristics of the RMSW collected in the research areas. The information gleaned from this study will help worldwide communities belonging to two different areas to check the effectiveness of separate waste collection. Moreover, the results of study will help increase the percentage of separate waste collection and the recycling rate, thus growing the amount of waste destined for material and energy recovery plants and processes, and help to create legislation that helps to achieve sustainable development goals through effective MSWM while also reducing costs associated with improving RMSW management.

Rest of the Paper

The following sections of the paper will explain the area of study in detail, focusing in particular on the organization of integrated waste management in the province of Avellino, where the sampling and the chemical-physical analysis of the collected waste were carried out. The results of the waste characterization, the monthly trends, the recycling potential of each identified component and its chemical and physical properties will be discussed point by point in the Section 3, with a focus on the percentages of individual RMSW fractions of European countries studied in the literature.

2. Materials and Methods

2.1. Study Area

The study area was individuated in Province of Avellino (Southern Italy) because of its two areas, rural and urban, that have differences in the production of RMSW, having an impact on both the quantity and the type of waste (Figure 3).

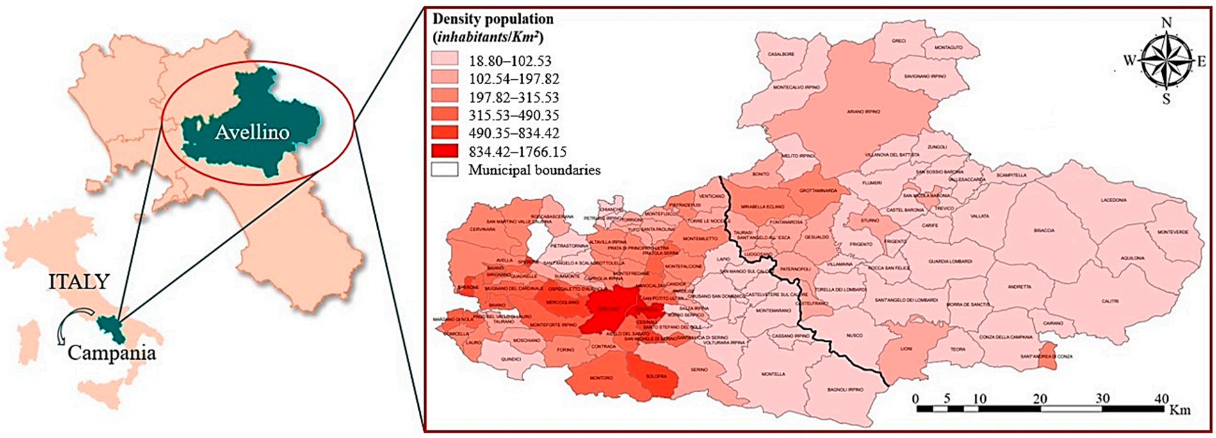

Figure 3. Map of the study area.

Italy has a long history of recycling and recovering garbage, ranking fifth in the world for efficiency in this area, according to the Organization for Economic Co-operation and Development (OECD) [50,51]. The Province of Avellino is composed of 118 municipalities, constituting a population of 402,929 inhabitants, with a population density of 143.6 inhabitants per km^2 [52]. The most relevant urban center of the province is Avellino city with 52,819 inhabitants, followed by all other municipalities that have a population of less than 10,000, while about 67% of the municipalities in the province have a population of less than 3000 [53].

The soil configuration in the study area is quite varied and is characterized by a succession of mountains and valleys, while the plain areas are almost absent [54]. As a result, the climate and flora vary greatly from area to area. Overall, it has a continental climate with a cool and rainy winter and a hot and dry summer [55]. It is particularly suited to agricultural practice, with a high value production of regional specialties such as wine and olive oil [56]. This is due to the minimal level of urbanization of some areas and vast hills [55,56]. From an economic point of view, in the Province of Avellino, there is a high proportion of shops (25%), agricultural producers are made up mostly of direct farmers (24%) and artisans (15%) [57]. Also, the tourism sector is greatly developed [56,57]. According to the Regional Territorial Plan of Campania [58], the whole territory of the region and specifically the province of Avellino is divided into Territorial Development Systems (TDSs), i.e., areas based on the various existing supra-municipal aggregations and considered homogeneous in terms of social, geographical characteristics and strategies of development [57,58]. The TDSs are aggregated according to kind of dominants, which indicate the types of development for each area: urban and rural. The urban area extends especially into the western zone (Figure 3), with the presence of various municipalities of medium and large size, including the city of Avellino, with a very high anthropic pressure on the provincial territory. It is characterized by a high population density and by the presence of industrial development areas: in the latter sector, the important traditional branch of the provincial economy of tanning and leather processing is highlighted. Among the main economic sectors of the province that are developed, especially in the urban area, we also find the metalworkers and the fashion industry [57]. This situation is, however, balanced by a territorial extension smaller than the rural area, which extends into the eastern zone (Figure 3). The rural area is characterized by a hilly territory, with a rarefaction of residential settlements and a low population density: here, the number of municipalities is much lower than in the urban area but these municipalities are much more distant from each other. In this side of the territory, there are remarkable elements of the natural landscape and environmental attractiveness. A low anthropization is combined with a strong presence of protected areas and quality crops that indicate the strong gastronomic vocation of Irpinia in this specific area. In fact, among the main economic sectors of the province, the growing importance of agri-food should be noted, which is the first sector in terms of exports [57].

These two different situations produce effects on both the quantity and type of waste produced and on the organization of the service, thus making the Province of Avellino an ideal area for the aim of the current study.

2.2. Waste Management in the Study Area

Due to its territorial characteristics, the Province of Avellino has developed a management system for the optimization of collection services and transport costs and for the reduction in waste handling. In fact, according to regional legislation 14/2016, one Optimum Territorial Area (OTA) has been identified in this province: an area of self-sufficiency [59], in which the waste management service is organized. It constitutes 114 municipalities and different kinds of infrastructures for the waste collection, transportation services, carried out by an in-house company (Irpiniambiente S.p.A), and treatment plants such as the waste shredding and packaging plants of Avellino and the transfer station of Flumeri (Figure 4) [57].

In this way, both economic and environmental benefits are increased [60]. The OTA of Avellino has been organized taking into account the spatial distribution both of municipalities and of the infrastructures such as plants, logistics centers (from which waste collection trucks depart) and transfer sites all over the provincial territory. Municipalities that belong to the urban area are served by the logistics centers situated in Rivarano Monteforte Irpino, Quindici, San Martino Valle Caudino and Montella (Table S1) and their waste is directly transported to the waste shredding and packaging plants of Avellino city (Figures 4 and 5A).

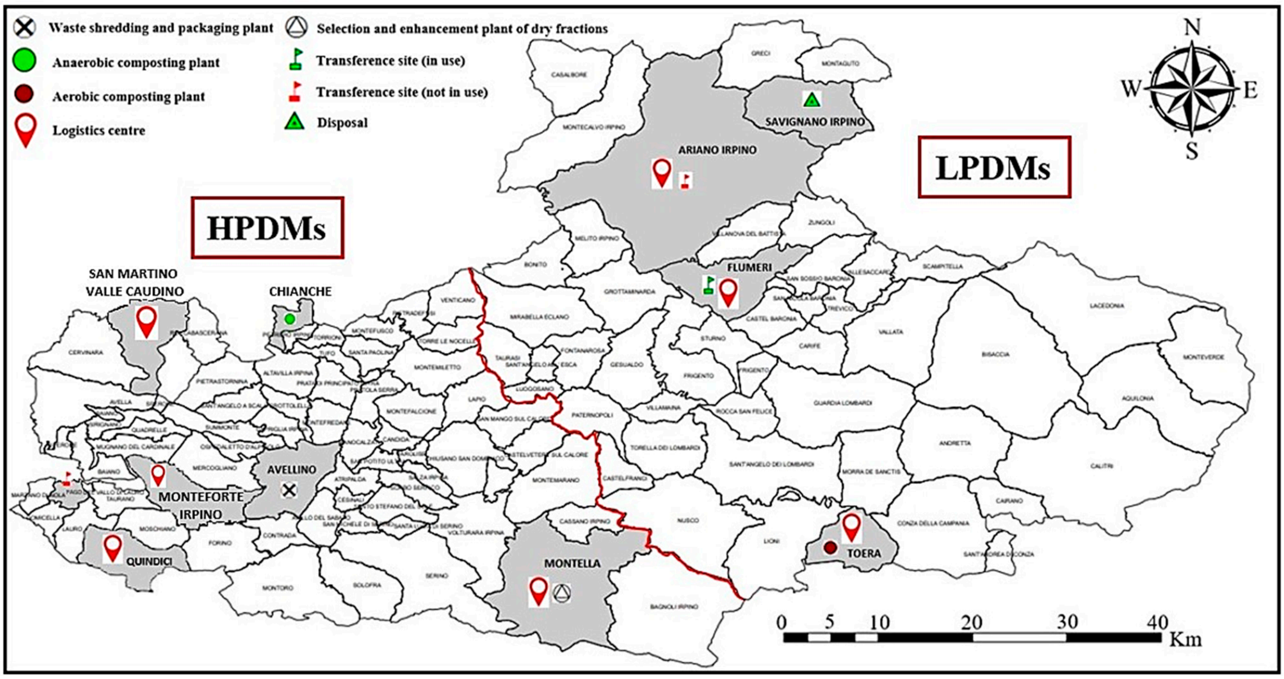

Figure 4. Transfer/compaction stations, logistics centers and other plants ofOTA. HPDMs are served by logistics centers situated in Rivarano Monterofrte Irpino, Quindici, San Martino Valle Caudino and Montella. LPDMs are served by logistics centers located in Flumeri, Teora and Ariano Irpino.

Figure 5. (**A**) Avellino waste shredding and packaging plant; (**B**) Flumeri transfer site.

For the purpose of this study, these municipalities are indicated with the name of "High Population Density Municipalities" (HPDMs). "Low Population Density Municipalities" (LPDMs) are labelled municipalities located in the rural area and served by the logistics centers situated in Flumeri, Teora and Ariano Irpino, and waste from these areas are transported to the transference site of Flumeri (Figures 4 and 5B).

2.3. Waste Sampling Procedure

In order to obtain samples of RMSW representative of waste produced by an urban area with a high population density and by a rural area with a low population density, a direct sampling campaign, as it has been carried out in previous studies [14,61], was performed once a month from November 2021 to October 2022, following the Technical Standard Procedure UNI 10802: 2013 [62]. According to this method, a random sampling of *n* units or increments was carried out in such a way that each unit has the same probability of being taken. The same sampling was carried out manually, that is, with the use of instruments for which human intervention is essential in their operation. Households, catering businesses, shops and Irpiniambiente S.p.A. represent the stakeholders involved in the waste trading system of the study area. The different actions of stakeholders can balance the use or conservation of resources while realizing long-term benefits for the environment, therefore providing solutions for effective waste management [63]. Thus, their different statuses and roles influence waste separation and consequently the waste management process. The main points of garbage extraction activities are community containers located near residential districts, markets and shopping centers. In this case, community containers (or waste bins) are foreseen for each commercial activity and for each medium/high-income multi-family house. The increments, or individual portions of waste of about 25 kg collected in a single operation, were taken from community containers of multi-family housing and commercial activities situated in four Italian municipalities located in Province of Avellino: Atripalda and Avellino (HPDMs), which represent the urban area, and Lacedonia and Calitri (LPDMs), which instead are representative of the rural area. The increments collected from sampling points in Avellino and Atripalda were united to form a single sample. The same was conducted for Lacedonia and Calitri, obtaining 12 samples (1 for each month) for HPDMs and 12 samples for LPDMs. These municipalities have the same source segregation scheme that provides the use of waste bins for the separate collection of recyclable materials and for residual solid waste (RMSW) both for multi-family housing and commercial activities (Figure 6).

Figure 6. Waste bins used for separate collection of recyclable components (plastic, paper, glass and organic) and for RMSW (indicated in the figure with circle red line).

Particularly, blue bins are used to collect plastic, white bins to collect paper, yellow bins for glass, green bins for the organic fraction and black bins for RMSW. The waste bins used by consumers for the collection of waste had volumes of 240 L and were provided by IrpiniAmbiente S.p.A. The waste segregated in the waste bins (Figure 4) was collected using paper and plastic sacks for temporary storage and transporting. About 825 kg of waste was collected each month from HPDMs and the same for LPDMs, for a total of 9900 kg of RMSW from both rural and urban areas. Collected waste was transported to the sorting area by a truck. There, garbage was unloaded on a tarpaulin and weighed using a balance. The whole amount of waste taken from each area underwent a quartering procedure to reduce the volume of the initial mass and obtain in this way a representative sample of 207 kg.

The direct sampling campaign was preferred over the sampling at the unloading point for waste collection vehicles because the sampled wastes cannot be accurately associated with the type of geographic area generating them [64]. To reduce logistical efforts, in this case, the waste shredding and packaging plants of the city of Avellino could have been used to sample RMSW produced by HPDMs and the Flumeri transfer site could have been used to sample RMSW produced by LPDMs. This restricts the use of the obtained data on the composition of RMSW. Additionally, because the majority of contemporary garbage collection trucks include a compaction mechanism [65], waste fractions taken from such vehicles could be influenced by mechanical stress and blending, which makes it extremely challenging to separate individual component fractions during manual sorting [14]. Cross-contamination between different fractions may happen as a result of mechanical stress and blending processes from collection vehicles, resulting in additional errors that cannot be measured or fixed after the fact. On the other hand, collecting trash directly from particular homes and/or from a specific area with a specified household type enables the waste data to be connected to the specific location [64].

2.4. Quartering Procedure

With the waste sample starting from a mass of 825 kg weighed using a balance, the representative sample was obtained by reducing the volume of the initial mass by the quartering method (UNI 10802:2013 [62]) to facilitate the sorting process and MSW sample transport to the laboratory. For preparation of the representative sample, the bags containing the waste were spread out on the floor to make separation and weighing of different waste fractions easier. The waste was mixed with a mechanical shovel on a previously and carefully cleaned paved or cemented quartering area. After mixing, waste was homogeneously distributed in such a way as to form a circular figure with a height of not more than 50–60 cm that was divided into four equal parts by means of two colored ribbons arranged at 90° and the material constituting two opposite quarters was removed with a shovel and broom. The remaining mass was mixed and redistributed again in the same way. The quartering operation was repeated, staggering two colored tapes at 45° compared to the first quartering operation. The material of two opposite quarters was discarded, while that of the remaining two parts was mixed. In this way, the waste starting mass of 825 kg was reduced to a quarter, obtaining the representative waste sample of about 207 kg used for the analysis of the waste components by sorting procedure. Other parts (each weighing about 5 kg) were taken from the residual waste removed during the quartering technique and sent to the laboratory for the execution of the physico-chemical analysis.

2.5. Sorting Procedure and Weighing of Sorted Waste

Components of RMSW samples were sorted by hand and classified into six major categories: paper, plastic, organic waste, textile, metals and inert materials. Classification was made according to the grouping system of the College and University Recycling Council [66], making necessary changes to accommodate the generated waste stream [67,68]. The found RMSW components of HPDMs and LPDMs were been grouped into six major categories: paper, plastic, organic waste, textile, metals and inert materials (glass). Components constituting each category are reported in Table 1.

Table 1. Components of waste fractions.

Fraction	Components
Organic waste	Foodstuffs, organic materials of vegetable or animal origin
Plastics	PET container, packaging plastic, plastic films, polylaminate (Tetra Pak) materials and plastic bags
Paper cardboard	Newspaper, notebooks and magazines
Textile	Clothes and sanitary textile waste such diapers and sanitary napkins
Metals	Aluminum cans, tin, mixed metal
Inert materials	Glass, porcelain, ceramics
Other	Ash, sand and minute material

All mixed and laminated objects (paper and plastic, glass with metal, plastic and aluminum inserts, etc.) were included in the category to which, according to visual evaluation, the material of membership exceeded 50% of the weight of the object in question. Moreover, fine particles were removed from the waste, making the sorting process easier and reducing the fractions, which could be identified as inerts. At the end of the manual sorting operations, the materials belonging to the different product categories were weighed with a balance. The percentage composition of each fraction was calculated using the following formula [69]:

$$\text{Percentage composition of waste fraction} = (\text{Weight of separated waste})/(\text{The total of mixed waste sampled}) \times 100 \quad (1)$$

2.6. Methods of Analysis

The chemical-physical characteristics of the wastes produced in the research area were also studied, including moisture content and metal analysis. The following is a quick summary of these techniques: the EPA 200 7/8 M standard [70] method was used to carry out the quantification of metals with a Thermo Scientific^{TM} ICAP^{TM} RQ Inductively Coupled Plasma Mass Spectrometer (Q-ICP-MS) (Thermo Fischer Scientific, Bremen, Germany), operated by QtegraTM Software (Version 2.7.2425.65); volatile matter, ash and pH were evaluated according to IRSA-CNR 2 Vol 2 Q64 (1984) methods; composition of Carbon (C) was evaluated according to the UNI EN 15169:2007 standard [71], while Nitrogen (N) was estimated with IRSA-CNR Vol 3 Q64 methods; for moisture content (MC), freshly ground samples were dried in an oven at 105 °C in porcelain cups for 24 h and kept in a desiccator to be brought down to room temperature. Samples were weighed again and MC was calculated using Equation (2):

$$MC = [(W - d)/W] \times 100 \quad (2)$$

where W is the initial weight of sample (kg), and d is the weight after being dried at 105 °C (always in kg).

3. Results and Discussion

3.1. Waste Composition and Seasonal Variation

The results of the sorting procedure of wastes collected at the sampling points of the study area are shown in Figure 7 as the average monthly percentage composition by mass of each fraction.

The plastic percentage of garbage, which consists mostly of packaging plastic as well as other plastic materials, is more prevalent than organic and paper and cardboard fractions in both HPDMs and LPDMs. Food waste is the largest component of organic waste, which constitutes about 8.4% of the waste stream from the HPDMs and 11.9% from LPDMs. Generally, rural areas produce RMSW constituted mostly of the organic fraction. In this case, the percentage of the organic fraction found is lower than other studies [28,29]. In fact, in accordance with study conducted by De Morais and Paulo, rural areas might produce a small amount of organic waste because people utilize it immediately after production for composting, burying, nourishing pets and livestock [48].

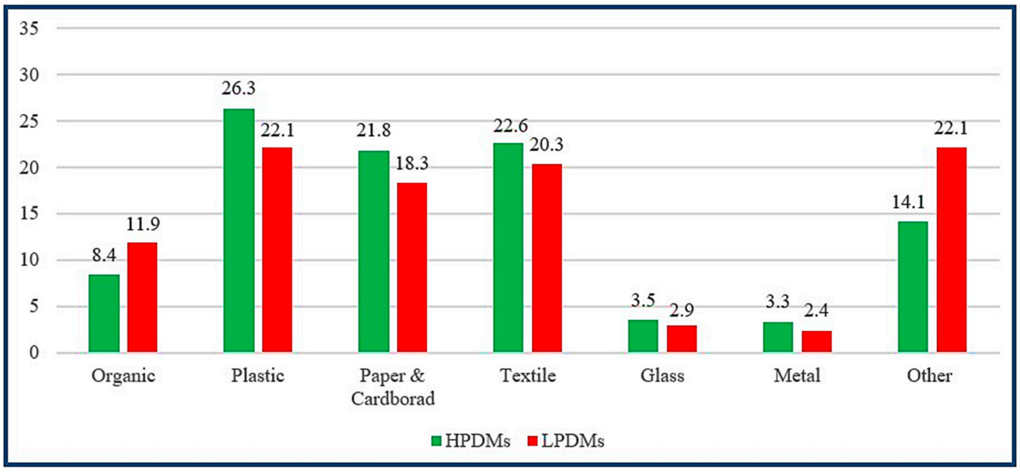

Figure 7. Waste fractions of HPDMs and LPDMs (%).

Plastic makes up the largest portion of solid trash, accounting for values between 25.2% and 27.1% for HPDM samples and between 21.2 and 23.3% for LPDMs. Polylaminate materials (Tetra Pak), plastic bags (shoppers) and plastic film, with a limited number of bottles being recovered, have been the most common types of plastic components that were discovered in the sorted waste streams. This is probably caused by the usage of the separate collection of waste made by the population, a diffuse culture of developed countries, which decreases at the source the amount of waste destined for disposal in landfills or incinerators [72,73]. The main fractions of paper waste were composed of cardboards and other kinds of material papers such as notebooks and magazines. The percentage values of paper fractions ranged from 20.5 to 22.3% for HPDMs and from 17.6 to 18.9% for LPDMs. Fractions such as metals and inert materials, mainly constituted of glass, ranged between 2.4 and 3.5%. The main component of textile waste, one of the three biggest fractions for both streams and which percentage is higher in HPDMs (22.6%) than in LPDMs (20.3%), is sanitary textile waste like diapers and sanitary napkins.

The availability of packaging components is usually lower in rural than in urban locations. This can be due to the decrease in the utilization of paper, plastic and electronic technologies [18,28]. Compared with the low population density area's stream, wastes from HPDMs had a slightly higher number of recyclables and a lower amount of the organic fraction given that town centers typically host a larger number of institutions, which normally produce relatively higher amounts of plastic, cardboard and glass [18].

With the fraction identified as "Other", components that are not classifiable according to the categories considered in this study, such as ash, sand and minute material not easily sorted, have been grouped together.

Figure 8 shows the seasonal average waste composition of the samples collected from the two areas.

Results showed that seasonal change did not significantly affect the composition of municipal solid waste, as reported and confirmed in other studies [69,74]. Despite these considerations, it was possible to establish certain trends. Particularly, during summer, RMSW samples outlined a greater amount of inert constituents (glass) and the percentages of organic waste were almost the same from both streams. A rise in restaurant activity during the summer season could have been the reason for the increase in the organic composition of urban wastes, which went from 8.1% in the winter to 10.5% in the summer. In fact, according to Zeng et al. [75], holiday activity events that take place in particular during the summer season could be the main variable influencing seasonal variation in RMSW organic composition. According to Gidarakos et al. [76], RMSW generation and composition are also influenced by visitor flows throughout the year in places where tourism has a significant impact on the local economy [76]. Also, agricultural activities, which have an impact on the production of food waste between September and October, could explain this trend [77]. Instead, organic components of municipal solid waste from LPDMs decreased from the winter to the summer season. The mean value of organic wastes in the winter period was 12.7%, while in the summer period, this value decreased to 11.3%. The reason for this slight decrease in the summer season could be explained by the evaporation of the water contained in the organic fraction, largely made up of fruit [5]. In fact, during the summer months, the culture of a healthier and lighter diet is widespread, rich in fresh products containing water such as fruit [78]. Nevertheless, food waste constitutes the most abundant material, both during the winter and summer seasons, together with the plastic and paper fractions.

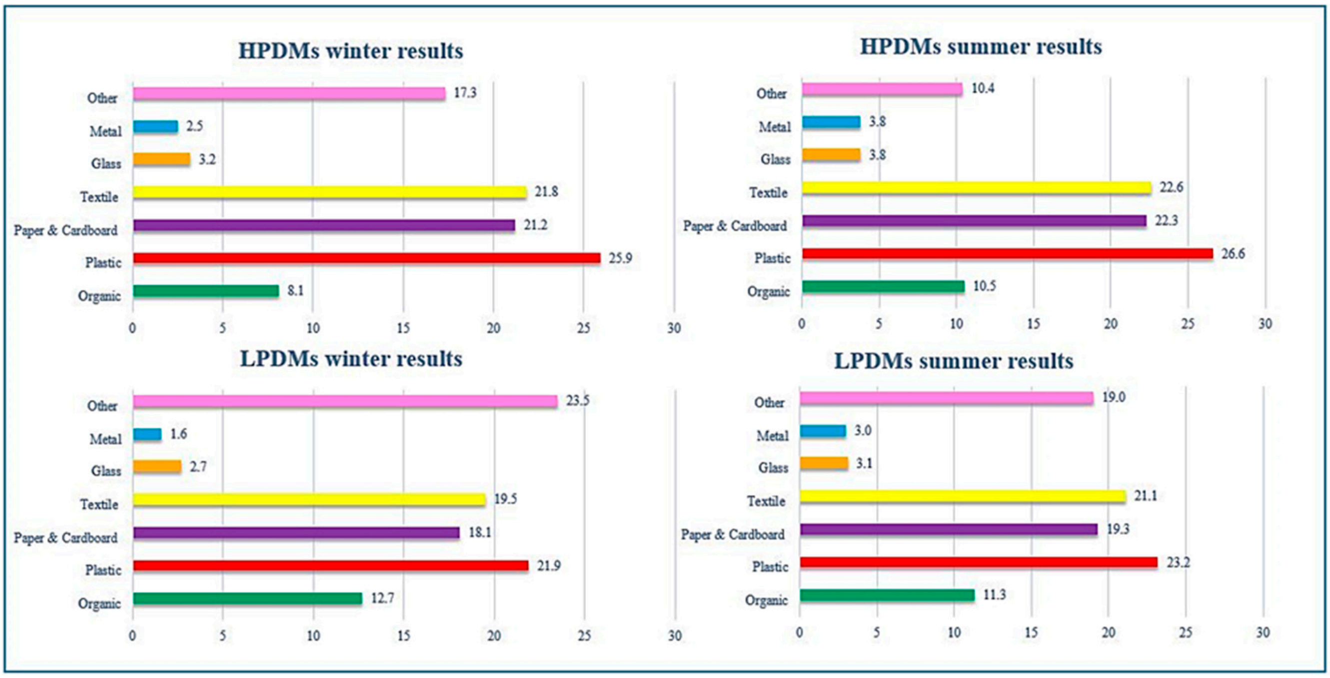

Figure 8. Detailed waste composition (%) of the HPDMs and LPDMs during summer and winter.

Throughout the year, several patterns continued, including the predominance of substantial plastic garbage and the scarcity of metals (Figure 8). Specifically, plastic bags continued to represent a significant proportion of the plastic fraction individuated in the samples. Also in this case, there is a slight increase in the amount of plastic found in the analyzed samples from both waste streams in the summer that passed the percentage of 26.6% for HPDMs and 23.2% for LPDMs. As also reported by Cheela et al. [79], the growth in the plastic fraction is probably due to the presence of plastic bottles of water and various drinks that are consumed in greater quantities during the hot season [79]. The different level of consumption due to hotter weather could also explain the increase in the amount of metals and glass observed during the summer season, although low, mainly for the presence in the RMSWs of aluminum cans and beverage glass bottles [13,20]. From waste collected in the HPDMs, the rate of glass in waste mass was 3.2% in the winter period, while this reached up to 3.8% during summer season.

A decrease in the quantity of textiles was also registered in the summer for the RMSW of HPDMs and LPDMs, which passed from 21.8 to 22.6% and 19.5 to 21.1%, which could be associated with the fact that towards the end of the cold season people change their clothes because of the coming summer [18]. These results are in contrast with those found by Adeleke et al. [80]: the less strong impact of climate change during the passage from hot to cold periods of the study area considered in this research can explain this inverse trend [80]. Ash, a type of residual waste that is classified as "Others", was detected during the winter season, primarily originating from heating stoves, especially for RMSW coming from locations with dense populations. However, there was a rise in the volume of paper disposed of throughout the summer. This can be ascribed partially to the end of the school year and, for this reason, many people tend to throw out old textbooks, notebooks and documents [18].

3.2. Recycling Potential

Table 2 reports the recycling potential of each component of the RMSW sample.

Table 2. Recycling potential of waste fraction's components.

	Recycling Potential		
Fraction	**Recyclable Waste**	**Potentially Recyclable Waste**	**Non-Recyclable Waste**
Organic waste			
Foodstuffs		X	
Organic materials		X	
Plastics			
Polylaminate (Tetra Pak) materials	X		
Plastic films			X
Packaging plastic			X
Plastic bags			X
PET containers (plastic bottles)	X		
Paper and cardboard			
Cardboard	X		
Newspaper		X	
Textbooks	X		
Notebooks		X	
Textile			
Sanitary textile waste			X
Clothes		X	
Metals			
Aluminum cans, tin	X		
Mixed metal			X
Inert materials			
Glass	X		
Porcelain, ceramics		X	
Other			
Ash, sand			X

According to the recycling classification (Table 2), the total waste collected in HPDMs is made up also of recyclables such as polylaminate (Tetra Pak) materials, PET containers, cardboard, textbooks, aluminum cans and glass. In fact, considering the percentages of recyclables in the RMSW shown in Table 3, the rate of package wastes in HPDMs' total solid waste was found to be 27.5% in the winter period and 29.1% in the summer period, with a mean value of 28.6% (Table 3).

Table 3. Percentage distribution of recyclable components of HPDMs' waste.

Recyclable Components	Average (%)
Paper and cardboard	14.3
Plastics	10.3
Inert materials (Glass)	2.2
Metal	1.8
Total (%)	28.6

These results are in accordance with those reported by Ozcan et al. who found a rate of package wastes in total solid waste of 26%, with high percentages of paper and cardboard, plastic, glass and metals among recyclable wastes [13]. Instead, De Vega et al. reported that the greater proportion of recyclable garbage of 33% is mostly constituted of paper and cardboard [67]. Polylaminate materials play an important role in the recycling process.

According to a recent study conducted by Buonocore et al. [81], recycled polylaminate sheets can be used to obtain panels with characteristics suitable for use in green building, through the optimized thermal method that does not use chemical or other binders [63].

In the case of waste coming from LPDMs, the largest portion is constituted of potentially recyclable components mainly composed of the organic fraction (11.9%), clothes (7.9%), porcelain (0.9%) and newspaper and notebooks (10.1%), with a total percentage of 30.8 (Table 4).

Table 4. Percentage distribution of recyclable components of LPDMs' waste.

Potentially Recyclable Components	Average (%)
Organic fraction	11.9
Textile (clothes)	7.9
Newspaper and Notebooks	10.1
Porcelain	0.9
Total (%)	30.8

In order to represent the previous results more clearly, the percentages are presented in Figure 9 according to the recycling category.

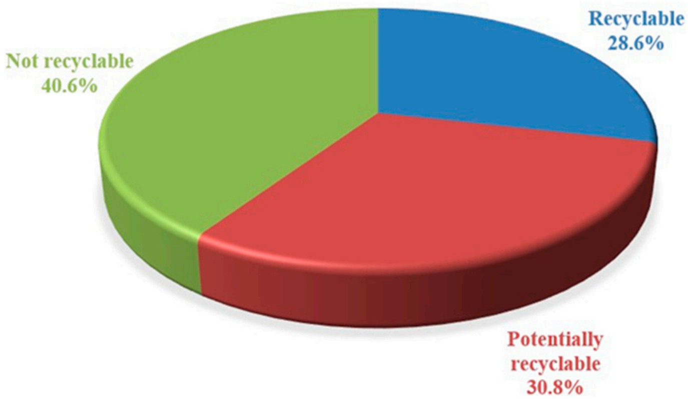

Figure 9. Waste percentages (by wt.) according to the recycling category.

When solid waste is analyzed as a whole, the proportions of recycling show differences between categories: characterized waste is made up mostly of non-recyclable components that constitute about the 40% of the total. Nevertheless, based on the results reported in Tables 3 and 4 and on the recycling classification (Table 2), a small portion of the waste generated in the study area could be recycled or is potentially recyclable on the basis of the physical-chemical condition of the components and the availability in the territory of opportune treatment plants.

As reported above, households could reuse these raw materials applying different kinds of composting [48]. On a larger scale, in the study area, two types of plants are available for the recovery of the organic fraction from the rural area: aerobic and anaerobic digestion plants (Figure 4). The position in the territory of the recovery plants suggests an aerobic composting treatment for the organic component deriving from the residual solid waste of the rural area, thus encouraging the use of the plant located in the municipality of Teora (LPDM) (Figure 4) rather than the anaerobic composting plant of Chianche (HPDM). The application of this recovery method is also favored according to Meena et al. [82]: indeed, compared to aerobic decomposition, with the anaerobic process, the probability of pathogens surviving in the compost is substantially higher [82]. Similarly, the percentage of recyclable material found in the waste sampled in the urban area can be sent to the dry fraction (plastic, paper and glass) selection and valorization plant located in the municipality of Montella (HPDM) rather than being disposed of in the Savignano landfill (Figure 4) or sent to Waste to Energy (WtE) facilities. In this way, the recycling process and the consequent recovery of material is optimized.

From an economic point of view, it is important to say that the reduced landfilling in favor of the increased recycling of materials leads to a lower environmental impact, lower consumption of energy resources and lower economic costs, as landfilling is the most expensive waste treatment due to the alternative cost for fulfilling the functional units. Moreover, landfill costs, including landfill tax, are naturally dominant. WtE or incineration could appear more competitive than the recycling options: total costs, for example, are slightly higher for plastic recycling than for incineration, due to the relatively low value of recycled plastic, making the WtE treatment more profitable and competitive than the recycling options. A possible exception is represented by the production of alternative fuels for cars (such as biomethane) that can be obtained from the organic fraction through anaerobic digestion. This process is slightly cheaper than the WtE treatment due to the high cost of petrol.

3.3. Solid Waste Composition in Europe

Table 5 shows the percentages of individual RMSW fractions of European countries studied in the literature such as Italy, Denmark, Spain, Finland, the United Kingdom and Poland [83–89] together with the percentage of each fraction found in this study.

Table 5. Fraction percentages of European waste (% in mass per wet basis).

	Fractions							
Country	**Organic**	**Plastic**	**Paper and Cardboard**	**Textile**	**Glass (Inert)**	**Metal**	**Other**	
Italy (Avellino)	10.2	24.2	20.1	21.5	3.2	3.3	18.1	Current study
Italy	12.6	27.6	39.2	/	5.9	2.4	37.5	AMSA, 2008 [83]
Denmark	45.1	9.2	23.2	/	6.4	3.3	12.8	Riber et al., 2009 [84]
Spain	58.0	10.7	19.0	/	4.0	3.0	5.3	Montejo et al., 2011 [85]
Finland	23.9	21.4	15.3	/	12.9	3.8	22.7	Horttanainen et al., 2013 [86]
United Kingdom	32.8	6.9	21.5	/	23.1	4.8	10.9	Burnley, 2007 [87]
Poland (Krakow)	10.2	40.5	10.1	1.8	12.1	22.6	2.7	Den Boer et al. [88]
Italy (Separate Collection Efficiency of 50%)	30.5	18.7	17.4	8.6	3.7	2.6	18.5	Calabrò and Pangallo [89]
Italy (Separate Collection Efficiency of 75%)	27.4	19.4	17.1	10.6	2.7	1.6	21.2	

Comparing the results of present study with the percentage compositions of fractions in Italian RMSW reported by A.M.S.A in 2008 [83], it is evident that there was a substantial decrease in the amount of paper and cardboard, organic, plastic and metal fractions. This trend has been recently confirmed [90]: since 2018 in the areas of the present study, a slight increase in the percentage of separate collection has been recorded. Particularly, it has gone from 63% in 2018 to 64% in 2021 [73], in line with the Italian mean value of 64% together with a recycling rate of 72%, higher than the European average of 53% [91,92]. In terms of total production of municipal waste, Italy recorded the most pronounced decrement with a loss of −1.2 million, passing from about 30 million tons in 2018 to 28.8 million tons in 2020 [91]. Carrying out selective collection results in a decrease in the potentially recoverable fractions in the residual municipal solid waste and consequently in a decrease in waste quantity transported to landfill. According to Rada et al. [93], areas where the selective collection of the organic fraction is implemented with high efficiency show decreases in its content in the RMSW. In the most extreme cases, the percentage of the organic fraction in the RMSW may fall below 10% [93]. Also, Calabro and Pangallo confirmed this tendency [89]. They analyzed the composition of residual waste as a function of the separate collection rate: the amount of the organic fraction, glass and metals decrease with the increase in the separate collection rate, resulting in the recyclable fractions being most impacted by separate collection [89].

Although the percentage of food waste varied significantly between research studies, the majority of them indicated that RMSW is made up mostly of the organic fraction.

The percentage compositions of the organic fraction, metal, inert materials and paper and cardboard of municipal solid waste obtained from current study are overall lower than the others. This can be explained by considering the years of the studies. Waste management practices in Europe have improved recently [91], as was previously mentioned for Italy [50,51]. Due to the separate collection method, a larger proportion of garbage is now recycled, which lowers the quantity of waste that needs to be landfilled or sent to WtE facilities. For the plastic fraction, the rise may be attributable to a higher plastic consumption in recent years than at the times that these earlier research studies were conducted and to the increase in the use of packaging not always accompanied by an increase in selective collection of this fraction [94]. Moreover, compared to other commonly used materials such as paper, glass and metals, recovery and recycling rates of plastic materials are generally low: even in countries with advanced waste management systems and much experience in recycling, plastic recycling rates are typically much lower than the rates of other materials [94]. This is partly caused by the huge variety of plastics, additives and composites used to make these materials more versatile [95]. Furthermore, household waste plastic is a heterogeneous and contaminated resource, which limits the potential for closed-loop recycling and results in recycled plastic with lower quality [96,97]. Consequently, the quality of the plastic material decreases, thus making it not suitable for recycling and then disposed of along with the RMSW [94,97]. The same considerations could be assumed for the percentage of textile fractions, whose amount is due to the increase in medical devices such as diapers and sanitary napkins [98].

Generally, the comparison of composition data makes it evident how difficult it is to compare data. Variables such as sorting procedures, income levels, demography and changes in purchasing patterns may also have an impact on the data. Even variations in source-segregation methods may be a potential explanation for these variances.

3.4. Chemical Conditions

The chemical conditions of the RMSW collected from the two different areas are reported in Table 6.

Table 6. Physicochemical properties of inorganic RMSW from the two urban and rural areas.

Variable	***HPDMs***		***LPDMs***	
	Winter	**Summer**	**Winter**	**Summer**
pH unit	6.7 ± 0.3	6.4 ± 0.3	7.0 ± 0.2	6.7 ± 0.3
Carbon (%)	45.2 ± 0.6	47.7 ± 0.7	43.3 ± 0.5	46.5 ± 0.6
Nitrogen (%)	2.4 ± 0.8	2.6 ± 0.6	2.5 ± 0.7	2.6 ± 0.5
Moisture content (%)	43.4 ± 0.9	45.3 ± 0.4	44.6 ± 1.0	47.1 ± 1.1
Volatile matter (%)	20.2 ± 0.8	22.6 ± 0.5	22.2 ± 0.7	23.5 ± 0.8
Ash (%)	5.7 ± 0.4	7.4 ± 0.4	5.1 ± 0.2	5.7 ± 0.3
***Metal Analysis** (mg/kg) unless stated otherwise*				
Aluminum (g/kg)	13.4 ± 0.9	12.9 ± 1.0	13.3 ± 0.8	13.1 ± 0.9
Iron	194.3 ± 1.5	197.1 ± 1.2	189.2 ± 1.0	191.4 ± 1.2
Zinc	112.2 ± 0.8	109.2 ± 0.9	110.7 ± 1.2	109.5 ± 0.9
Manganese	19.1 ± 0.5	18.8 ± 0.6	18.7 ± 0.5	18.5 ± 0.7
Copper	47.3 ± 0.8	46.7 ± 0.8	48.2 ± 0.7	47.9 ± 0.6
Vanadium	2.9 ± 0.4	2.7 ± 0.3	2.8 ± 0.4	2.6 ± 0.5
Cobalt	<2	<2	<2	<2
Nickel	<2	<2	<2	<2
Mercury	<2	<2	<2	<2
Cadmium	<2	<2	<2	<2
Arsenic	<2	<2	<2	<2
Tin	<2	<2	<2	<2
Lead	<2	<2	<2	<2
Thallium	<5	<5	<5	<5
Selenium	<10	<10	<10	<10

The percentage of total carbon detected in the samples may be owing to the presence of specific components among paper and plastic fractions [96]. As Massoud and Mokbel found in their study, the percentage value of nitrogen found in the analyzed samples was explained by the amounts of organic and textile fractions that constituted about 30% of both waste streams (Figure 5) [18,99]. The moisture content of the samples was relatively high with values ranging from 43.4 to 47.1, given that food waste represented a not negligible portion of the organic fraction, with the moisture content of food waste typically being very high [18]. While the amount of ash indicates the inorganic portion present in the wastes, volatile substances may be used as an indicator for the quantity of organic materials [100,101]. Moreover, organic matter content in solid waste composition is an important factor which increases MC. Despite these considerations, results from the current study (Table 6) showed lower values of volatile matter (20.2–23.5%) and higher values of ash (5.7–7.4%), contrary to what was found by Massoud et al. [18], confirming the presence of recoverable components such as plastic, paper and textiles in both waste streams.

Aluminum (Al), Iron (Fe), Zinc (Zn), Manganese (Mn) and Copper (Cu) were the metals with the highest concentrations in our samples, and these metals correspond to some of the most notable metals normally detected in leachate [102]. Because of their potential effects on the quality of soil and water, heavy metals constitute a severe hazard to population and environmental health. Generally, heavy metals have the capacity to enter the ecosystem and have an impact on the sustainability and effectiveness of regional ecological systems [103]. The analyzed heavy metals in this case had levels below the detection threshold. Therefore, the metal content of the waste did not invalidate the quality of the recyclable components or of the possible compost resulting from the organic fraction, as is the case for mechanically separated waste that has levels of contamination higher than those segregated at the source [18]. As the composting process of organic wastes raises the level of heavy metals by removing moisture and volatile organic content, the heavy metal quantity detected into the compost is typically higher than that in the starting soil it is added to [104]. Compost quality, which is influenced by the processing method, the composition of the raw materials, the goodness and the cost, is a limiting factor for its usage, demand and marketability [105,106]. As a result, source separation of municipal garbage is crucial.

3.5. Chemical Requirements for Composting Organic Matter

Composting is the aerobic decomposition of organic waste under regulated circumstances by organisms into a soil-like substance known as compost [107]. Organic waste is under monitored conditions when it has a sufficient amount of oxygen with a good carbon to nitrogen proportion, significant MC and a favorable temperature with a neutral pH. Table 7 lists the status of organic waste collected for this investigation from a chemical point of view along with the suggested conditions required for effective composting [43,108].

Table 7. Physicochemical properties of organic waste from HPDM and LPDM sources.

Variable	*HPDMs*	*LPDMs*	*Recommended Value*
pH unit	6.6	6.9	5.5–9.00 [37]
C/N ratio	17.6:1	18.3:1	20:1–40:1 [37]
Moisture content (%)	44.7	46.5	40–65 [37]

The obtained results showed that not all the ideal conditions for composting were satisfied. Neither the organic waste from LPDMs nor the organic waste from HPDMs had attained the necessary carbon–nitrogen ratios of 17.6:1 and 18.3:1, respectively. With the inclusion of wastes that are rich in carbon in a readily degradable form, the organic fraction from HPDM and LPDM households and commercial activities will have a higher carbon to nitrogen ratio [18].

Only the organic fraction from the rural area met almost all standards. With the addition of a small amount of lime or any other alkaline ingredient and thorough mixing, organic wastes from the two sources will have higher pH values [43].

4. Conclusions

Considering the differences in waste components based on population density, it was found that the highest organic waste rate was found in the rural area having the lowest population density (LPDMs). Instead, HPDMs produced RMSWs with a presence of recyclable fractions constituted by plastic, paper and cardboard, inert materials and metals. In addition, the different seasonal conditions did not significantly affect the composition of RMSW streams from the areas under investigation. A portion of the generated waste could be recycled or is potentially recyclable, supplying a potential reliable source of raw materials for recycling facilities. Indeed, the recyclable components' quality and any potential compost produced by the organic portion are not invalidated by the presence of heavy metals.

The most crucial aspect of integrated waste management is the characterization of waste to establish its fate. The presence of territories with clearly contrasting characteristics could affect the composition of RMSW and consequently the treatment methods for recovery. In light of the results obtained, it was shown that residual municipal solid waste from urban areas, especially the recoverable packaging waste, and the organic fraction from rural areas may be reclaimed for the economy by efficient waste management planning. These trends are consistent with those found in the literature. Despite the efforts made to carry out a comprehensive and consistent study, this document presents some restrictions. Because socio-economic parameters, demographics and educational levels differ between countries in the world, the implementation and the optimization of an integrated waste management system in rural and urban regions cannot go hand in hand. Furthermore, data standardization is a difficult procedure that requires the simultaneous evaluation of several variables. On the other hand, through the dissemination and application of these studies, we can start to strengthen the exchange of information between the various local administrations that manage the various phases of the integrated waste cycle (ranging from collection to disposal/recovery) both in rural and urban areas, in order to induce cross-improvement of the whole waste management system obviously by adapting it to local conditions and available territorial resources. Therefore, with the elaboration of more in-depth studies aimed at optimizing and standardizing the management methods of residual municipal solid waste, these data will be extended and used by all the areas defined by these two dominants to design suitable recovery and/or disposal plants and for the maximum use of existing recycling plants with advantageous economic interventions. This will lead to cost savings in integrated solid waste management design.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/su151813378/s1, Table S1: Avellino's Municipalities served by the logistics centers of Rivarano Monteforte Iripino (HPDMs) and Flumeri (LPDMs).

Author Contributions: Conceptualization, M.T., P.M. and P.P.; Data curation, B.D.S., I.R., E.D.R., F.D.D., V.C. and P.P.; Formal analysis, B.D.S., I.R., E.D.R., F.D.D. and V.C.; Investigation, B.D.S.; Methodology, B.D.S., I.R., E.D.R. and F.D.D.; Project administration, M.T., P.M., C.C. and S.D.; Resources, C.C., V.C. and P.P.; Supervision, M.T., P.M. and S.D.; Validation, C.C., V.C. and P.P.; Writing—original draft, B.D.S., E.D.R. and F.D.D.; Writing—review and editing, P.M., C.C. and S.D. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data that support the findings of this study are available upon reasonable request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

Conflicts of Interest: The authors declare no conflict of interest.

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