Journal of Circular Economy (2025) 3:3, 556-581
https://doi.org/10.55845/joce-2025-3365

RESEARCH ARTICLE

Minimizing then closing material cycles: the ignored potential of food waste reduction to transform the urban food metabolism of the Paris metropolitan area

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Received: 13. October 2024 / Accepted: 21. December 2025 / Published: 24. December 2025

Abstract

Food waste constitutes the majority of biowaste in cities. Although its reduction is prioritized on political agendas, its potential to minimize environmental impacts from urban consumption and to limit the scale of closed material loops has been disregarded. This paper aims to quantify food waste at city level and to qualify its minimization potential by developing a method using the urban metabolism framework and a set of granular data sources, taking the Paris metropolitan area (France) as a case study. The findings show that, in 2014, food waste at the level of Paris metropolitan area amounted to 783 kt, that is, 101 kg per capita. They also show that a minimum of 29% of this food waste was subject to reduction policies since this share concerned once edible food wasted by households, the biggest contributing sector. Local authorities should monitor waste composition closely, at least for households and public institutions. A distinction should moreover be made between edible and inedible parts, as the politically desired increase of biowaste collection should be limited to the waste of inedible parts of food, controlled by means of efficient reduction policies for wasted food. This quantification study for the year 2014 can be considered a starting point, or a baseline, for the future assessment of food waste. Reduction targets for food waste announced by the government of cities like Paris can be effectively controlled only when a methodology and appropriate data are available to monitor progress.

Keywords Circular Economy · Urban Sustainability · Biowaste · Material Flow Analysis · Urban Food System · Nutrients · Urban Food Flows · Wasted Food

1. Introduction

Reducing food loss and waste is seen as a promising way both to foster the sustainability of food systems by making them more efficient, less resource intensive and less climate impacting (Kummu et al., 2012; Xue et al., 2024), and to improve food security and nutrition (Garcia-Herrero et al., 2018; Usubiaga et al., 2018). In high-income countries, food waste stems largely from activities at the retail and consumption stages, accounting for 71% of the 131 kg of food waste per capita produced in the 28 EU member states, on average, in 2020 (EUROSTAT, 2022). Given that cities are the main locus of food waste producing activities (NRDC, 2019), they are host not only to large populations, but also to their waste (Hoornweg et al., 2013; UNEP DTU, 2021). Besides other demand-side enablers like diet change (Clark & Tilman, 2017; Tilman & Clark, 2014), food waste reduction is one of the only fields where cities – many of which have committed to voluntary

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reduction targets (*Milan Urban Food Policy Pact*, s. d.) – can act towards mitigating environmental pressure from food systems while achieving urban sustainability. Most food-related life cycle emissions occur outside of cities and their field of action, notably during agricultural production (Goldstein et al., 2017).

In parallel, increasing organic waste treatment and directing nutrients (carbon, nitrogen, and phosphorous) from urban food flows to nearby food production, thereby helping to close nutrient loops and replace chemical fertilizer (Papangelou et al., 2020, Padeyanda et al., 2016; Arosemena Polo et al. 2024), are seen as ways to reduce the environmental impacts of urban food supply (Walker & Beck, 2012) and to implement circular economy strategies in cities (Czernik et al., 2025). Based on circular economy principles, EU policy-makers moreover see urban biowaste undergoing anaerobic digestion as a valuable source of energy (European Commission, 2022). Yet, despite EU law (European Commission, 2018), food waste in the EU, the largest proportion of urban biowaste, still mostly ends up disposed of in landfills or incinerators (Kircher et al., 2023).

Determining relevant strategies to achieve urban sustainability regarding waste, at the level of a city or any geographic area for that matter, requires absolute waste amounts to be considered and the composition of waste to be thoroughly characterized. Defining appropriate methodologies and frameworks for food waste quantification has generated debate in the scientific literature due to ambiguities in the definition of food waste (Teigiserova et al., 2020) and differences in approaches used, including mass flow analysis and waste statistics (Caldeira et al., 2021; Corrado et al., 2019). Efforts have been made at national scale, for instance in Switzerland (Beretta et al., 2013), France (Income Consulting AK2C, 2016), Cyprus (Ioannou et al., 2022), and at the scale of the EU (Caldeira et al., 2019, 2021), followed by mandatory reporting for EU member states since 2022. However, to date the literature has paid scant attention to the quantification of food waste at city level. In a review of the environmental footprint of urban food demand, Goldstein et al. (2017) show that food waste has been addressed only roughly, reduced to biomass and often limited to the organic part of municipal solid waste (MSW). Consequently, food waste not collected as MSW – e.g. liquid food waste, business food waste collected separately, or food waste managed on-site – tends to slip through assessments at territorial scale. Food waste results cannot either be scaled down directly from countries to cities without accounting for city-specific features. These should include the proportion of tourists and commuters in a city's eating population (Mirabella & Allacker, 2021; Stone et al., 2023) and the over-representation of out-of-home consumption and specialized distribution channels (e.g. delis, grocery shops), considering their specific food waste profile (Eriksson et al., 2016; Filimonau et al., 2019; Sundin et al., 2024). At urban scale, the waste management literature has analyzed the recycling of food waste for its potential to reduce urban environmental impacts, generally limited to the household and municipal solid waste part of urban waste (Tonini et al., 2020; Turner et al., 2016; Zeller et al., 2019). Some authors have performed flow analysis of phosphorous (Papangelou et al., 2020) and nitrogen (Esculier et al., 2019; Forkes, 2007; Svirejeva-Hopkins et al., 2011) to study hotspots of nutrient losses and the disruption of nutrient cycles, which are shown to be wastewater and to a lesser extent solid waste treatment. As nutrient flows are unevenly distributed across food categories, using them to inform strategies for urban sustainability requires additional metrics such as those used in this study, including the mass of fresh weight and characterization relevant for minimization. Overall, the literature on urban environmental impacts has paid little attention to the food waste minimization potential, even though the environmental benefits of food waste prevention and recycling have largely been demonstrated (Bernstad Saraiva Schott & Andersson, 2015; Gentil et al., 2011; Salemdeeb et al., 2017). Some authors approach it through concepts like edibility – leaving it up to households to interpret what that means (Moreno et al., 2020; Nicholes et al., 2019; Okayama et al., 2024) –, avoidability – in relation to discarded edible parts normally intended to be eaten by consumers (Leverenz et al., 2019) or when associating it with cosmetic standards that remove fresh fruit and vegetables from the market (Porter et al., 2018). By defining actionability, authors draw on different causes that to varying degrees are hard to manage when it comes to reducing food waste in households (Li et al., 2024). These concepts are applied mostly at the level of individuals and households, and much less so at the level of cities or food systems as a whole (Beretta et al., 2013). The main contribution of this study is to provide a simple and comprehensive approach to characterizing and quantifying food waste, including wasted food, at the level of cities. Wasted food (sometimes called avoidable food waste) is distinguished from inedible parts, as it alone qualifies for waste minimization, which is the waste management option related to the largest environmental benefit (Redlingshöfer et al., 2020). Wasted food could have been eaten had it been handled differently and in time, for example meal leftovers or food beyond expiration date. The terminology of wasted food highlights that above all, our focus lies on food and not waste (Oldfield et al., 2016; Ryen & Babbitt, 2022). In contrast, inedible parts (e.g. vegetable peels, bones, and eggshells), separated in the course of food processing, preparation and consumption, are usually not eaten, although this may depend on the food culture in a given place. As inedible parts are intrinsically part of food, they cannot be avoided – unlike wasted food –, but they can be recycled.

By considering wasted food as avoidable, the act of contributing to food waste minimization is simplified, unambiguous, and independent of any one interpretation. As food gone to waste can thus be seen as a result of the food system's dysfunction and deficiency, the goal can be set to strive for this to be remedied.

A socio-metabolic framework seems well suited to characterizing and quantifying food across all food system sectors, up to it being discarded as waste. It provides a set of theories and a methodological toolbox that can serve to analyze the material dimension of a society's functioning and related knowledge about the actors, institutions, policies and techniques driving and shaping the so-called social metabolism (Fischer-Kowalski & Weisz, 1999; Weisz et al., 2015), or the urban metabolism in the context of cities (Barles, 2009; Weisz & Steinberger, 2010). Urban food flows have been increasingly researched in urban metabolism studies to understand their role in urban sustainability and to inform local policy-makers on the biophysical dimension of food production, distribution, consumption and waste (Guibrunet et al., 2024; Guibrunet & Sánchez Jiménez, 2023). However, in the case of food waste, a comprehensive framework for its quantification at the urban scale is also still lacking in the literature, and the availability and quality of empirical data at this scale are poor. Given the complexity of food waste as part of the urban food metabolism, two questions structure this research. First, which methods and data could be used to characterize and quantify food waste in urban food metabolism studies? Second, what role can food waste reduction play in transforming the urban food metabolism from a sustainability perspective? Taking Paris and its dense urban surrounding area as a case study, this paper[2] presents a method to quantitatively analyze food waste at the urban scale, including the part of wasted food, and thus to exploit the potential to transform urban societies' food metabolism through food waste minimization.

2. Material and Methods

2.1. Material flow analysis

Material flow analysis (MFA), a central tool in urban metabolism studies, is based on the mass balance principle, a physical principle whereby matter can neither be created nor destroyed in any physical transformation process. Using MFA, the transformation of natural resources and other materials, from their extraction to waste, can be visualized for a given economy, complementarily to conventional economic monitoring systems (Eurostat (2018). Given the focus of this study on urban flows, MFA was used with reference to the seminal work of Barles (2009), who validated the Eurostat method in the case of an urban system and suggested that waste be separated from export flows to reflect that cities manage their waste both locally and remotely. To account for food as a specific part of biomass and, in line with Barles (2009), food waste as a distinct flow, adjustments to the Eurostat methodology were necessary on the output side. Consumption was conceptualized and therefore computed as distinct from waste, in contrast to the original indicator of apparent consumption or domestic material consumption suggested by the Eurostat method. These and all other adjustments have been comprehensively described in Redlingshöfer (2022).

[2] Preliminary results were presented at the Socio-Economic Metabolism (SEM) conference of the International Society for Industrial Ecology (ISIE) in May 2019 in Berlin and in September 2022 in Vienna. The relevance of the approach for informing food waste policies was discussed in (Redlingshöfer, 2024).

The principles of food flow analysis applied to the urban system can be summarized as follows:

- All food flows are expressed in mass of fresh weight.
- Only food flows and tap water used for drinking at the consumption stage are accounted for, whereas ancillary material flows involved in the food system are excluded: packaging, agricultural input (fertilizer, pesticides, etc.), non-food uses of agricultural biomass, water, and energy carriers.
- The territorial principle applies: flows accounted for are flows defined by and within the physical boundaries of the system under study. The flows generated by the activities of non-residents, e.g. tourists and commuters, are part of the analysis.
- Input flows relate to imports, agricultural production, including livestock and crops from within the urban system, and the supply of tap water to drink. Products from livestock are accounted for as food and as part of the urban system's food supply, through imports or its own production. Output flows relate to food intake, food exports and food waste. Food intake has been calculated for the eating population of the urban system, including tourists and commuters, according to an original method developed in Redlingshöfer (2022). Food intake was retained for the sake of simplicity, although strictly speaking, food once consumed leaves the urban system as human waste and respiratory gases, obtained from food through human metabolic processes. Food waste is food that has not passed through the human metabolism, ends up uneaten and is managed as waste (see section 2.2). Food waste can be managed within the urban system and released into the urban system's natural environment or outside of it.

Drawing on these principles, Figure 1 illustrates the conceptual model of the urban food metabolism.

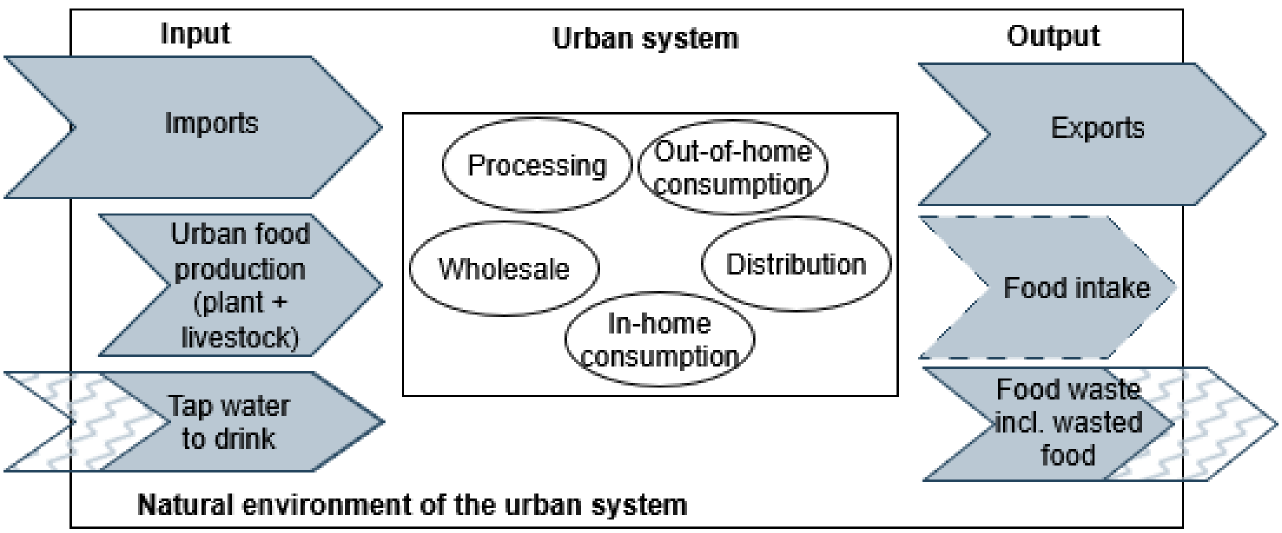

Figure 1. Conceptual model of the MFA used for the urban food metabolism; Source: adapted from Eurostat (2018). Inner-urban sectoral food system activities participate in the urban metabolism by processing, preparing and distributing food, and directing it toward consumption, exports, and waste. The wavy parts of the arrows "Tap water to drink" and "Food waste including wasted food" indicate that part of the matter involved can optionally stem from or be directed to the natural environment outside of the urban system. For the sake of simplicity, food intake was retained as an output flow (shown with dashed lines), even though food leaves the urban system as human waste and respiratory gases once consumed.

2.2. Conceptualization of food waste in socio-metabolic studies

For food waste, the definition rooted in European law in Article 4a of the latest European waste directive applies: "'food waste' means all food (…) that has become waste" (European Commission, 2018) although with one exception (European Commission, 2019): at agricultural production stage, food loss at field level is included in the analysis. Although agricultural production is limited within urban systems, data show that food loss at field is far from negligible and must not be overlooked (WWF, 2021).

A food waste minimization indicator has been developed to determine how much a food waste flow can theoretically be minimized, based on its composition. This is a simple metric that captures the extent to which food waste can be reduced in theory and help to reduce the urban food metabolism's use of material.

Food Waste Minimization Indicator: FWMI = wasted food available in food waste / total food waste (1)

Food waste has been conceptualized as a composite flow informed by four parameters: food system sector, waste category, food waste profile (solid, liquid, mixed or separated), and waste management, including output product and hosting compartment (Figure 2).

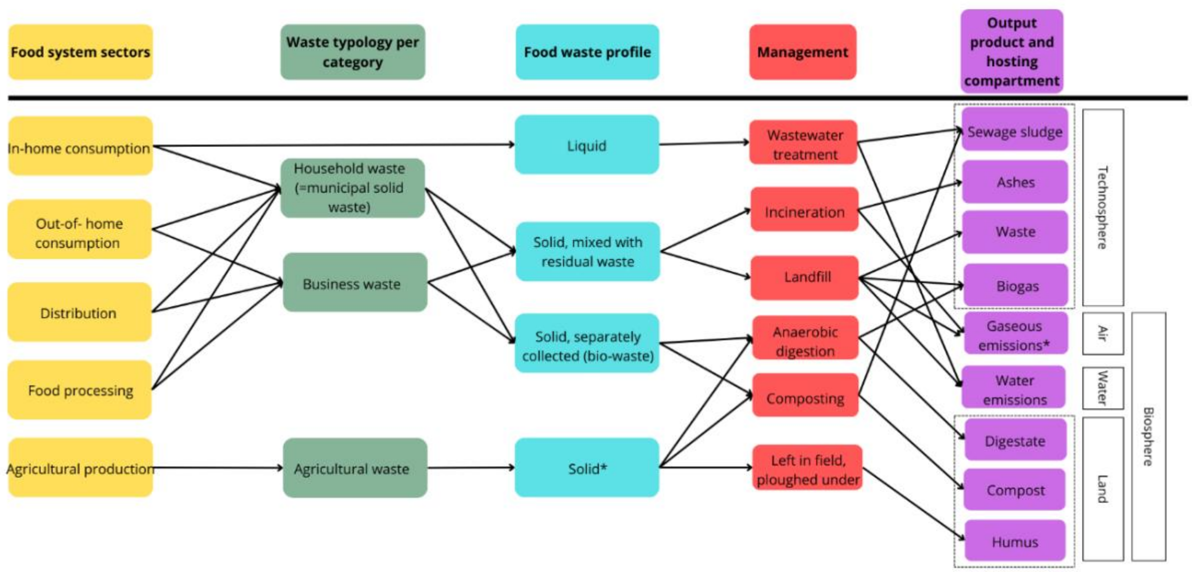

Figure 2. Correspondence chart between food system sector, waste category, food waste profile, and waste management and output products (Source: author)

** All waste management technologies release gaseous emissions
* Food loss in agriculture includes liquid food items (not considered here), for example, milk, which can be discarded due to food safety concerns and either used as feed for calves or else poured onto the land.
Not included: food waste composted at home or in neighborhood composting units; liquid food waste from the food processing industry treated in a wastewater treatment plant. By definition, surplus food from the food industry, retailers, and restaurants that is donated to charity is not waste and is therefore not included.

Official waste categories reflect not so much waste-generating food system sectors but a fundamental distinction between the public or private services in charge of its management. "Household waste", a common term for MSW or residual household waste, is from households and small businesses, mostly small shops, restaurants, and other facilities that have similar waste profiles and amounts. It is collected together by the public service and generally incinerated. Business waste, in France, is usually collected by private companies and derives from sectors not eligible for public service waste collection, primarily industry, retail, administration, the education system, the medical system, and the service sector. Waste generated by agricultural production is overseen by farmers themselves, who are responsible for its management. Food waste can be found in all three waste categories. In terms of EU law (European Commission, 2008) and transposed to French law (Journal Officiel, 2010, 2020), all producers of biowaste, the category including food waste, are required to sort and manage this waste separately. In France, these requirements have progressively changed since 2012, so that since 2024, any producer of biowaste has had to be offered options for the organic management of biowaste. When biowaste is not sorted and separately collected as biowaste or managed on-site – which at the time of this research was the predominant situation and still is today –, it ends up in MSW or mixed business waste, depending on the producer category.

2.3. Case study area: Paris Petite Couronne

Paris Petite Couronne (PPC) consists of Paris and the neighboring administrative *départements*: Hauts-de-Seine (92), Seine-Saint-Denis (93) and Val-de-Marne (94) (Figure 3 a). The city of Paris alone would have been too restrictive for this analysis as the urban area spreads further within the Île-de-France region. It can adequately be captured by Paris Petite Couronne with its 6.7 million inhabitants. Paris Petite Couronne and four neighboring *départements* of the Grande Couronne together constitute the Île-de-France region, home to more than 12 million inhabitants (Figure 3 a and b). An additional administrative unit, the Greater Paris metropolis founded in 2016, is similar to PPC. Table S1 in the Supplementary Information (SI) shows some characteristics of the four administrative areas. Paris and the Île-de-France region is France's main center of political, cultural, and intellectual life.

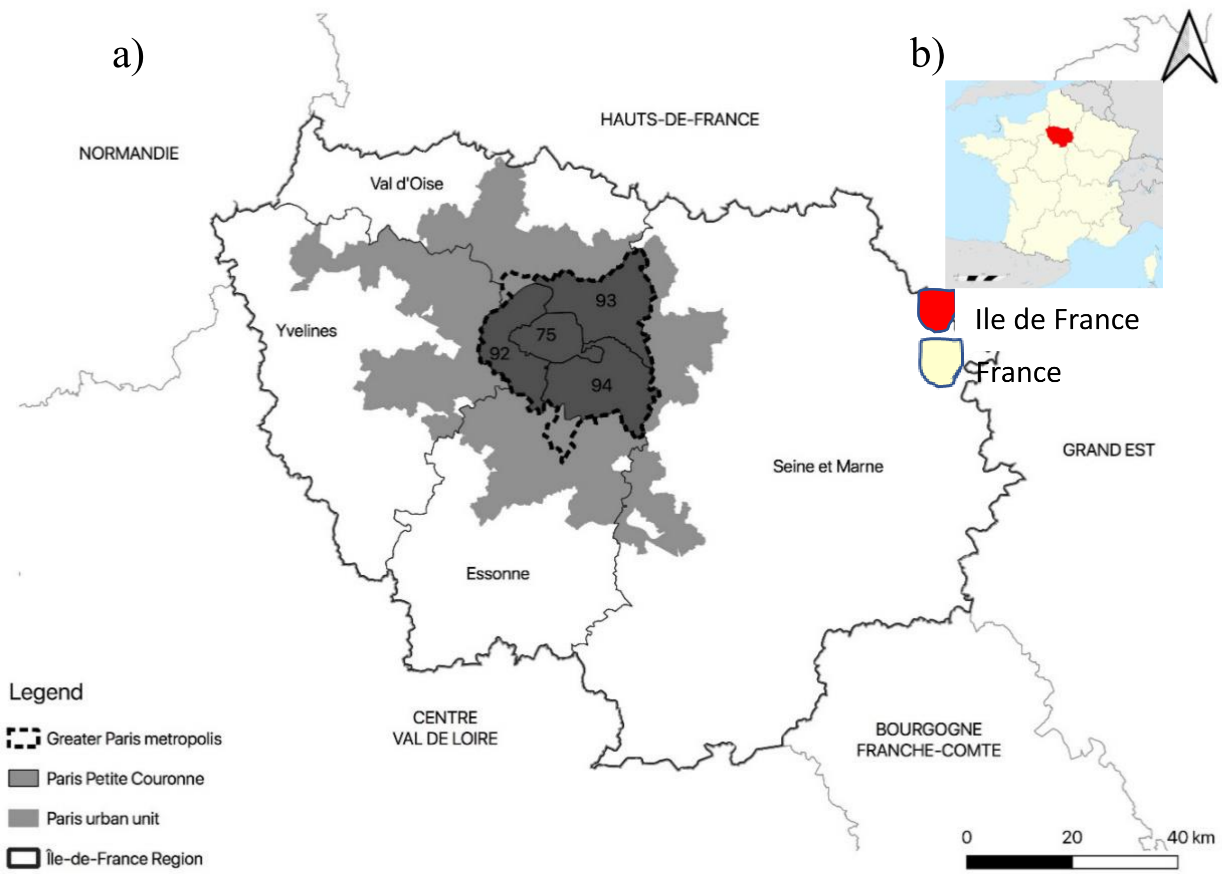

Figure 3. The respective geographical scope of Paris Petite Couronne, Île de France, Paris urban unit, and Greater Paris metropolis (a) and the location of Île-de-France in France (b) (*Source:* data of the National Institute of Geographic and Forest Information (IGN))

2.4. Data sources for estimating food and food waste flows in Paris Petite Couronne

For the purposes of this study, the particular administrative status of Paris Petite Couronne as a group of *départements* was a benefit as most of the required data were available at this scale (food import and export flows) or could easily be used to quantify food flows (agricultural production). This would probably not have been the case for metabolism studies of other cities in France.

As Table 1 shows, only some of the data used for the food and food waste flow quantification derive from official statistics, and those that do have varying periodicities and spatial scales. Where scaling processes are applied, additional data are required, as described in Table 1.

Table 1. Data sources and their characteristics used for the quantification of input and output flows of the urban food metabolism for the year 2014

Input flows	Data sources	Periodicity	Spatial scale	Comment	Equation
Urban food production	Agricultural statistics (Agreste); Ministry of Agriculture	Annually	Municipal	Detailed production area and average yield at the level of the *département* for field crops, vegetables, potatoes and fruit; no livestock in the case study area.	Production area * average yield
Food import	Freight statistics (SITrAM), Ministry of Transport	Annually	*Département*	Detailed annual mass data at the level of the *département*, including detailed nomenclature of products.	Direct data input
Tap water to drink (Balancing item)	French food and drink intake survey (Anses, 2017)	Approx. every 7 years	National	Individual daily intake data computed as annual supply to the eating population.	Daily tap water intake * 365 * eating population size
	Census data, additional information about tourists	Annually	Municipal	Estimation of the eating population according to Redlingshöfer (2022).	
Output flows					
Food intake	French food and drink intake survey (Anses, 2017)	Approx. every 7 years	National	Individual daily intake data computed as annual intake.	Daily food intake * 365 * eating population size
	Census data, additional information about tourists	Annually	Municipal	Estimation of the eating population according to Redlingshöfer (2022).	
Food export	Freight statistics (SITrAM), Ministry of Transport	Annually	*Département*	Detailed annual mass data at the level of the *département*, including detailed nomenclature of products.	Direct data
Food waste				Compilation of various data sources	
- In residual household waste	Waste statistics	Annually or less	Local authority in charge of waste collection	See Table 2	Share of food waste * per capita MSW * population size
	Waste characterization campaigns	Occasionally			
	Census	Annually	Municipal		
- Of which wasted food	Waste characterization campaigns	Occasionally	Local authority in charge of waste collection	See Table 2	Share of wasted food * per capita MSW * population size
	Census	Annually	Municipal		

Table 1 (cont.). Data sources and their characteristics used for the quantification of input and output flows of the urban food metabolism for the year 2014

Input flows	Data sources	Periodicity	Spatial scale	Comment	Equation
- In mixed business waste	Estimate based on coefficients, company database (SIREN)	Upon commission	Regional	Estimate to inform the regional plan for waste prevention and management (Conseil Régional Ile-de-France, 2019).	Direct data * scaling coefficient
	Regional Ministry of Agriculture (DRIAAF, 2018)	Annually	Regional, *département*	Scaled with the coefficient of the number of employees in the food industry in PPC compared to ÎdF.	
- To the sewerage system	Per capita annual food waste from the literature (Stenmarck et al., 2016)	None	None		Per capita food waste * population size
	Census	Annually	Municipal		
- Separately collected as bio-waste	Regional waste statistics and complementary data (ORDIF/Institut Paris Région)	Annually or less	Regional	Detailed data of biennial survey (ITOM) about waste treatment of MSW and business waste survey at the level of the region.	Direct data * scaling coefficient
	Regional Ministry of Agriculture (DRIAAF, 2018)	Annually	Regional, *département*	Scaled with the coefficient of the number of employees in the food industry in PPC compared to ÎdF.	
- Used frying oil	Survey results	Upon commission	Regional	Survey to inform the regional plan for waste prevention and management (Conseil Régional Île-de-France, 2019).	Direct data * scaling coefficient
	Regional Ministry of Agriculture (DRIAAF, 2018)			Scaled with the coefficient of the number of commercial restaurants (including street food) in PPC compared to ÎdF.	
- Food loss	Redlingshöfer (2017)	Upon commission	National	Coefficients of food loss at agricultural production according to product categories	Food production * food loss coefficient per category

Regarding food waste, this study's data were compiled using various data sources and scaling processes (Table 1). Officially, food waste is not classified as a waste category and lies hidden between the organic part of the "household waste" and "business waste" categories. Moreover, the administrative unit of a *département* or compound of *départements,* as in the case study of this research, is not a regular unit for the establishment of waste statistics. For food waste in residual household waste, per capita results from the MSW survey for Greater Paris (ORDIF, 2014) and proportions of characterization campaigns carried out for Paris and Île-de-France (Table 2) were used to obtain the arithmetic mean per capita quantities and multiply them by the population size of Paris Petite Couronne. As shown in Table 1, data in the regional waste planning technical reports and in the literature were used for the other food waste categories and profiles. With the exception of residual household waste for which we used the literature, proportions of wasted food, relevant for estimating the system-wide FWMI, were based on estimates of edibility and assumptions (Table 3) considering that food that is or has once been edible and has ended up as food waste, could have been handled differently. Estimates of proportions of wasted food are available for food systems across sectors, thanks to European reporting (Eurostat, 2023), but are incompatible with the framework of this study.

Table 2. Quantities of residual household waste (MSW), biodegradable waste (BdW) and food waste (FW), and proportions of biodegradable waste, food waste and wasted food (WF), in various administrative units in Île-de-France and in France, in various years between 2010 and 2017

Administrative unit	Year of data	Quantity (in kg/cap/y)			Proportion of MSW (in %)			Data source
		MSW	BdW	FW [a]	BdW	FW	WF	
Paris	2014	384	67	62	18	16	4[1]	Ville de Paris (2014)
	2015	382	85	74	22	19	7[1]	Ville de Paris (2015)
	2015	358	79	67	22	16	6[1]	Ville de Paris (2017)
Greater Paris	2014	313						ORDIF (2014)
Île-de-France	2010-2015	293[b]	82	66	28	23		ORDIF (2017)
France	2017	254	83	67	33	27	12[2]	Ademe (2017)
Paris Petite Couronne		**313**		**67**		**21**	**10**[c]	**Own estimation from ORDIF (2014, 2017), Ville de Paris (2014, 2015, 2017) and Ademe (2017)**

[1] Packaged, unopened; [2] packaged, opened and unopened;
[a] Per capita FW was determined from the FW proportion in per capita MSW, except for Île-de-France, for which ORDIF (2017) provided this data. To obtain per capita FW for Paris Petite Couronne, the case study area, we calculated the arithmetic mean from per capita FW values for Paris and Île-de-France.
[b] Calculated from proportion and normalized biodegradable waste in residual household waste (ORDIF 2017).
[c] Aligned with the per capita value of 31 kg/cap derived from the 2017 Ademe study, which includes the wider category of wasted food (packaged, opened and unopened). For Paris Petite Couronne, 31 kg/cap of wasted food in MSW makes up a part of 10%.

Table 3. Share of wasted food in food waste category and profile

	Share of wasted food (in %)	Comments
Food loss in agriculture	100	Despite inedible parts in crops, fruits, vegetables and potatoes, food lost at the production stage is considered lost to consumption.
Food waste in residual household waste	50	10% of MSW equals 50% in FW ; Table 2
Food waste in mixed business waste	50	Assumption: we assume a profile comparable to Table 2 (composition of edible and inedible parts due to processing activities in restaurants/industry).
Food waste to the sewer	100	Liquids (e.g. milk, juices) and semi-liquid foods (e.g. soup, sauces) are poured down the sewer rather than thrown into the waste bin.
Separately collected bio-waste	50	Assumption: we assume a profile comparable to Table 2 (composition of edible and inedible parts due to processing activities in restaurants/industry).
Used frying oil	0	Frying oil is used for food preparation but not ingested as part of a meal.

The year 2014 was retained as the reference year for this research. Although that was a decade ago, it was close to the time the study was carried out (2017-2019) as part of the author's doctoral research. The latest available data (up to 2022) on household food waste and food waste collected separately as biowaste are used in the discussion of the results to allow an at least partial albeit incomplete update of the food waste flows – despite the fact that food consumption practices were disrupted by the recent Covid 19 pandemic.

3. Results

3.1. Quantities of food and food waste flows

A complete overview of the urban food metabolism of Paris Petite Couronne is provided in Figure 4 in the form of a Sankey diagram and in Table S2 in the Supplementary Information.

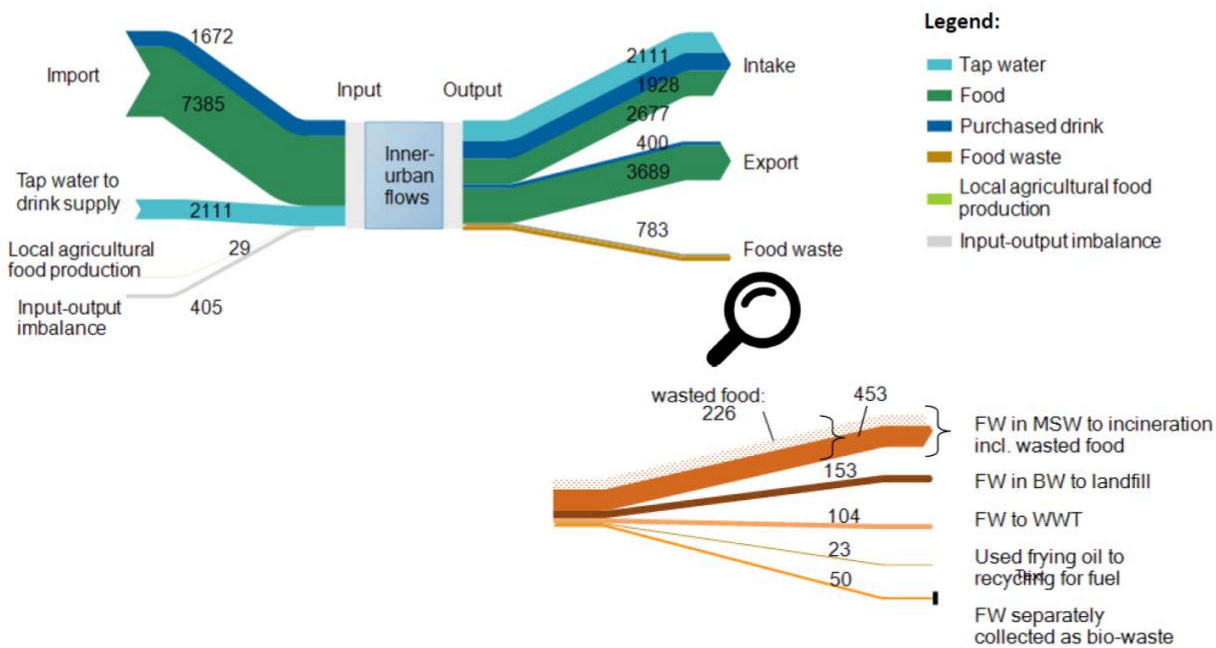

Figure 4. Urban food and drink flows, Paris Petite Couronne, 2014, in kilotons (Source: Author's calculations. Abbreviations used: FW, food waste; MSW, residual household waste; BW, business waste; WWT, wastewater treatment; AD, anaerobic digestion; ÎdF, Île-de-France; not included: food waste directed to individual or neighborhood composting and to pets. The shaded part of the FW in MSW flow stands for wasted food.)

Food waste, generated from the various food system sectors within the urban system, amounted to 783 kt in 2014 (Figure 4) or, normalized with population, to 101 kg per capita. Looking at solid food excluding drink, food waste constituted 20 % of food supply for consumption, which is food intake and food waste combined. The proportion of food waste reflects how well the food system performs in relation to urban food demand.

With 453 kt, food waste mixed with residual household waste was the biggest part of total food waste. Another 153 kt was food waste mixed with business waste, and 104 kt was estimated to be drink or semi-liquid food (sauces, yoghourt etc.) that households dispose of through the sewage system. Food waste collected separately as biowaste amounted to 50 kt and another 23 kt was used frying oil collected separately. As agricultural production is almost unavailable in the dense urban area of Paris Petite Couronne, food loss played almost no role.

Food waste collected separately as biowaste and recycled, mostly through anaerobic digestion, amounted to 50 kt in 2014 and accounted for 8% of total food waste, excluding drink, generated in Paris Petite Couronne in 2014. Part of the recycling concerning an estimated 14 kt took place at distant sites, outside of Île-de-France. This matched the spatial distribution observed for biowaste generated in Île-de-France, where, in 2014, according to ORDIF, 21 kt of biowaste collected was treated elsewhere, compared to 55 kt treated in Île-de-France (B. Barrault, personal communication, November 18, 2019).

To complete the findings, the urban food metabolism of Paris Petite Couronne consisted of an input of 11,197 kt and an output of 11,602 kt, as Figure 4 shows. With a difference of -405 kt (or 4%), the metabolism was almost balanced. The 9,057 kt of food input mostly stemmed from food imports, since local food production within the boundaries of the urban system of PPC was insignificant (29 kt). Unsurprisingly, a major part (58%) of the input was directed to consumption and ended up eaten (6,730 kt). Another part (35%) was exported (4,089 kt). The remaining output flow consisted of food waste.

3.2. Food waste minimization potential at the scale of Paris Petite Couronne

Roughly half of all residual household food waste, that is, 226 kt, amounting to 29% of the total food waste generated in Paris Petite Couronne, was estimated to be wasted food (Table 4). The magnitude of wasted food underlines the importance that tailored public and private policies that support households and businesses in avoiding or donating surplus or reprocessing leftovers can play, thus more closely tailoring urban food supply to demand. When wasted food in business waste in separately collected biowaste and household liquids are additionally considered, albeit based on rough estimates, the proportion of wasted food made up more than half (55%) of total food waste generated in Paris Petite Couronne. This points to an even bigger margin for action against food waste.

Table 4. Food Waste Minimization Indicator (FWMI), in %. For calculation, refer to Table 3 for the share of wasted food and Figure 4 for the quantities, per food waste category and profile.

Food waste category and profile	FWMI
food loss in agriculture	0
food waste in residual household waste	29
food waste in mixed business waste	10
food waste to the sewer	13
separately collected bio-waste	3
used frying oil	0
Total food waste	55

4. Discussion

This study adds to the scarce literature quantifying food and food waste flows systemically at the urban scale. The findings show first of all that, taken comprehensively, a significant amount of food in cities ends up as food waste. Cities thus reveal a low level of efficiency in the food system's handling of food, but significant potential for waste minimization.

Echoing the first research question about the methods and data required to characterize and quantify food waste, the discussion that follows outlines considerations pertaining to data (4.1), and to the study's findings in relation to the scientific literature (4.2). The role that reducing food waste can play in transforming the urban food metabolism from a sustainability perspective, which is the second research question, is discussed with respect to the often neglected potential minimization of waste (4.3). We conclude this section by discussing the study's scientific contribution to the literature (4.4).

4.1. Discussion of data and data sources and recommendations for future work

As in the case of other biophysical accounting tools, data availability and uncertainty is a challenge for this research and to date still limits the use of this MFA methodology as a tool for food waste monitoring at urban scale. Apart from monitoring, the scalability of this method needs to be assessed in light of the data. Given that various administrative entities are relevant sources of data – some of which require additional calculations of varying levels of complexity (see Table 1) –, applying the method to cities with administrative boundaries other than Paris Petite Couronne might require further adjustments. Trade statistics, for example, are available at the level of the French *département*, which is useful for Paris as a case study since it happens to be both a city and a *département*, but they may require further adjustments for cities at other scales. To report on the uncertainty of the data sources used in this research and help guide scalability, we provide a classification (Appendix S3) drawing on data quality indicators according to the original Pedigree Matrix method (Weidema & Wesnæs, 1996), adapted by Hoekman and von Blottnitz (2017).

The sourcing of data and data quality call for caution in interpreting the results. For instance, data for food waste sent to the sewage system were drawn from a European research project (Stenmarck et al. 2016), and had therefore not been produced for the context of this study, nor even for France. It is possible that liquid or semi-liquid food leftovers are handled differently in households in France than in other countries, and that the estimate used in Stenmarck et al. (2016) does not fully reflect the situation in the present case study. Overall, liquids are often neglected in studies about food waste and data on the subject are scarce (Malefors et al., 2024). Including liquid food waste in national waste statistics and reporting would help build better data.

For business waste, little information is available on the study carried out as part of the regional plan for waste prevention and management (PRPGD) (Conseil Régional Île-de-France, 2019). The question is whether the data used on average quantities of biowaste in companies are robust and sufficiently take into account diversity in the food industry.

Coefficients for wasted food must also be considered to be lacking in robustness, as the results of characterization campaigns have revealed a wide range of varying interpretations of the sorting and classification of food waste, such as for packaged unopened food, opened food, meal leftovers, and kitchen waste, for example. Further characterization campaigns should be carried out using clear guidelines to refine our understanding of the composition of waste, and to distinguish wasted food – including meal leftovers and packaged unopened and opened food – from inedible parts (Silvennoinen et al., 2022). Characterization campaigns have been unavailable so far for mixed business waste and separately collected biowaste, handled in most cases by private companies. The rough assumption that the same characteristics apply for businesses and separately collected waste as for residual household waste should be revised.

While residual household waste is closely monitored, some gaps do exist. For on-site food waste disposal such as feeding pets or composting, no data were available about the quantities at individual or household level. Syctom, the biggest public service provider for waste treatment in Île-de-France, reported that, in 2015, 2% of the population of 6 million inhabitants covered by its services had access to composting equipment. This accounted for a rough estimate of 6 kt of food waste (Syctom, 2016). Paris alone has nearly one thousand composters installed for its more than 2 million residents, with an estimated total capacity of 1 kt of food waste (Ville de Paris, 2021), which shows that our quantification is unlikely to have missed much of the food waste handled by decentralized options. In fact, a city cannot return massive amounts of compost to soil within its boundaries, which underlines the limits of this option for circular systems. Therefore, in 2017, ahead of the European law-driven mandatory management of biowaste for all producers (Journal Officiel, 2020), the Paris municipality started the separate collection of household food waste in three arrondissements, collecting respectively 0.6 and 3.3 kg/cap in 2021 and 2022. Other local authorities have run similar experiments with households from which less than 2 kt of food waste were collected in Île-de-France in 2021 (De Oliveira, 2023). Syctom, whose scope of intervention is close to PPC, collected 9.2 kt of food waste, mostly from schools and wet markets, in 2022, primarily anaerobically digested in and around Île-de-France (Syctom, 2022). These figures, non-existent in 2014 and still very low today, will need to be closely monitored in the future as local authorities are required by law to develop such solutions, which should increase the quantities of recycled food waste.

Considerations about updated figures lead to the legitimate question of whether this quantification study, based on data from 2014, is still relevant more than a decade later. Few data updates are available and those that are do not suggest a major change from the 2014 situation. In 2022, in the city of Paris, residual household waste, the largest contributor to all urban food waste, still included 24% (i.e. 76 kg) of biowaste (Ville de Paris, 2022) – a figure close to the data we found for 2014. Unsurprisingly, in line with the legal framework, the quantity of biowaste collected separately in Île-de-France doubled between 2014 and 2018, reaching around 100 kt (and dropping to 65 kt possibly due to the Covid 19 pandemic), with half of it being treated outside of Île-de-France (Barrault & Lemaire, 2022). The uncertainty about the evolution of food waste amounts is biggest for commercial food waste from supermarkets, restaurants, and the food industry. The impacts of the French food waste policies are however starting to be seen, according to a recent French study (Comerso, 2025) showing that 92% of the retailers and 84% of the food industry managers interviewed have reported donating food to non-profits. However, companies seldom disclose accurate figures about the amounts of food rescued or wasted. At national scale, monitoring has been set up since 2020 within the framework of European reporting requirements, but there is nothing similar at the city level.

The lack of sufficient organic waste management infrastructure, in Paris and the Île-de-France region, has led to a situation where waste has been shipped to distant sites for treatment and land-spreading – at a huge environmental cost. Shipping waste to distant treatment sites may be explained by the limited capacity in Île-de-France which, in 2014, had an annual capacity of no more than 40 kt per year, that is, less than 10% of the household food waste alone. This capacity reached 104 kt in 2022 and was expected to reach 287 kt by 2025 (Barrault & Lemaire, 2022), a figure still far below the food waste estimated for PPC, and the total biowaste generated in Île-de-France, estimated at close to one million tons (De Oliveira, 2023). The task is therefore gigantic. Meanwhile, most of the food waste is being incinerated and, to a lesser extent, landfilled in facilities located in Île-de-France (Conseil Régional Ile-de-France, 2019).

4.2. Comparison with other food waste studies at urban and supra-urban scale

Few metabolism studies with detailed analysis of food waste have been carried out at urban scale. When they do exist, comparisons are often not possible, as for example when a biogeochemical approach focusing on nitrogen and phosphorous flows (Esculier et al., 2019; Papangelou et al., 2020) or different metrics (Tseng & Chiueh, 2015; Turner et al., 2016) are used. Most food waste quantification studies with a spatial dimension have been performed at a national or supra-national scale (Caldeira et al., 2021). Yet countries and global regions have their own food production, unlike most cities (J. R. Porter et al., 2014), at least to varying degrees, which adds to the generation of food waste and makes comparison with food waste studies at urban scale of limited value. The few existing metabolism studies with detailed food waste analysis can be used for comparison of the order of magnitude of food waste.

Overall, the annual per capita food waste of 101 kg calculated in the present study appears to be somewhat low compared to most of the findings of the few similar studies (Table 5), with the exception of Bahers and Giacchè (2018) and Zeller et al. (2019). One reason could be that the methodological approach and data sources used in this study differ significantly from those adopted in the other studies. Codoban and Kennedy (2008) for example calculated food waste as the difference between availability and intake, and obtained annual per capita food waste of 249 kg. This figure is high compared to the results of the other studies in Table 5, including the literature review of Goldstein et al. (2017), which lie in a range between 100 and 200 kg/cap/y. It is especially high as Codoban and Kennedy (2008) exclude food waste generated at out-of-home consumption, which has been shown to be significant (Betz et al., 2015). Most of the cited studies used waste statistics for calculation. Caldeira et al. (2019) show that in studies at national scale, food waste estimates from waste statistics are generally lower than those obtained by mass flow analysis which combines statistical information on the production and trade of food products with food waste coefficients. For the urban scale, further research and more in-depth analysis remains to be done on the effect that the quantification approach, the method, and the origin of the data have on the results. This would be helpful for interpreting the results and disentangling the effects of urban food system characteristics on food waste generation. Furthermore, the nature and proportion of wasted food, unaddressed by the available studies, would need to be assessed in order to ascertain how urban food system characteristics are used in these studies to determine the generation of wasted food, which is relevant for waste prevention.

Table 5. Comparison of the food waste figures obtained in this study with results from other studies

	Goldstein et al. (2017)	**Codoban and Kennedy (2008)**	**Zeller et al. (2019)**	**Bahers and Giacchè (2018)**	**Liu et al. (2020)**	**This study**
	14 cities (8 cities in OECD countries)	**Neighborhood of Toronto (households)**	**Brussels**	**Rennes Metropolitan Area**	**Bangkok**	**Paris Petite Couronne**
Waste data	Waste statistics at various administrative levels	Difference between food availability and intake	Waste statistics	Waste statistics	Waste statistics	Waste statistics, technical reports, scientific literature
Year(s) of data collection	From 1990 to 2013	2000	2014	2012	2016	2014
Population size (in thousand)	Mostly cities of several million	Not given	Not given	426	9,166	6,754
Annual per capita food waste (kg/cap/y)	200+/-100	249	138	70	192	101

4.3. Avoidability and the minimization potential to inform cities' food waste management strategies

While the amount of wasted food can potentially be reduced, this is hard to achieve at a large scale. Various instruments, including policies and regulations, standards and labelling, voluntary agreements, and information-based approaches, have been developed and have targeted consumers above all, but evidence as to their effectiveness is scarce (Casonato et al., 2023; Reynolds et al., 2019). While information and awareness-raising, for example, have been widely used with the aim of changing people's behavior, strategies providing information alone are likely to be among the least successful interventions to foster pro-environmental behavior (Vermeir & Verbeke, 2006). Citizen science methods have been explored not only to help measure food waste and collect data, but also to engage citizens in action (Pateman et al., 2020; Sanz Sanz et al., 2023). By definition, citizen science projects are co-created with community members and are therefore a prominent field where local authorities can build momentum towards locally tailored reduction strategies. Although a few examples of effective interventions stand out, it is hard to derive recommendations applicable at the scale of society as a whole. It is therefore unclear what a realistic target of a food waste reduction strategy might look like. "Zero waste" does not appear achievable, not even by the most committed actors. Cutting food waste in half, a goal set by national and European governments and the SDD 12.3 for the distribution and consumption stages, seems to be an essentially political target, rather than one derived from evidence or informed by successful intervention.

With regard to the estimated potential for food waste minimization highlighted in this study, the above considerations suggest that the edibility of wasted food, prior to and at the time of disposal, does not appear sufficient. People have different perceptions of what is edible (Nicholes et al., 2019), what is worth eating

(Gojard et al., 2021), and what is fresh. The normative demand for eating fresh food, equated with healthy food, has become an important driver of food waste (Evans et al., 2019). Overall, there are many barriers to food waste minimization in households (Nunkoo et al., 2021; van Geffen et al., 2020). Equating edibility with avoidability is therefore not accurate enough to assess the food waste minimization potential. In response to the difficulty of assessing the avoidability of food waste, the concept of actionability has recently been introduced by Li et al. (2024) who categorized household food waste based on how easy or difficult it is for consumers to act to avoid waste.

For business operators, the avoidability of food waste tends to be associated with costs and knowledge of useful digitalized tools (Aramyan et al., 2021). Avoiding food waste can also involve management options for surplus food such as donating to the needy through charities (Lai et al., 2022; Sundin et al., 2023). Local governments can take on an important role in coordinating supply and demand of leftover meals and surplus food from various food system sectors, at city level (Redlingshöfer et al., 2024), as Californian state law has recognized (SB 1383). Alternative recycling strategies keep surplus food in the economic system by adding value through upcycling (Aschemann-Witzel et al., 2023). Prominent examples which are still niche markets are beer brewed with surplus bread, cookies made from "bread flour", mushrooms raised on stale bread (Gómez & Martinez, 2023; Guerra-Oliveira et al., 2021), and bio-products derived from bread waste (Haroon et al., 2016). Including management options with third-party operators complexifies the concept of avoidability as the operators' capacity would additionally have to be assessed, which can be done in a case study but hardly on a large scale.

The development of a food waste avoidability framework applicable to households and, after adaptation, to other food system sectors and business operators generating waste can nevertheless serve to determine a more realistic potential for food waste minimization. It can thus allow for more subtle changes in the part of wasted food in urban biowaste to be monitored.

4.4. Contribution to the literature

"Minimizing then closing material cycles: the ignored potential for food waste reduction", the title of this paper, captures the argument that closing loops or material cycles should start with using less and wasting less material, and that food waste reduction is a powerful but underexploited way to transform cities' food metabolism. In this light, the main contribution of this study is to provide a simple and comprehensive approach to characterizing and quantifying food waste, including wasted food, at the city level. We quantified and qualified food waste for its minimization potential, defining wasted food as the part of food waste that can be reduced. Another contribution of this research lies in the comprehensive approach to food system sectors, including businesses and households (due to the urban setting of our case study, food losses at the farming stage could be ignored).

To the best of our knowledge, no other study has conducted spatially-explicit MFA, as we have, with a focus on both food waste and wasted food. In our study, the conceptualization of urban food waste flows was to a large extent determined by the waste management system, characterized by waste categories, food waste profiles, and waste management options (sanitation for liquid food waste), as the availability of waste statistics is a prominent entry point when it comes to studying food waste (Zhang et al., 2023). Although spatially-explicit food waste data (other than in MSW) is limited and does not distinguish between food system sectors (see 4.1), the use of waste statistics is a rather straightforward approach and is often employed in metabolism studies, as the comparison of our results with the literature shows (see 4.2).

The link to the food system sectors is nevertheless hard to establish, as waste is categorized according to the size of waste-producing businesses, except for farms, and its similarity with household waste. Conceptually, there is a loose link between food and waste systems, which makes it hard to extend the discussion of the results to possible food waste reduction strategies and tools, as these are usually sector-specific (Diaz-Ruiz et al., 2019; Moraes et al., 2021). Alternatively, Olano-Oteiza et al. (2025) propose a food loss and waste quantification methodology at municipal and regional scales drawing on waste characterization sampling data, to compare waste fractions, generator types and waste collection systems. Furthermore, a material input-output or supply-use analysis per food system sector could provide sector-level food waste data, similar to the approach used by Codoban and Kennedy (2008) who assessed food waste in a neighborhood using household availability and intake data. The availability of spatially explicit mass data for food supply and use could however be a barrier to this approach.

To date, cities have failed to monitor food waste and the effectiveness of food waste reduction policies. One reason may be that they lack the tools and methods to do so. The Food Waste Minimization Indicator (FWMI) proposed in this study can provide a useful tracking metric, provided that cities gain access to and help improve the relevant data and statistics, as discussed in (4.3). There is a need for strengthening the monitoring system for policy making by local authorities. There is also a need for encouraging future research in this respect.

5. Conclusions and recommendations

In this paper we analyzed the food flows in the food system of Paris metropolitan area. At least 29% of the food wasted in this area was the target of food waste reduction policies and could potentially be minimized, since it concerned food wasted by households, the biggest contributing sector. Minimizing waste and then closing material cycles has the potential to substantially increase the sustainability of the city's food system. This is where the contribution of this study lies: it provides a simple but comprehensive approach to characterizing and quantifying food waste – including wasted food as the specific part relevant to waste minimization – at the level of cities. To date, cities have failed to monitor food waste and the effectiveness of food waste reduction policies.

This quantification study for the year 2014 can be considered a starting point, or a baseline, for the future assessment of food waste. Reduction targets for food waste announced by the government of cities like Paris can be effectively controlled only when a methodology and appropriate data are available to monitor progress. Yet, difficulties in monitoring food waste are expected to persist in the future, as food waste is poorly identified, characterized, and quantified, and is therefore likely to continue slipping through the cracks in the governance system. City governments can help to centrally collect and analyze data from food waste audits which have become mandatory in France for the institutional catering sector, including school canteens, which are under their jurisdiction. In the case of Paris, a cross-sectional analysis of amounts of waste generated by school meals, as well as by situations identified as 'hotspots' and/or addressed by action plans in the 20 school districts, could generate new momentum. With the gradual implementation of the legal framework, attention is increasingly turning to the monitoring of separately collected biowaste which, to date, has mainly been anaerobically digested in the context of Paris and its metropolitan area. However, there is a risk that the leitmotif of "the more (food waste is collected), the better (for the environment)" may lead to conflicting policy objectives and be misleading as to what can be interpreted as a success. Shedding light on these conflicting policy objectives, with their biophysical and environmental implications, represents an important policy support task for research.

Reducing food waste on the one hand and increasing urban biowaste management on the other are two seemingly conflicting strategies which are nevertheless both grounded in urban sustainability objectives and therefore concern the same issue: food waste as a proportion of urban biowaste. There is thus an opportunity here for local authorities in Paris Petite Couronne to reduce food waste and thereby to scale down the magnitude of urban biowaste management projects, which are already lagging behind legal targets in terms of required infrastructure and changes in social practices. To achieve policy integration of these two seemingly distinct aims, a task force on "reducing wasted food and recycling food waste" could be created, as suggested by a group of researchers in a report on governing urban organic matter (GREC Île-de-France, 2024), with representatives of different government departments (e.g. waste, climate change, sustainable food, food insecurity, and urban green spaces). With a strong mandate for a new strategy to tackle the various aspects of food waste reduction, such a task force would necessarily have to include the administrative entities involved, which go beyond cities and urban areas.

Acknowledgements The author would like to thank Helga Weisz and Sabine Barles for their support in carrying out this research. We would like to express our sincere gratitude to the anonymous reviewers for their insightful comments and suggestions which have significantly improved the quality of the paper.

The Journal thanks Matéo Vigné and Gabi van der Velde-Kraft for their administrative assistance in the editorial process.

Author contributions Not applicable.

Funding This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Data availability The datasets generated and/or analyzed during the course of the current study, which are not publicly available and referenced above, are available from the corresponding author on reasonable request.

Declarations

Competing interests The author declares that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary information

Table S1. Administrative delimitation, population, surface area, and density of Paris and related administrative units (Source: INSEE (2014) except for Paris urban unit (2015) and Greater Paris Metropolis (2019))

Area	Administrative delimitation	Population (inhab.)	Surface (km^2)	Density (cap/km^2)
Paris	*Départment* 75	2,220,445	105	21,067
Paris Petite Couronne	*Départements* 75, 92, 93, 94	6,754,282	763	8,852
Greater Paris Metropolis	*Départements* 75, 92, 93, 94 and 7 municipalities of the *Grande Couronne*	7,094,649	814	8,713
Paris urban unit	429 municipalities of Paris, *Petite Couronne* and part of the *Grande Couronne*	10,706,072	2,845	3,763
Île-de-France	PPC + *départements* 77, 78, 91 and 95	12,027,565	12,012	1,001

Table S2. Input and output flows of the urban food metabolism, Paris Petite Couronne, 2014

	FOOD AND DRINK	Wasted food including drink	FOOD excluding drink
	Quantities (kt)	**Quantities (kt)**	**Quantities (kt)**
INPUT FLOWS			
Food and drink imports	9,057		7,385
Agricultural production	29		29
- livestock products	--		--
- crops, dairy and eggs	29		29
Tap water to drink	2,111		
Total input flows	11,197		7,414
OUTPUT FLOWS			
Food and drink intake incl. tap water	6,730		2,677
Food and drink exports	4,089		3,689
Food waste	783	433	679
- food loss in agriculture	1	1 226 77 104 25	1
- food waste in residual household waste	453		453
- of which: wasted food	*226*		*226*
- food waste in mixed business waste	153		153
- food waste to the sewer	104		--
- separately collected biowaste	50		50
- used frying oil	23		23
Total output flows	11,602		7,045
INPUT-OUTPUT	**-405**		**369**
Ratio of food waste to food supply [1] (in %)			20
Ratio of total wasted food to total food waste (in %)		55	
Annual per capita food waste incl. production (kg/cap/y) [2]			101

[1] Ratio refers to food supply built from food intake (excluding drink) plus food waste
[2] Normalized with legal population

Table S3. Data quality indicators for the principal data sources

	Reliability	Complete-ness	Temporal correlation	Geo-graphical correlation	Access	Additional steps	Frequency	Informality and illegality
Input flows								
Urban food production	3	2	1	1	2	2	1	2
Food import	3	3	1	1	3	2	1	2
Tap water to drink	2	2	3	3	1	4	4	2
Output flows								
Food intake	2	2	3	3	1	4	4	2
Food export	3	3	1	1	3	2	1	2
Food waste								
- In residual household waste	2	3	1	3	1	3	2	2
- In mixed business waste	3	5	4	4	1	2	4	3
- To the sewerage system	5	5	5	5	2	2	5	4
- Separately collected as bio-waste	2	4	1	2	1	2	2	4
- Used frying oil	3	5	1	2	1	2	5	3
- Food loss	4	5	5	2	2	2	5	2