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Analysis of the Structure and Seasonal Variability of Food Waste in Urbanized Areas: Possible Actions for Achieve Sustainable Development

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ABSTRACT

Food waste is a major global challenge with profound environmental implications. As urban populations continue to grow, effective waste management strategies will become increasingly important. This study aims to quantify food waste generated within mixed municipal waste from residential buildings and to analyze its seasonal variations. It examines consumer behavior, including motivations and barriers to food waste sorting. To achieve this, an analysis of mixed municipal waste and a questionnaire survey using computer-assisted web interviewing were conducted to gather insights from residents. The analysis revealed that food waste accounts for approximately 19.11% of mixed municipal waste, with notable seasonal variations, particularly during the summer months, when increased volumes are observed. Fruits and vegetables account for the largest share of avoidable food waste, with a peak in waste during the summer months. The results show seasonal fluctuations in food waste, highlighting the need for targeted waste management strategies. Consumer behavior analysis highlights key factors that influence the effectiveness of food waste collection, including the availability of infrastructure and motivational tools. To achieve a circular economy in cities, it is essential to implement efficient food waste sorting systems and improve consumer education. Optimizing these systems can significantly contribute to sustainable waste management. Raising consumer awareness and introducing appropriate motivational tools are key steps. This study supports efforts to achieve the sustainable development goal by proposing strategies to reduce food waste and improve urban waste management systems.

1 | Introduction

Approximately one-third of all food produced globally is wasted, with significant environmental, economic, and social consequences. From a financial perspective, food waste (FW) represents a direct loss for households, businesses, and governments. In the European Union (EU), households discard an estimated 88 million tons of food annually, amounting to 143 billion euros in economic losses, with two-thirds of these costs (98 billion euros) attributed to household FW (Stenmarck et al. 2016). Beyond its economic burden, FW has severe environmental implications. Each year, an estimated 1.3 billion tons of food is wasted, contributing to approximately 22% of global and 6% of EU man-made greenhouse gas emissions (GHG) (Blakeney 2019; Friedman-Heiman and Miller 2024; Marouli 2024). Additionally, FW depletes essential resources,

FIGURE 1 | Food waste and key SDGs, including SDG 3, 6, 11, 12, 13, 14, and 15.

such as freshwater and arable land, further exacerbating environmental pressures. At the same time, FW has a significant social dimension. While vast amounts of edible food are discarded, 828 million people worldwide suffer from hunger (FAO 2022). In high-income countries, waste occurs primarily at the retail and consumer levels, whereas in low-income countries, more waste occurs at the production and post-harvest stages due to poor cold chain infrastructure, consumer behavior, and inconsistent supply chain standards (Friedman-Heiman and Miller 2024; Todd and Faour-Klingbeil 2024). Potential solutions include implementing localized supply chains, improving cold chain logistics, and transforming FW into value-added products, offering both environmental benefits and viable business opportunities (Friedman-Heiman and Miller 2024; Narisetty et al. 2022). However, some argue that addressing food distribution and access to ensure that food reaches those in need is just as important as efforts to reduce waste.

FW is a significant global issue with serious environmental impacts, arising throughout the entire food chain, from initial production to final consumption (Nicastro and Carillo 2021; Scherhaufer et al. 2018). Households, as the end consumers, play a central role in generating FW (den Boer et al. 2023; Heidig et al. 2025; Kandemir et al. 2020; Nunkoo et al. 2021). In households, FW generation occurs due to inefficient shopping planning, improper food storage, and inadequate food processing (Fan et al. 2022; Ilakovac et al. 2020; Veselá et al. 2023). This waste represents not only an environmental burden but also a waste of economically valuable resources (Tonini et al. 2018). Therefore, optimizing the management of FW presents opportunities not only to reduce environmental harm but also to utilize the waste as a resource in alignment with the principles of a circular economy (CE) (Bhatia et al. 2023). For example, FW can be repurposed for energy production, including biogas generation (Bulmau et al. 2019; Florkowski et al. 2018). However, the key to utilizing FW as a resource is the presence of well-designed, consumer-friendly waste sorting systems that ensure the waste is in a suitable condition for further processing (Bai et al. 2022; Leeabai et al. 2022).

The greatest potential for the collection and sorting of FW from households is seen in highly urbanized areas, such as housing estates, where there is no possibility to compost FW in gardens or use it in other ways at home (Kormaňáková et al. 2021; Pocol et al. 2020). Although there are numerous studies on the proportion of FW in mixed municipal waste (MMW) (Edwards et al. 2018), research focusing on the specific conditions of residential areas and regional differences remains underexplored, with studies reporting significant variation in the proportion of FW. For example, Edwards et al. (2018) found that FW in Australian households accounted for 35%–45% of the total volume of MMW. These differences highlight the need for regionally specific approaches to waste management (WM) that reflect local conditions.

The issue of FW is closely linked to the achievement of several Sustainable Development Goals (SDGs) defined within the 2030 Agenda (Elsheekh et al. 2021; Grosso and Falasconi 2018; Halkos and Aslanidis 2024; Roy et al. 2023). Specifically, they influence several key goals (Figure 1), including SDG 3 (Good Health and Well-being) (Fernandez 2020), SDG 6 (Clean Water and Sanitation) (Kookana et al. 2020), SDG 11 (Sustainable Cities and Communities) (de Visser-Amundson 2022; Kutty et al. 2020; Nicholls et al. 2020), SDG 12 (Responsible Consumption and Production) (Ardra and Barua 2022; Arora and Mishra 2023; Carlsen 2021), SDG 13 (Climate Action) (Ardra and Barua 2022; Franco et al. 2020; Leal Filho et al. 2022), SDG 14 (Life Below Water) (Molony et al. 2022; Palomino 2020; Prokic et al. 2022), and SDG 15 (Life on Land) (Chakrabarty and Das 2020).

Reducing FW and implementing effective sorting systems is a critical step toward achieving these goals and transitioning to a more sustainable WM, as well as building a more resilient world for future generations (Puntillo 2023; Roy et al. 2023). This paper addresses critical issues related to achieving sustainable development (SD) by proposing strategies to reduce FW and improve waste sorting systems in urban areas, thereby directly contributing to the achievement of several SDGs. We highlight strategies that can be applied to support the goal of halving FW by 2030, including developing advanced infrastructure for sorting, introducing economic incentives for waste reduction, and considering data-driven technologies, such as artificial intelligence (AI) for future waste monitoring (Al-Raeei 2024; Fang et al. 2023; Olawade et al. 2024). Case studies from cities such as Paris, Milan, and Tokyo show that localized policies, including mandatory sorting programs and public–private partnerships, have successfully reduced FW while supporting the SDGs (Manea et al. 2024; Mourad 2022; Okayama et al. 2021; Okayama and Watanabe 2024; Redlingshöfer 2023). These examples suggest that scaling up these policies globally, along with further research and forecasting on the effectiveness of such initiatives, will be essential to achieving the 2030 FW reduction targets.

The aim of our study is to quantify the actual amount of FW produced within MMWs in residential estates (defined as multi-family buildings or apartment complexes that are typical of urban areas and often lack private gardens for composting) and to identify its structure in detail over different seasonal periods. The research is unique because it focuses on the specific conditions of housing estates, where options for the management of FW, such as composting, are significantly limited. Another focus of the research is to uncover the motivations and potential barriers for consumers to collect and sort FW, in conjunction with the perspectives and capabilities of municipalities. By integrating knowledge from multiple disciplines, including WM, environmental science, sociology, and economics, this research advances the understanding of how to manage FW in urban environments. This study specifically addresses gaps in the existing literature by investigating the seasonal variability in FW production and consumer behavior in urban settings, areas that have been largely underexplored in previous research. The research uses a variety of methods to assess the potential for FW collection in residential areas, providing data critical to making decisions about effective waste sorting and collection strategies. The findings will provide specific recommendations for policymaking and the implementation of waste sorting systems in urban areas, contributing to the transition to a CE in WM and the achievement of the SDGs.

2 | Literature Review

2.1 | Introduction to FW Management

In the face of growing environmental challenges, the need for research focused on optimizing food management strategies has become more urgent. Such research is essential to ensure the efficiency of the overall life cycle assessment (LCA) and to evaluate policies aimed at minimizing the impact of FW. Previous studies have highlighted the value of LCA in comparing the environmental sustainability of current WM strategies. In addition, LCA can be used to assess the environmental impacts of FW management technologies and policies, as well as to identify the optimal combinations of these strategies that maximize environmental benefits (Omolayo et al. 2021). However, FW management is a complex issue influenced by a wide range of internal and external factors. For urban WM, FW separation plays a critical role in reducing GHG emissions and saving energy (Subramanian et al. 2021). According to Kavitha et al. (2020), FW consists of organic matter that is intended for consumption but is ultimately discarded, wasted, decomposed, or spoiled. This FW, whether avoidable or unavoidable, represents the final stage of the food life cycle (Notarnicola et al. 2017).

2.2 | Consumer Behavior and Participation in FW Sorting

Since the highest levels of FW occur in consumer households (Fan et al. 2022; Ilakovac et al. 2020; Katt and Meixner 2020; Zhang et al. 2020), where FW is disposed of in MMW, it is important to motivate consumers to sort their waste so that it can be subsequently processed for energy production, biogas generation, or other resource recovery applications. The concept of CE plays a central role here, emphasizing the recovery and recycling of organic waste (OW), including FW, into valuable resources. In a CE framework, FW is viewed not as waste but as a potential resource that can contribute to the sustainability of urban systems by reducing dependence on virgin materials and minimizing environmental impacts (Bhatia et al. 2023).

Current studies indicate that when consumers are appropriately motivated and informed (Florkowski et al. 2018), they are largely willing to participate in FW sorting. The main motivators for them include personal belief, environmental values, and social pressure (Bai et al. 2022; Czajkowski et al. 2017; Stancu et al. 2016). However, there are also significant barriers that hinder effective FW sorting. Some consumers are willing to sort FW, but do not have a place to do so because separate FW collection is not implemented in their area of residence (Jamal et al. 2019). Expanding the WM infrastructure thus becomes a necessary part of the transition to a circular model for food management (Oehman et al. 2022; Shahid and Hittinger 2021). It is essential to ensure an adequate number of containers for sorted waste and locations for FW collection that are easily accessible to consumers (Bai et al. 2022). Another significant barrier is that consumers often lack sufficient knowledge about how to properly sort FW or are unaware of the impact that waste sorting has on the environment (Bai et al. 2022; Wang et al. 2020). This lack of awareness can subsequently lead to a reluctance to engage in waste sorting or improper handling of waste. Overcoming these obstacles and increasing consumer awareness and motivation requires coordination and support from policymakers (Tian and Zheng 2022). They should create conditions for effective FW sorting that meet the needs of consumers, municipalities, and FW processing entities, ensuring the highest possible level of engagement from these stakeholders (Nunkoo et al. 2021). In this context, it is important not only to deepen research in this area to provide sufficient data for policymaking but also to communicate the findings and insights to the public. This could help raise knowledge about FW and sorting, encourage public engagement, and strengthen political support for measures aimed at promoting a CE (Bulmau et al. 2019; Nainggolan et al. 2019).

2.3 | Urban and Rural Differences in FW Generation

Critical areas where the largest amounts of FW are concentrated and should be prioritized for targeted interventions include highly urbanized regions (Adelodun et al. 2021; Kormaňáková et al. 2021; Lebersorger and Schneider 2011). Consumers in urban areas produce larger amounts of FW compared to rural areas, where there is an opportunity to use FW for animal feed or for composting in private gardens (Adelodun et al. 2021; Kubíčková et al. 2021; Richter and Bokelmann 2017; Vaverková et al. 2020). Individuals living in rural areas or closer to agricultural regions, where they can observe crop growth or engage in their own cultivation, exhibit lower levels of FW. This behavior contrasts with that of residents of urbanized areas, who often do not have direct access to knowledge and understanding of the work and effort involved in food production (Tokareva 2014). Given these facts, it is appropriate to focus on housing units without gardens (such as apartment complexes), where there is the greatest potential for sorting FW from households (Pocol et al. 2020).

2.4 | Estimating and Analyzing FW

From previous studies (Dou and Toth 2021), it is evident that the most reliable method for measuring the actual amount of FW in MMW and uncovering its potential for further processing or reduction is to conduct a MMW analysis (Elimelech et al. 2018; Fan et al. 2023). This is because consumer estimates obtained through surveys or diary studies tend to be significantly distorted (van der Werf et al. 2020). Herath and Felfel (2016) point out that while interest in this issue is increasing, there is still a lack of sufficient empirical research, likely due to the high costs associated with collecting objective data (Grainger et al. 2018). Most existing studies, with a few exceptions (Adelodun et al. 2021; García-Herrero et al. 2019; Werf et al. 2020), also overlook the crucial aspect of seasonal variability in FW, which is essential for designing effective reduction strategies. This waste varies significantly throughout the year in both volume and structure. Foods with a short shelf life, such as fresh fruits, vegetables, baked goods, dairy products, meat, and fish, are particularly susceptible to changes (Caldeira 2019; den Boer et al. 2023; Parizeau et al. 2021; Pinotti 2020). In addition to these categories, households often dispose of homemade prepared meals (Kubíčková et al. 2021; Silvennoinen et al. 2014). In contrast, meat is generally the least wasted food item (Hazuchová et al. 2020). The results of a seasonal analysis can serve two purposes: (i) informing reduction strategies that focus on minimizing the generation of FW at its source, and (ii) improving alternative methods of managing FW, such as composting or biogas production. These approaches require tailored strategies depending on the seasonal variations and composition of FW, providing valuable insights to better understand FW dynamics and improve sustainability efforts.

2.5 | Linking FW Management to the SDGs

The lack of relevant data on the amount of FW produced by households prompted the authors of the article to conduct an extensive survey of Czech households, with the following objectives: (i) assess the structure and quantity of FW produced by households in residential areas, (ii) identify factors influencing the quantity and composition of FW in urban areas, (iii) evaluate the motivations and barriers for consumers to participate in the FW sorting process, (iv) analyze the potential benefits of sorting FW for the reduction of environmental impacts and the efficient use of resources.

The research is primarily related to SDG 12, which focuses on sustainable consumption and production. Specifically, this study addresses reducing FW and the optimizing of food management, contributing to Target 12.3: "By 2030, halve per capita global FW at the retailer and consumer levels." This goal is part of a broader SD agenda aimed at minimizing the negative impact of human activities on the environment and improving the quality of life in line with sustainability principles (Figure 2a).

The research also relates to SDG 11, which focuses on sustainable cities and communities. The authors address the issue of FW in urbanized areas, particularly in residential settlements. Improving food management and reducing FW in these urban communities contributes to the creation of more sustainable and resilient cities, which can better utilize their resources and minimize negative environmental impacts. Such an approach aligns with Target 11.6 of the SDGs, which aims to "improve the overall quality of life in cities, including safety, sustainability, and resilience to risks, by 2030" (Figure 2b).

An innovative approach to FW is presented by focusing on the specific conditions of the residential environment in the Czech Republic (CR), where effective disposal options are significantly limited. The emphasis on the SDGs, in particular SDG 12.3, underlines the global relevance of the project, as it aims not only to reduce FW but also to optimize food management. In this way, the research contributes to global efforts to improve the efficiency of food systems and provides concrete recommendations for policy makers and local communities, with the potential to have a significant impact on environmental protection and quality of life. By addressing the specific challenges faced by urban populations, it provides new ways to effectively implement the CE and ensure sustainable WM, a crucial step towards achieving sustainability in urban areas.

3 | Material and Methods

This study employs a mixed-methods approach, combining quantitative and qualitative data collection to provide a comprehensive understanding of FW management in urban housing estates. The first method involves the analysis of MMW, where waste samples are manually collected and sorted, allowing a detailed assessment of the types and quantities of FW produced by households. This method was repeated in different seasons to capture variations in MSW production. Given the complexity of MMW composition, a direct seasonal sampling approach was chosen to ensure greater accuracy. Analyzing waste composition across all four seasons over 3 years provided a robust empirical assessment while remaining logistically feasible. This method offers a more precise understanding of waste generation patterns than extrapolated seasonal trend models, which may not fully capture the heterogeneity of MMW. The second

FIGURE 2 | (a) Connection of the research to SDG 12, focused on reducing FW and promoting sustainable consumption. (b) SDG 11, supporting sustainable cities through improved FW management in urban areas.

method involves collecting primary data from municipalities using an online survey to assess their willingness and strategies for implementing FW sorting systems. Finally, the third method involves a consumer survey to explore motivations, preferences, and barriers to sorting FW, which helps to identify factors influencing consumer behavior. By combining these methods, the study provides a holistic view of the current state of FW management, highlighting both the waste characteristics and the attitudes of key stakeholders involved in the process.

3.1 | Analysis of Mixed Municipal Waste

FW is generally defined differently across studies and organizations, depending on where the food is in the supply chain and whether it includes inedible or necessary waste (Heidig et al. 2025; Marouli 2024; Patel et al. 2024). FW refers to food intended for human consumption that is either discarded, redirected for animal feed, or disposed of, including both edible and inedible parts (Dhir et al. 2020). It can be classified into three types: (a) avoidable waste, which was once edible but is no longer fit for consumption; (b) unavoidable waste, such as eggshells; and (c) potentially avoidable waste, like potato skins. Scholars note that these categories may vary across cultural contexts. While some use “food loss” and “food waste” interchangeably, others distinguish food loss as occurring earlier in the supply chain and FW at the end. For this study, FW is specifically defined as the disposal of edible parts of food that are avoidable, that is, food that is still fit for consumption but is discarded. This definition excludes inedible components such as peels, bones, and other necessary waste, which are often considered unavoidable waste. The study focuses on both plant-based and animal-based kitchen waste, as well as beverage leftovers, to understand the composition of FW in urban residential settings. A detailed composition of the FW analyzed in this study, including specific food categories and examples, is presented in Table 1.

Data on the volume of FW were obtained through the analysis of MMW, conducted over 3 years, from the summer of 2019 to the spring of 2022, with assessments occurring every quarter. The composition analysis of MMW was carried out in urban housing estates, specifically in apartment buildings without gardens. Households in these areas do not have the means to utilize FW on-site, and FW is not sorted separately. Overall, MMW from 300 households was analyzed, with three different locations (housing estates) selected, as highlighted in Figure 3. These locations were situated in the city of Brno, specifically in the districts of Lesná, Jundrov, and Nový Lískovec. The selection of these areas was intended to ensure a representative sample by covering different collection zones across the city. This approach helped reduce potential measurement errors and capture variations in FW generation. Waste was collected and analyzed from approximately 100 households per week at each location.

Based on secondary data regarding the permanent residence records of individuals in the analyzed collection routes, which we obtained from the municipal office, we were able to calculate the amount of waste per capita (kg/per capita).

The analysis of MMW was conducted separately for each complex. The composition of MMW was determined by analyzing a subsample of waste, which weighed approximately 200 kg and

TABLE 1 | Structure of food waste.

Food category	Specific foods
Kitchen waste of vegetable origin	
Fruits and vegetables	Potatoes and other vegetables, fruits and mushrooms for consumption or in the state of decomposition
Bakery products and their leftovers	Bread, buns, baguettes, cakes, pies and other baked and confectionery products, including their leftovers
Packaged ready meals of plant origin	Ready meals (e.g., cooked vegetables, meatless soups) intended for immediate consumption, including packaging (food boxes)
Packaged foods of plant origin, including packaging	Packaged (intact) food products: flour, sugar, legumes (uncooked), coffee, tea, cocoa, dried fruits, yeast, uncooked pasta, compotes, pickled vegetables, oil, vinegar, purées, dressings, honey and salt, all including packaging
Ready meals of plant origin without packaging	Prepared (cooked) meals (e.g., cooked vegetables) intended for immediate consumption
Foods of plant origin without packaging	Food products completely or mostly without packaging, cereal products, sugar, legumes (uncooked), coffee, cocoa tea, dried fruits, yeast, pasta in the dry state (except bread), honey, and salt
Kitchen waste of animal origin	
Ready meals of animal origin, including packaging	Ready meals (cooked) intended for immediate consumption, including packaging (food boxes)
Packaged foods of animal origin, including packaging	Packaged (intact) food products from animal tissues (e.g., sausages), all including packaging
Packed meat and eggs	Raw meat (including fish and seafood), raw eggs, all including packaging
Packaged dairy products	Cheese, yoghurt and other dairy products, all including packaging
Ready meals of animal origin without packaging	Ready meals (cooked) intended for immediate consumption, completely or mostly without packaging
Foods of animal origin without packaging	Food products from animal tissues (e.g., sausages), completely or mostly without packaging
Meat and eggs without packaging	Raw meat (including fish and seafood), raw eggs, completely or mostly without packaging
Unpacked dairy products	Cheese and other dairy products, completely or mostly without packaging
Leftover drinks	
Leftover drinks	Leftovers non-alcoholic and alcoholic beverages (weight without packaging—weight of packaging is deducted in the final balance)

was collected from the gathered waste using the quartering method. This method involves dividing the waste sample into four equal fractions, discarding two opposite fractions, and then mixing the remaining parts before dividing them again into four equal fractions. This process is repeated until a representative sample weighing approximately 200 kg is obtained. This sample is then subjected to detailed examination using sieve analysis and manual sorting into pre-defined material groups (see below). For the sieve analysis, screens with hole sizes of approximately 40×40 mm were used. The fractions that passed through the sieve were further divided into FW and other materials (the detailed structure of sorting the individual components of waste was not adhered to for the undersized fraction). Subsequently, the actual amount of FW in the given location was recalculated from the subsample.

The collection and analysis of MMW were conducted in each season (spring, summer, autumn, winter) to assess the seasonality of FW production. The choice of this period corresponds to the changes in the basic characteristics of waste, such as variations between heating and non-heating periods, changes during the summer holiday season, and shifts in vegetation conditions.

Due to the limited number of measurements per season (nine values), statistical tests such as ANOVA were not applicable; therefore, seasonal variations were assessed using descriptive

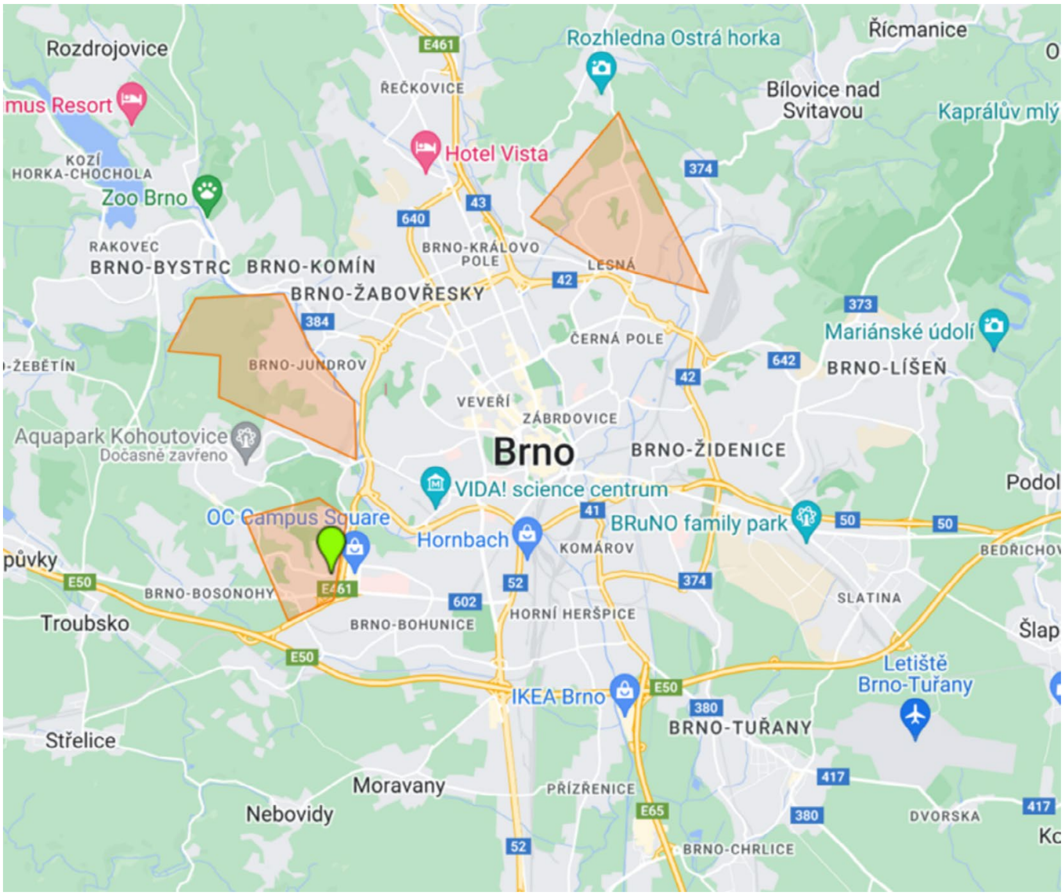

FIGURE 3 | Analyzed locations with residential complexes.

statistics, including arithmetic and geometric means for waste composition data, percentages for category distribution, and graphical visualization.

3.2 | Research on Municipalities' Expectations

Another dataset processed in this study comprises primary data obtained from representatives of municipalities with urban housing estates to determine their preferences and willingness regarding FW sorting within their communities. The proposed research instrument in the form of a questionnaire survey was initially tested in a pilot phase in which five representatives of municipalities participated and suggested adjustments to the questionnaire. The questionnaire was piloted in 2023, 2 months before the start of the final data collection. Based on the feedback received during the pilot phase, the questionnaire was modified. In particular, response options were added to the closed questions that were considered relevant by the municipal representatives. The final data collection was conducted online using the Computer-Assisted Web Interviewing (CAWI) method in 2023. The collected data include responses from 59 respondents, representing 59 municipalities in the CR. The respondents of the questionnaire are municipal representatives, namely mayors or vice-mayors. The selection criterion for approaching the municipality for research was the presence of a housing estate in the municipality. All regions of the CR were included in the survey. Once the selection criterion was met, representatives of the municipalities in each region were selected using a random sampling method. Notably, 97% of the data pertain to municipalities with populations exceeding 5000 residents. The most represented regions are the Central Bohemian Region (12%), the Moravian-Silesian Region (12%), the South Moravian Region (10%), the Prague Region (10%), and the Pardubice Region (9%). The representation of respondents in other regions is below 7%.

The questionnaire mainly investigated the willingness of municipal representatives to implement FW sorting, the motivations and barriers associated with it, and the preferred aspects of implementing FW collection (collection container, collection point, etc.). Subsequently, respondents were asked about their preferred form of communication with citizens based on their previous experience. The obtained data were processed in IBM SPSS Statistics and Power BI software using descriptive statistical methods.

3.3 | Research on Consumer Preferences

The third research instrument applied to assess consumer preferences. A consumer questionnaire survey investigated how often consumers disposed of FW and how they disposed of it. The following food categories are considered in the questionnaire: Pastries, Fruit and Vegetables as whole, Fruit and Vegetables as cuttings, Dairy products, Meat and Eggs, and Prepared meals. Regarding FW disposal, respondents were offered the following options in the questionnaire: MMW, Home composter, Biological waste, Animal feeding, and Toilet or sink. The questionnaire also revealed consumers' willingness to participate in a FW collection and sorting scheme. It identified consumers' preferred FW collection containers and preferred communication about the correct way of FW sorting. The questionnaire survey was conducted in the last quarter of 2022 using the CAWI method, targeting consumers living in housing estates in the CR. The data collection was conducted by a research agency with a base of respondents living throughout the CR. Recruitment began with a filter question asking whether the respondent lives in a housing estate. If this criterion was met, the respondent began to fill in the given questionnaire. The research sample included 1332 respondents. To ensure the representativeness of the data within the broader population, seven quota criteria were utilized: sex, age, educational attainment level, activity status, household disposable income, number of household members, and number of children in the household. As the quotas were gradually met, data collection focused on sharing the questionnaire with the target groups of respondents who were missing (according to the quotas set). Recruitment was thus guided. The fulfillment of quotas when selecting respondents is documented in the following table (Table 2), which compares the structure of the questionnaire respondents with the actual structure of the population living in apartments, according to the EU Statistics on Income and Living Conditions survey conducted in 2022 (Eurostat 2023).

The data collected were processed using IBM SPSS Statistics software, employing descriptive statistical methods (proportions and frequencies: percentages—category distribution, relative frequencies—occurrence ratios and average ratings). Dependencies between variables were verified using the χ^2 test at a significance level of 5%. All data sets are compared and provide a unique perspective that integrates real data on the quantity and structure of FW from households with the preferences, motivations, and willingness of both consumers and municipal representatives to engage in the system for collecting sorted FW. The visualizations of the collected data were created using Power BI software.

4 | Results

Based on the data obtained from the waste analyses (a total of 7.3 tons analyzed), it can be stated that, on average, 48.59% of the MMW in urban residential areas consists of OW, with 19.11% being classified as avoidable FW, indicating a significant level of wastefulness. Figure 4 illustrates seasonal variations in FW composition. The highest proportion of avoidable FW in the sample is observed in summer, accounting for 21.58% of the MMW. In the following seasons, avoidable FW gradually declines in autumn and winter, reaching its lowest share in spring. The seasonal differences in FW generation can be attributed to multiple factors. The elevated proportion of avoidable FW in summer is likely driven by increased consumption of perishable foods with shorter shelf lives, higher ambient temperatures accelerating spoilage, seasonal changes in household routines, such as vacations, which may disrupt food management practices, and the increased availability of fresh produce during this period. In contrast, during colder months, lower temperatures naturally extend food freshness, and consumption patterns

TABLE 2 | Structure of respondents.

	Questionnaire Sample ($N=1332$)	Czech population living in apartments according to EU statistics on income and living conditions
Sex		
Male	48%	47%
Female	52%	53%
Age (years)		
18–24	9%	8%
25–34	17%	18%
35–44	17%	19%
45–54	19%	18%
55–64	15%	13%
65+	23%	24%
Educational attainment level		
Primary	2%	0%
Secondary	67%	76%
Tertiary	31%	24%
Activity status		
Employees	57%	50%
Self-employed persons	8%	8%
Old age pensioners	24%	25%
Unemployed persons	2%	3%
Students	4%	7%
Maternal and parental leave	3%	5%
Other	1%	2%
Household disposable income		
Less than 1250 EUR	25%	28%
1251–1875 EUR	30%	24%
1876–2500 EUR	24%	20%
2501–3125 EUR	12%	13%
More than 3125 EUR	9%	15%

(Continues)

TABLE 2 | (Continued)

	Questionnaire Sample (*N* = 1332)	Czech population living in apartments according to EU statistics on income and living conditions
Number of household members		
1	19%	23%
2	39%	35%
3	22%	20%
4	17%	17%
5 and more	3%	5%
Number of children in the household		
0	68%	60%
1	19%	21%
2	12%	16%
3 and more	1%	3%

Source: Own questionnaire, $n = 1332$; Eurostat (2023).

shift towards preserved or non-perishable foods, contributing to lower FW generation.

Overall, we will be interested not only in the structure of the analyzed waste but also in its total quantity during the different seasons. Based on the total amount of collected waste from each location and the total number of people producing the waste, the total amount of MMW and avoidable FW per capita is calculated according to the analyzed sample. This indicates how much food is actually being wasted. The volume of waste production and FW per capita by season can be seen in Figure 5.

Overall, a consumer in a residential area produces 242.18 kg of MMW per year, with 47.41 kg of this being avoidable FW. For the purpose of evaluating the potential for sorting FW, a significant portion of the waste also comes from unavoidable waste, such as peels, shells, bones, etc. This accounts for an average of 17.58% of MMW. Most often, this consists of plant-based unavoidable waste, as shown in Figure 5.

The highest rate of MMW production is observed during the summer, at 65.59 kg per capita. In residential areas, there has been a significant decrease in waste production during the autumn season, dropping to 55.08 kg per capita, likely also due to COVID-19-related restrictions that temporarily altered consumption and waste generation patterns. In contrast, during winter, people in these areas produce 60.43 kg per capita, while in spring, the amount is 61.07 kg per capita.

Focusing on the amount of avoidable FW, it can be stated that over the three observed years, an average of 47.41 kg per capita per year is wasted in residential areas. The individual seasons do not show significant deviations and oscillate around 11 kg per capita, with the exception of summer, where the seasonal influence is evident, resulting in an average increase in waste to 14.29 kg per capita. People in these urbanized areas waste the least food in spring, averaging 9.94 kg per capita.

It is therefore important to further focus on the structure of discarded food in the examined samples of MMW (a total of 36 samples, with an average sub-sample weight of 204.2 kg) to identify the causes of differing amounts of waste across the individual seasons. We therefore focused on typical categories of food, such as fruits and vegetables, bread, meat and eggs, dairy products, and prepared meals. Figure 6 illustrates the development of the waste structure according to these categories.

At first glance, it is evident that the highest amount of FW is generated in the fruits and vegetables category, while the lowest occurs in meat and eggs. The increase in FW during the summer is primarily driven by higher waste of fruits and vegetables, likely due to their perishability and seasonal

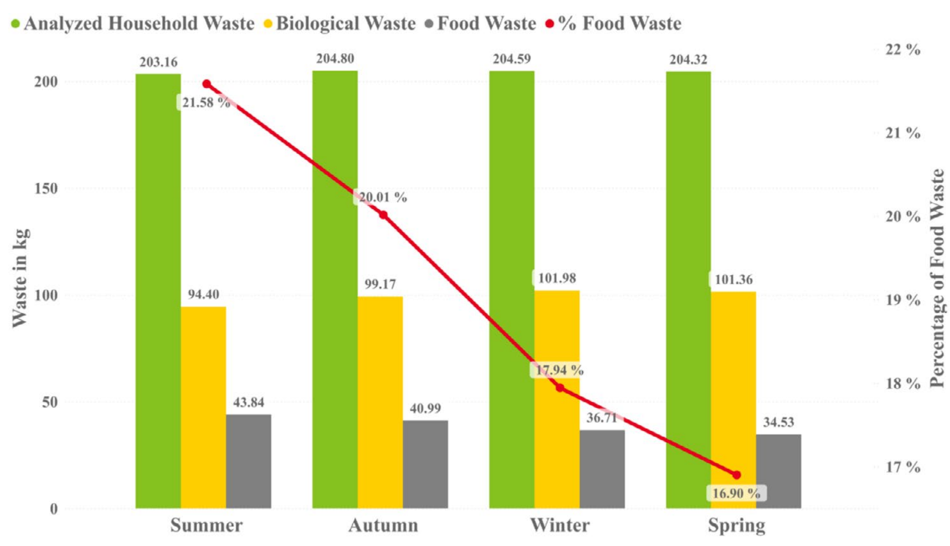

FIGURE 4 | Structure of FW. *Source:* Waste analysis.

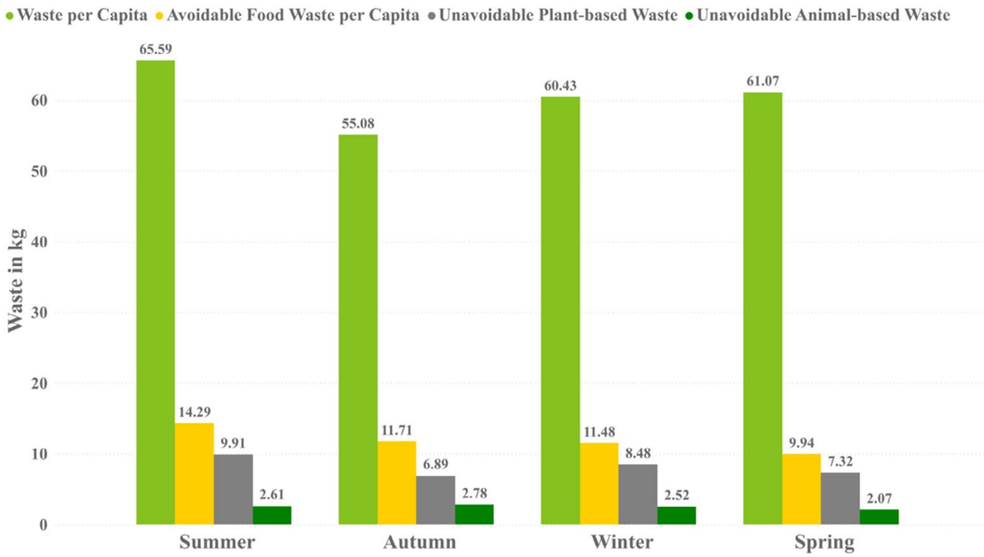

FIGURE 5 | The amount of MMW, avoidable, and unavoidable FW per capita (kg). *Source:* Waste analysis.

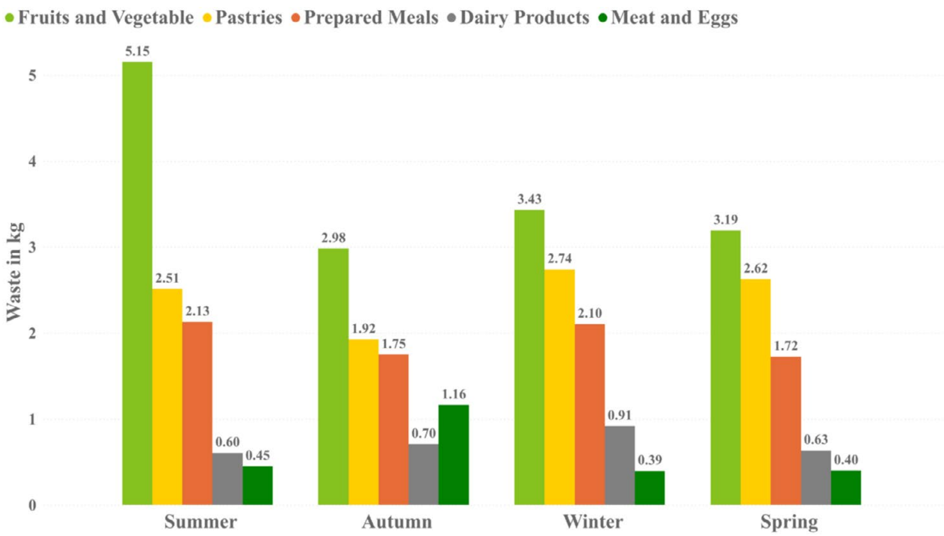

FIGURE 6 | Structure of wasted food in the analyzed waste per capita (kg). *Source:* Waste analysis.

availability. While in other seasons, the amount of discarded fruits and vegetables in the analyzed waste is around 3 kg, in the summer, it reaches an average of 5.15 kg. In the autumn, we can observe an increase in the amount of discarded meat. While in other seasons the amount of discarded meat and eggs is around 0.4 kg, in the autumn, this category becomes more prominent in the waste structure, averaging 1.16 kg. This may be related to seasonal dietary shifts, including higher consumption of meat-based dishes and increased slaughterhouse activity. In winter, we can observe a slight increase in the category of dairy products, with an average of 0.91 kg of these foods in the waste, compared to the usual values of around 0.6 kg. This trend could be linked to higher purchases of dairy products during colder months. In spring, the amount of wasted pastries increases, reaching an average weight of 2.74 kg in the samples for this season. This reflects seasonal consumption patterns, as the higher prices of fruits and vegetables during this period may lead to increased consumption of alternative food categories.

The consumer questionnaire survey (Figure 7) shows that consumers most frequently throw away unavoidable waste, specifically fruit and vegetable cuttings (F&V cuttings), with the majority of respondents indicating they discard this type of waste several times per week: 36% of respondents reported discarding 1–2 times per week, and 33% reported 3–6 times per week. Among avoidable FW categories, pastries are discarded most frequently, with 22% of respondents reporting disposal 1–2 times per week, 29% discarding them 1–3 times per month, and 23% once per month. Whole pieces of fruits and vegetables (F&V whole) follow, with the most common responses being 1–3 times per month (30%) and once per month (30%). However, due to the lower weight of discarded pastries compared to fruits and vegetables, the total mass of wasted fruits and vegetables remains higher in m analyses. In contrast, dairy products and prepared meals are discarded less frequently, with the majority of respondents (52% and 48%, respectively) indicating disposal only 1–2 times per year. Meat and eggs represent the least frequently discarded category, with 54% of respondents reporting disposal at this frequency.

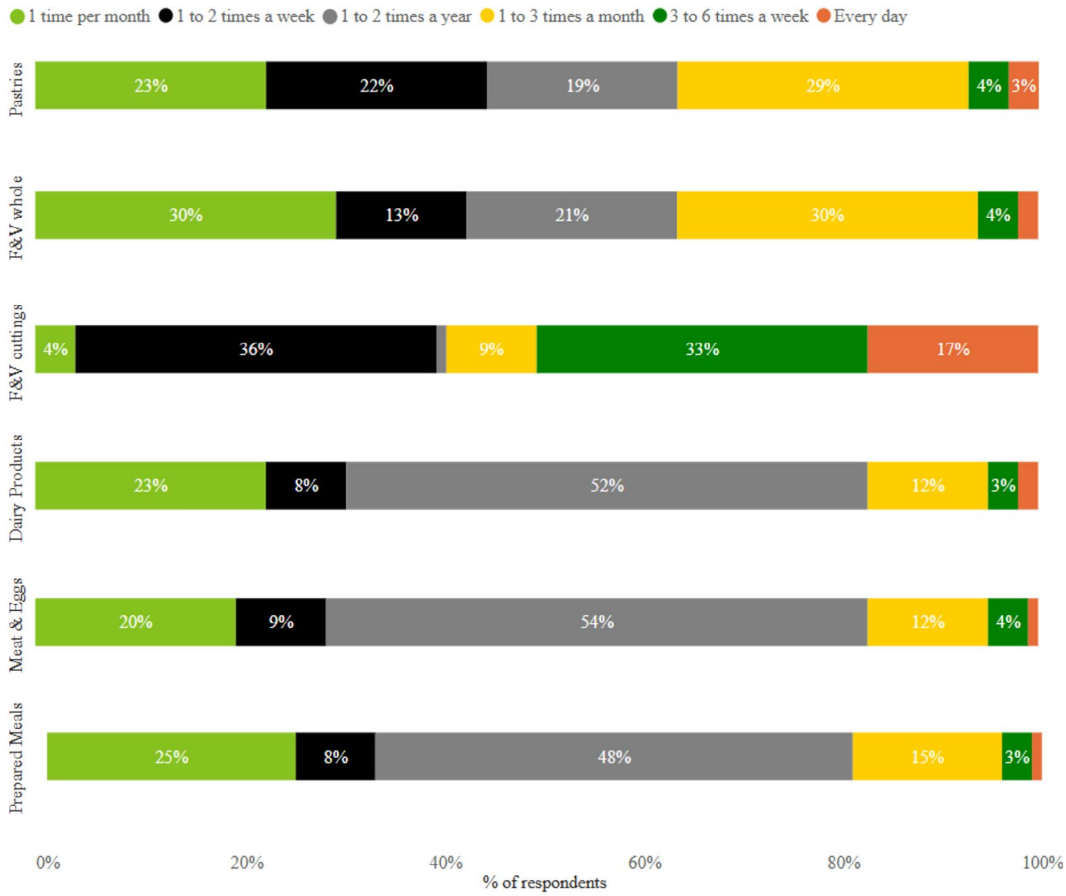

FIGURE 7 | Frequency of FW disposal in households. *Source:* own consumer questionnaire, $n = 1332$.

The questionnaire also sought to ascertain how consumers manage FW and the disposal methods they utilize for various foodstuffs. It is evident that food most commonly ends up in MMW (Figure 8). For pastries (e.g., bread), a significant portion (44%) is also fed to animals as leftovers. Only a small percentage of respondents use a home composter (9% for Fruit and Vegetables and less than 5% in other FW categories). Twenty-two percent of respondents report that they dispose of fruits and vegetables in the biological waste (OW) Dairy products (e.g., milk, yoghurt) are most often disposed of in the MMW, but 37% of consumers pour them down the sink or toilet. The disposal of meat, eggs, and prepared meals is predominantly via MMW.

Consumers demonstrated their willingness to sort waste. They are accustomed to separating waste into categories such as plastics, paper, and glass; however, FW is essentially not sorted at all. In the previous Figure 8, FW disposal in MSW dominates in all categories. A small proportion of respondents report that they compost FW at home. For example, 9% of respondents reported composting fruit and vegetables. For other types of FW, the use of composters for waste disposal is lowers (Figure 8). In the following question, 46% of those respondents who are willing to sort FW stated that they do not have access to sorting options. The willingness to sort is dependent on the age of the respondent (p value from the χ^2 test < 0.001). There is a high willingness to sort waste among the age group of 18–24 years, which decreases with increasing age; however, there is an exception for the group aged 65 and over.

It is desirable to leverage consumers' willingness to sort FW and propose a sorting method that is acceptable to both consumers and municipalities. Both consumers and representatives of municipalities expressed their preferences for operational sorting matters using a rating scale (1 being the least preferred and 7 being the most preferred). Consumers prefer to use biodegradable bags for collecting FW (average rating of 5.1); however, they are not willing to pay for them and would prefer to have them available at the collection point (the average value 5.1) where they usually go to dispose of sorted waste or alternatively for pickup at the municipality office (Figure 9). The second preferred option among consumers is to use their own bag or bucket from home (5.0 in the Figure 9). Another preferred way is to pick up a collection bucket at the municipal office (4.3 in Figure 9). Municipalities only commented on the attributes relevant to them. There is a predominant preference for picking up biodegradable bags at the municipality office rather than at the collection point. Another preferred option from a municipal perspective is to pick up a bucket at the municipality office.

Another closed question in the questionnaire was used to determine consumer preferences regarding the location of FW collection containers. In a Waste Hub with MMW: 49% of respondents prefer this option. In a Waste Hub with Other Sorted Waste: 38% of respondents favor placing FW containers in hubs where other types of sorted waste are collected. Door-to-Door Collection System: 12% of respondents support this collection method. Other: 1% of respondents. Among representatives of

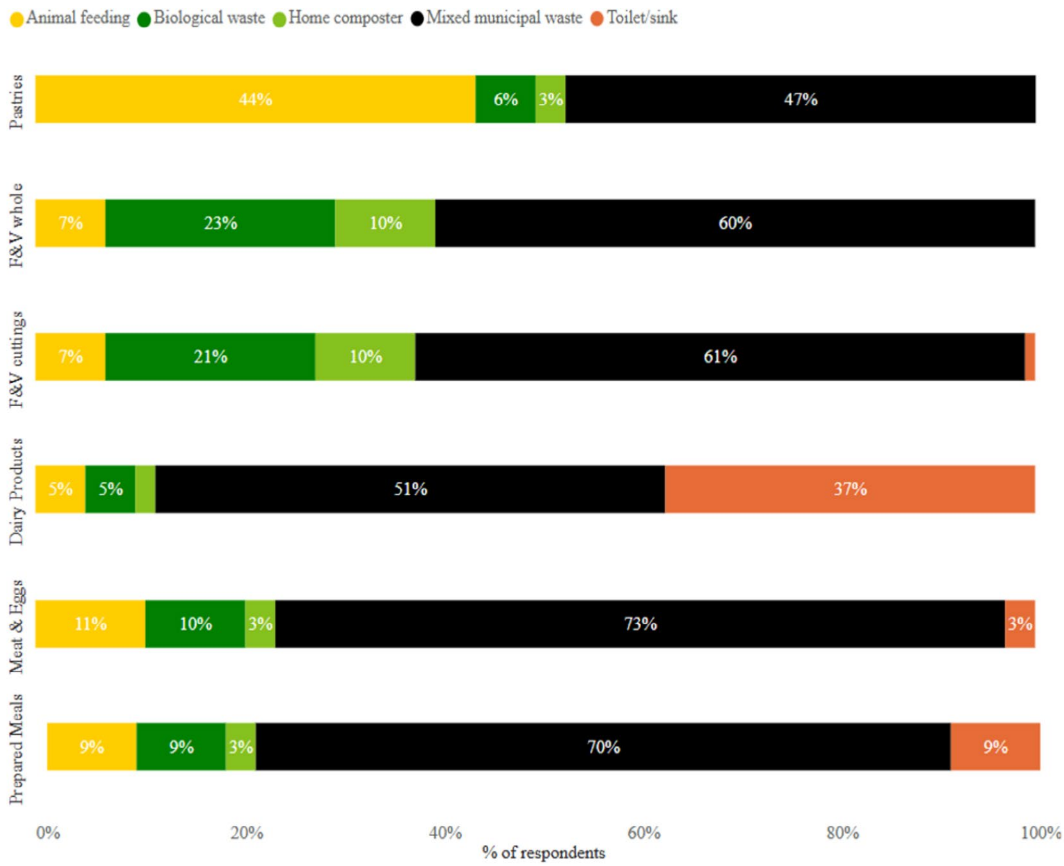

FIGURE 8 | FW disposal. *Source:* own consumer questionnaire, $n = 1332$.

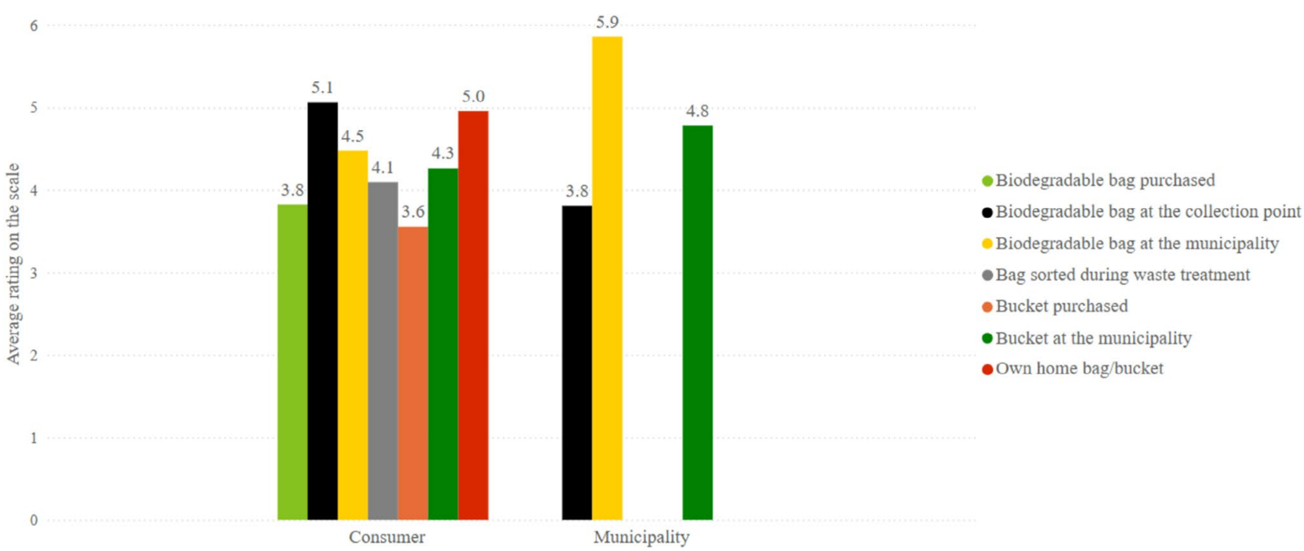

FIGURE 9 | Preference for FW collection containers. *Source:* Own Consumer Questionnaire ($n = 1332$) and Municipality Questionnaire ($n = 59$).

municipalities, no single alternative predominates; preferences for each option are balanced.

To ensure the effective functioning of a sorted waste collection system, it is essential to engage consumers and motivate them to recycle. Consumers assessed their motivations using a rating scale from 1 (the lowest) to 7 (the highest motivation). The strongest motivations identified by consumers are Ensuring an Adequate Number of Containers (average rating of 5.9), Ensuring a Clean Collection Environment (average rating of 5.6), Awareness That Waste Will Be Reused (average rating of 5.5), Improving the Environment (average rating of 5.4), and Reducing Fees for MMW Collection (average rating of 5.4). From the perspective of municipalities, the biggest motivator for implementing a FW collection system is reducing landfill waste in the area of the municipality (4.6) and citizen satisfaction (4.2).

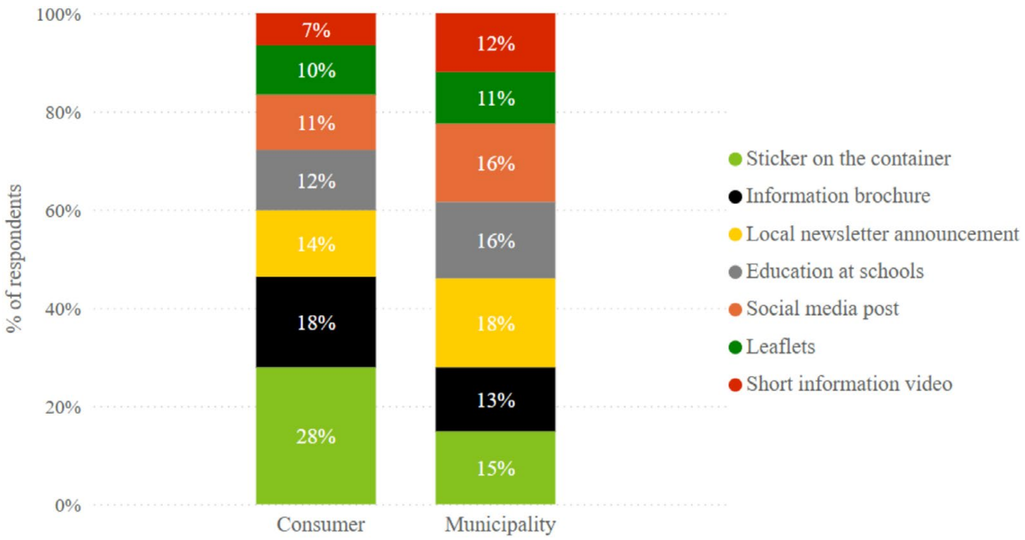

FIGURE 10 | Preferred communication channels by consumers and municipalities. *Source:* Own Consumer Questionnaire ($n=1332$) and Municipality Questionnaire ($n=59$).

Perceived barriers include a lack of containers (5.4), odor (5.2), insects (5.1), rodents (4.8), and the proliferation of harmful microorganisms (4.8). Municipalities see the greatest barrier as the financial burden of sorting FW (4.6) and the difficulty of ensuring a clean collection environment (4.6). Additionally, they are concerned about the poor sorting of waste by citizens (4.5). For this reason, it is essential to emphasize educating citizens and choosing appropriate communication channels (Figure 10).

Consumers would appreciate a sticker directly on the collection container as the most suitable communication tool (stickers account for 28% of all marked communication options). Labels on the container in the form of stickers are also among the more common responses among municipalities. However, municipalities tend to rely most on announcements in the local newsletter, which rank third among consumer preferences. Conversely, communication in the form of short information videos is least appreciated by consumers, and leaflets are also among the least preferred communication methods by municipalities.

Regarding the content of the message, consumers are most interested in operational information—specifically about what should and should not be placed in the collection container, the location of the container, and information about the usability of the waste.

5 | Discussion

5.1 | Key Results

The aim of this study was to analyze the quantity and structure of MMW in Czech residential areas, with a special focus on avoidable FW. The results show that MMW from residential households contains a significant amount of biological waste, including avoidable FW. On average, 47.41 kg of food is wasted per capita per year. Despite the overlap of the data collection period with the COVID-19 pandemic, the structure of FW remained stable across seasons, showing no significant deviations. While temporary shifts in consumer behavior during lockdowns may have influenced total waste generation, they did not alter the seasonal patterns observed in FW composition. This further supports the conclusion that seasonality plays a key role in FW generation, regardless of external disruptions. Our study also highlights the impact of seasonality on waste composition, a factor often overlooked in waste analyses. The highest amount of FW occurs during the summer months, at 14.29 kg per capita (21.8% of MMW), primarily due to the spoilage of perishable foods such as fruits and vegetables. This seasonal variation is consistent with the findings of Adelodun et al. (2024), who observed that summer had the highest FW generation rates, followed by fall, spring, and winter. The similarities between these trends suggest that seasonality is a globally influential factor in FW generation (Adelodun et al. 2021; Kormaňáková et al. 2021). Compared to previous research in the CR, which estimated FW generation at 57 kg per capita using diary surveys (Nováková et al. 2021), our study reports a lower amount (47.41 kg per capita). This difference likely reflects methodological variations, as diary surveys rely on self-reported data, which can lead to overestimation. Additionally, prior studies did not account for seasonal variations, whereas our findings confirm that FW generation fluctuates throughout the year, peaking in summer. These insights emphasize the need for targeted WM strategies that address seasonal trends in FW disposal. Based on these findings, targeted WM policies should focus on reducing food spoilage during peak seasons, especially summer. Reducing FW at the household level requires practical and accessible strategies. Simple consumer actions, such as better meal planning, proper food storage to extend shelf life, and freezing leftovers, can significantly reduce avoidable FW. Raising awareness about expiration labels and promoting the consumption of food close to its expiration date can further minimize waste. Additionally, municipalities and retailers can support FW prevention by offering discounts on near-expiry products and providing clearer guidance on food storage best practices. Implementing these measures could contribute to more effective FW reduction. Adelodun et al. (2024) emphasized the development of intervention strategies to reduce FW and align WM with the United Nations SDG 12.3. Adopting the waste hierarchy principles of "reduce, reuse, and recycle" is critical to effectively minimizing avoidable FW. A combined approach at both individual and systemic levels could further enhance FW reduction efforts and support broader sustainability goals outlined in SDG 12.3.

5.2 | Correlation Between Waste Analysis and Questionnaire Survey

The correlation between the waste analysis and the results of the questionnaire survey reveals consistent patterns in FW behavior, particularly for fruits and vegetables, baked goods, and prepared meals, which are consistent with the findings of Bilska et al. (2019) and Djekic et al. (2019). Fruits and vegetables, the most wasted category (Prelez et al. 2023), are highly perishable due to their moisture content and microbial susceptibility, with seasonal ripening in summer exacerbating waste. Baked goods, often discarded due to staling or mold, have a short shelf life and are often over-purchased as household staples (Dymchenko et al. 2023). Similarly, cooked meals are a significant contributor to waste, often due to over-preparation and improper storage that leads to rapid spoilage (Jain et al. 2023; Chia et al. 2024). These findings underscore the need for targeted interventions to address the waste of perishable and frequently wasted food categories.

5.3 | Environmental Impact of FW

Prevention and reduction of FW can have a significant environmental impact due to GHG emissions (Cattaneo et al. 2021; Xue et al. 2021) and the use of natural resources such as land and water (Read et al. 2020; Diana et al. 2022). Data simulations conducted in the EU and the United Kingdom (UK) have shown that reducing FW by 25%–50% could save 0.5% of agricultural land used in the EU (Philippidis et al. 2019). Preventing FW by 20% in the UK could avoid emissions of 3.2 Mt CO_2 equivalent (equivalent to 2.3 million cars on the roads each year) (Diana et al. 2022). Even a 2% reduction in FW could save 0.48 Mt CO_2 equivalent annually, which is equivalent to 342,000 cars on the roads each year (Slorach et al. 2020). A study in Sweden simulating the minimization of FW found that it could lead to a reduction in GHG emissions of 800–1400 kg CO_2 equivalent per ton (Schott and Andersson 2015). In addition, eliminating FW at the household level can also reduce the water footprint (Kashyap and Agarwal 2020; Marston et al. 2021; Wen and Chen 2023).

5.4 | Challenges in WM Systems

According to respondents, the majority of FW is disposed of as part of MMW, a practice that severely limits its potential for recovery and reuse. This challenge represents a significant barrier to achieving the SDGs, particularly SDG 12, which emphasizes sustainable consumption and production. A notable paradox emerges: while consumers express a willingness to separate and sort FW, nearly half do not have access to adequate infrastructure to facilitate this behavior. This highlights a critical gap in the WM system that must be addressed to effectively support sustainable practices. Previous studies, such as Musicus et al. (2022) and Allison et al. (2024), have highlighted the key role of the availability of collection containers in the process of sorting FW from households. Moreover, the design and accessibility of waste collection containers play a critical role in influencing WM behaviors and recycling rates. Research highlights that convenience, such as curbside collection methods where containers are easily accessible at home, significantly increases user participation in waste sorting (Thalía and Gustavo 2023). Additionally, strategically placed drop-off containers can promote recycling, although they may face challenges such as improper use and management inefficiencies (Trujillo et al. 2024). Technological advancements, including the development of smart containers, further contribute to improved efficiency and user engagement by streamlining waste collection processes (Singh et al. 2023).

5.5 | The Role of Municipalities in Waste Sorting

The lack of a suitable or an appropriate residential collection system that is accepted by consumers, municipalities, and collectors is therefore a major barrier to effective sorting. Without adequate support from municipalities and a significant increase in the availability of containers for OW, sorting remains ineffective (Aschemann-Witzel et al. 2015). Therefore, it is essential for municipalities to invest more in specific practical solutions, such as improving access to FW containers, placing containers closer to residential units, or providing easier ways to obtain biodegradable packaging. This is in line with the study by Allison et al. (2021), where consumers prefer to use biodegradable bags available at the containers for collecting FW, while municipal representatives prefer their collection at the office. However, both parties are opposed to additional costs associated with packaging. It is therefore necessary to strike a balance between controlling the distribution of packaging and ensuring that it is easily available to the public. It can be assumed that the expenditure of the municipalities on these bags would be reflected in a reduction of the waste that ends up in the MMW, which would lead to a reduction in landfill fees.

5.6 | Economic Incentives for Reducing FW

Another way to reduce FW at the household level is through economic incentives implemented through fees, charges, taxes, and subsidies. For example, "Pay as You Throw" (PAYT) is a popular economic incentive implemented worldwide (Diaz-Farina et al. 2023; Ukkonen and Sahimaa 2021). PAYT can be implemented based on the volume, frequency, or weight of waste, using individual or shared containers, or prepaid bags, tags, stickers, or tokens (Romano and Masserini 2023). PAYT is a system based on the "polluter pays" principle (Zhen et al. 2023) and has been implemented in Europe, the United States, Canada, and several countries in Asia (Gradus et al. 2019; Magrini et al. 2020). For example, South Korea has successfully reduced FW at the household level by implementing this system (Cho and Kang 2017). However, the success of the PAYT system can vary from region to region. Studies in European countries have shown that the PAYT system alone has not significantly reduced the overall amount of waste generated in the long term (Bilitewski 2008). This suggests that PAYT systems should be tailored to local contexts, considering demographic, cultural, and economic factors that influence household behavior. For example, regions with high population density might benefit more from shared containers or prepaid bag systems, while rural areas might require alternative solutions to accommodate lower waste collection frequencies.

In such case, the effectiveness of the PAYT system requires additional national or regional policies, including regulatory and information policies, awareness campaigns, tax regulations, and so on. (Morlok et al. 2017; Park 2018). In addition, integrating PAYT systems with digital tools and AI can significantly improve WM efficiency and encourage recycling by creating a more responsive and accountable framework. The use of digital identification systems, such as smart cards or biometric scans, allows for accurate tracking of individual recycling efforts, enabling personalized feedback and rewards that encourage greater participation in recycling programs (Kontogianni et al. 2014). AI technologies further contribute by optimizing waste collection routes and schedules, reducing operational costs and environmental impacts (Alsabt et al. 2024; Faiz et al. 2024; Olawade et al. 2024; Vishnu Vardhan and Vijaya 2024). In addition, predictive modeling can forecast waste generation patterns, allowing municipalities to allocate resources more effectively and manage landfills with greater precision (Faiz et al. 2024).

5.7 | Importance of Education and Communication

The willingness to sort waste is also significantly increased by communication about the further utilization of FW. A study by Qi and Roe (2017) and Rasool et al. (2021) states that informing consumers about landfilling and its negative impacts reduces the amount of FW. In addition to technical and infrastructural solutions, it is essential to focus on education and effective communication regarding FW sorting. Consumers greatly appreciate practical information and clear instructions on where different types of waste belong, particularly in the form of simple visuals directly on the collection containers or in the local newsletter. Surprisingly, informational posts or educational videos are the least preferred option, which may be due to information overload, low engagement with passive content, or skepticism toward generic awareness campaigns. Providing more interactive and hands-on approaches, such as community workshops or gamified educational tools, could enhance consumer engagement and improve the effectiveness of FW reduction efforts (Soma et al. 2020). Educational intervention information was effective in reducing FW by 27.85% among participating households in the study by Xu et al. (2025).

5.8 | Recommendations for Future Research

Despite the findings being focused on urban residential areas and not necessarily reflecting the overall situation in other regions, they provide a significant insight into the handling of FW. While the selected housing estates represent urban environments, they may not fully capture FW generation and sorting behavior in smaller municipalities or rural housing estates, which are rare in the CR. Future research could explore suburban and rural settings, where households have different WM options, such as home composting or livestock feeding, to enhance the generalizability of our findings and inform tailored waste reduction strategies.

In addition, longitudinal studies are needed to monitor the impact of improvements in the collection system and communication campaigns on the level of sorting of FW over time, which would provide valuable data on the sustained effects of these interventions.

To achieve the SDGs and fulfill environmental commitments, an integrated approach is necessary, combining technical measures, economic incentives, and educational campaigns. This requires the essential involvement of all stakeholders—consumers, municipalities, and government—in creating an effective FW sorting system. Policymakers can use the study's findings to support policies that reduce FW, such as promoting biodegradable packaging and improving waste collection infrastructure, especially in residential areas where FW is most prevalent. City planners and waste managers can prioritize accessible FW bins in residential areas and consider economic incentives, such as PAYT systems, to encourage waste reduction at the household level. Our research also highlights the importance of effective communication and education about FW sorting, suggesting that campaigns and infrastructure need to focus on clear, practical guidance for residents to improve sorting behavior. For non-specialists, the study highlights the environmental impact of FW, particularly its contribution to GHG emissions and water consumption. The findings provide clear, actionable insights for reducing waste and promoting sustainable practices at the individual and community levels.

6 | Conclusions

This study confirms that FW accounts for approximately 19.11% of mixed municipal waste, with notable seasonal variations, particularly in the summer months. Fruit and vegetables account for the largest share of avoidable FW, with significant increases in the warmer seasons. While consumers are willing to participate in sorting FW, limited access to effective sorting systems remains a key barrier.

Accessible and efficient FW sorting systems are essential to achieving the SDGs, particularly in reducing FW and minimizing its environmental impact. These systems must consider seasonal variations and be adapted to consumer habits. Ensuring sufficient infrastructure, effective public communication, and consumer education are critical for successful implementation.

We recommend that future policies prioritize improving the infrastructure and efficiency of FW sorting, while taking into account seasonal trends in FW generation. Such measures will go a long way to reducing FW and its environmental impacts and fostering more sustainable urban communities.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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