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Bio-waste: A Unique and Valuable Resource with Significant Recovery, Prevention and Management Challenges

Tremier Anne, Julia Barrault, Rémy Bayard, Sylvaine Berger, Mathilde Besson, Manon Vivière Bevan, Isabelle Zdanevitch, Etienne Paul

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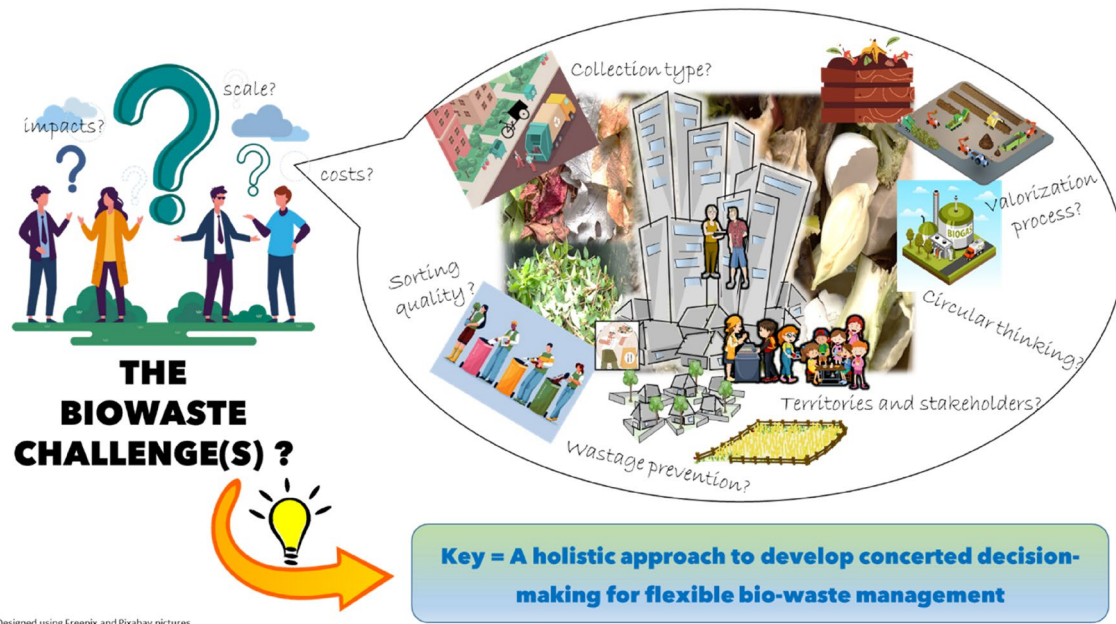
Tremier Anne^{1,6} · Barrault Julia^{2,6} · Bayard Rémy^{3,6} · Berger Sylvaine^{4,6} · Besson Mathilde^{5,6} · Vivière Bevan Manon^{2,6} · Zdanevitch Isabelle⁶ · Paul Etienne^{5,6}

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Abstract

As part of the move towards a circular economy and the transition to a more sustainable society, it is necessary to reduce the quantity of municipal solid waste and improve the overall management of its organic fraction, i.e. bio-waste. Proper management of this bio-waste is essential to avoid numerous nuisances, limit its environmental impact and promote its agronomic recovery, while contributing to the production of renewable energy. Arguing that bio-waste is not biomass waste like any other, the authors, drawing on their own experience of the subject as well as on the results of the literature, highlight the challenges associated with optimising the management of bio-waste and food waste in particular: reducing its production, sorting it at source, collecting it efficiently, treating it and recovering it. The paper explains how the specific characteristics and multiple territorial contexts of bio-waste management need to be taken into greater account in order to improve the performance of each stage of the management system. Beyond the challenges associated with improving the technical stages of bio-waste management, the paper highlights the need for a systemic approach to the design of bio-waste management systems. The multiple factors influencing system design as well as modelling tools and the need for co-construction with all stakeholders to support the design of the management system are discussed. Throughout the discussion, recommendations are made on the issues that research should address to help improve the management and recovery of bio-waste.

Graphical Abstract



Extended author information available on the last page of the article

Keywords Bio-waste management system · Sorting · Collection · Valorization · Stakeholders' involvement · Decision-making

Introduction

At a time when environmental issues are of major concerns, the transition to more responsible production and consumption practices and the need to complete C, N, P geological cycles have become pressing. In this context, bio-waste management is emerging as a specific challenge and an opportunity to contribute to the circular bio-economy [1].

Defined by the European Commission, bio-waste includes biodegradable waste from gardens, parks, households, restaurants, caterers, retail outlets and food processing plants [2]. Although it accounts for a relatively small proportion of all recoverable organic waste and residues in Europe—around 114 million tons a year—bio-waste is a unique resource with specific characteristics that requires a particular management approach to maximize its value while minimizing the environmental impact [3].

To this end, presenting bio-waste as a specific resource, we highlight four major characteristics of bio-waste: its multiple origins, its management largely under the responsibility of public authorities, its high bio-reactivity and its recent emergence as a research subject. Bio-waste, and especially food waste, comes mainly from human consumption, generated by various and widespread producers. It is currently largely collected and processed by the public authorities responsible for household waste management, which makes it different from other sources of waste, such as agricultural effluents. Finally, despite the environmental and health risks associated with its collection and biodegradation [4], the high bio-reactivity of bio-waste offers opportunities for recovery via biological, physical and chemical transformation processes [5], particularly when it is sorted at source [1].

These characteristics stirred up technical, regulatory and organizational challenges for the recovery. National and European policies have been put in place to encourage this recovery, notably by setting targets for sorting at source and reducing food waste: European framework directive [2], circular economy package [6], French law on the fight against waste and the circular economy (AGEC law) [7], etc. Despite these regulatory incentives, and the need for innovation, research into bio-waste is still recent compared with other areas such as wastewater management. However, interest in this subject has gained momentum recently, with a clear challenge: to propose a management adapted to the recovery of this specific biomass.

With this in mind, we propose a critical analysis of the organizational and technical challenges involved in optimizing the bio-waste recovery system. In addition to this, particular attention will be paid in assessing the territorial suitability of the bio-waste management system.

Why Bio-waste is a Unique Resource?

A Resource Linked to Production, Consumption and Sorting Habits

Bio-waste: a Multi-origin, Diversely Collected and Poorly Quantified Resource

There are three main streams of bio-waste to be treated, the annual flows of which are given for France and Europe in Table 1: (1) green waste from households or various entities (towns, professionals); (2) food waste from households; (3) food waste from professional activities, which is collected either by private operators or by local authorities under certain regulatory conditions. This waste is managed differently depending on its origin and category. Selective collection of households' bio-waste varies widely from one country to another in Europe (Table 1). In France, for example, it is still marginal, although it is beginning to evolve. More generally, many European countries are under-exploiting their bio-waste potential [1].

Beyond its different streams, bio-waste also vary depending on the area under consideration and geographical constraints concerning collection and processing. Consequently, a wide range of technical combinations has been implemented: local composting solutions (individual, collective or institutional) coexist with separate collection (door-to-door, voluntary drop-off points, public interest sites or on-demand collection) combined with recovery on composting or anaerobic digestion platforms on a larger scale. For collection, dedicated vehicles are used alongside compartmentalized vehicles, and soft means are also used [8]. The type of collection influences the collection rate and the quality of bio-waste [9]. Indeed, there is sometimes a lack of consistency in the types of waste accepted by collection systems. Some garden waste or soiled paper, paper towels, tissues, Kraft paper and napkins may be included in the food bio-waste collection, depending on the recycling options available. This can change considerably the quantity and quality of bio-waste collected.

Table 1 Estimated bio-waste potential per year in France and Europe (data published between 2017 and 2022)

	France	References	Europe	References
Collection rate (%)	6.2	[11]	Up to nearly 70% (Luxembourg, Norway)	[12]
Percentage of Bio-waste in household waste (%)	32	[13]	34	[1]
Bio-waste annual production	23 Mt (economic activities + households)		86 Mt (households only) 113.8 Mt (economic activities + households)	[1] [12]
Food waste	9.4 Mt		59.9 Mt	[12]
Households	5.3 Mt	<i>Calculated from ADEME data [14]</i>		
Economic activities (food distribution + catering)	4.1 Mt			
Green waste	14.2 Mt		53.9 Mt	[12]
From households and collected separately or at waste collection centers	5.1 Mt	[14]	N.A	
From economic activities and collected separately or at waste collection centers	3.2 Mt		N.A	
Home managed	5.1 Mt		N.A	
Mixed collections	0.8 Mt	[13]		
Agricultural manures (given for comparison)	120 Mt	[15]	1.4 billion t	[16]

N.A not available

Bold value signifies waste main categories

Due to these collection differences and to a lack of database at a local level (for example, there is no specific database for urban areas [10]) quantifying the amount of bio-waste generated and or collected is therefore challenging as well as comparing the data from different accounting sources. Some global estimated figures may however be gathered at a national or European scale (Table 1).

In view of the above, better identifying and quantifying bio-waste flows is a specific challenge for this biomass, with the aim of better understanding its management and recovery.

Bio-waste: Challenging to Characterize

As well as the knowledge of the flows, discussed in previous section, an in-depth knowledge of characteristics of bio-waste is also necessary to (a) choose waste management and treatment methods, (b) establish preventive measures to minimize waste production and regularly assess the impact of their implementation, (c) determine the proportion and nature of impurities in sorted waste and the capacity of products to be used in recovery chains, (d) plan and optimize waste collection and treatment services, (e) minimize risks (to health and the environment) and nuisances (odors) and (f) communicate with citizens and local and national authorities on the various aspects of bio-waste management.

There are several ways of characterizing bio-waste:

- Sorting by category according to the composition of the bio-waste. A distinction is made between food waste, often classified into five categories (fruit and vegetables, meat and fish, cereals, dairy products and eggs, other food residues such as coffee grounds and impurities [17], and green waste (lawn waste, leaves, branches, etc.). This categorization offers a view of consumption habits as well as an assessment of the ability to sort and may facilitates waste management and treatment. Another type of categorization considers uneaten food, partially eaten food, leftovers and unidentifiable waste in order to assess the effect of reducing waste [18]. A widely shared and standardized typological characterization between European countries would enable sorting instructions to be standardized, data to be compared more easily and possible changes in the waste stream to be better understood, particularly by distinguishing avoidable bio-waste from that which cannot be avoided. There is a need to replace the “bin audit” (i.e., analysis of the volume and composition of waste) which is highly time-consuming and costly. New methods such as photo-coding which has proved to be efficient and reliable to decipher food types and status should be developed [19].
- Bio-physic-chemical characterization also appears to be essential for the proper operation of treatment plants [20]. Relatively few studies have accurately determined the bio-physic-chemical composition of biodegradable food waste, as shown by the review by Fisgativa et al. [21] and

even fewer regarding green waste. Regarding food waste, The main characteristics are a low pH of between 3.5 and 5 due to the rapid accumulation of organic acids (lactic acid, etc.), a dry matter content of between 10 and 25%, a C/N of between 14 and 37, a high methanogenic potential of between 400 and 500 NL CH₄/kg Volatile Solids (VS). The total nitrogen, phosphorus and potassium contents are around 2.8, 0.5 and 1.2% of dry matter respectively. A high sodium content has also been observed. However, a high variability was also highlighted. Moreover, very few studies have looked at the physical characteristics of bio-waste, such as the rheological properties of the mixture, its density, the size and shape of the particles, the crystallinity of the material or its thermal properties, although these are important for the design and operation of treatment processes [22].

- It is crucial to consider the differences in characteristics between fibrous green waste and food waste, as these influence collection and transport methods and materials, biodegradation properties and therefore treatment methods. These differences relate to density (around 0.6 for food waste and 0.2 for green waste), moisture (around 70% for food waste) and fiber content, which is much higher for green waste. Fibrous organic matter that is storable and less compactable is ideal for composting. In contrast, the moist organic matter in food waste needs to be collected frequently and is ideal for producing biogas and digestate. The seasonal nature of production is very marked for green waste, but not significantly so for food waste.

For the majority of physicochemical, biochemical or elemental characteristics, average values cannot be considered representative of all types of bio-waste, especially when considering food waste [23]. Each stage of the treatment chain will therefore have to be able to adapt to the characteristics and variability of bio-waste, which will thus have to be characterized better and more frequently.

Bio-waste: Opportunities and Constraints for Recovery

The agronomic recovery of bio-waste helps to restore soil quality and replace synthetic fertilizers (nitrogen, phosphorus and potassium), thereby reducing dependence on non-renewable resources and environmental impacts. 20 to 30 kt/year of phosphorus, a 'critical element' [24] used for food production in France, is found in bio-waste, representing almost 10% of the consumption of phosphate fertilizers used on agricultural soils since 2012 (www.fao.org). For Europe (EU 27), this quantity is around one Mt/year. As far as nitrogen and carbon are concerned, the flows from bio-waste are low compared with those from other organic waste (livestock waste in particular). Nevertheless,

the recovery of these elements should be considered in order to reduce the consumption of synthetic fertilizers, thereby limiting greenhouse gas emissions and increasing carbon storage in the soil. However, bio-waste should only be returned back to the soil if it is of good quality and without risk for health. This concern applies in particular to food waste that faces specific constraints.

Food waste can contain pathogens such as *Salmonella*, *Escherichia coli*, *Clostridia* spores and possibly *Staphylococcus aureus* [25]. The potential presence of animal by-products in food waste makes hygienization mandatory when using the final residues as soil improvers [26]. Although it appears to be limited, as is also the case for residual household waste, a microbiological risk cannot be ruled out when managing bio-waste with source separation. It has to be considered particularly in the event of prolonged storage of bio-waste in the kitchen or on the pavement, when cleaning the bio-bucket, when collecting the containers and when handling the compost (turning, sieving, spreading). The exposure of workers to high concentrations and potentially dangerous species of microorganisms described, for example, by Georganas et al. [27] should be better studied. Moreover, food waste is a wet highly fermentable matter with a tendency to emit strong odorous compounds, to attract animal pests, factors that still add sanitary handling constraints.

Food waste can also contain up to 20% of inert materials. These impurities are typically composed of plastics, bones, glass, porcelain, metal, stone and residues of food products when mechanically unpackaged [28, 29]. They give rise to numerous technological constraints and significant additional costs [30]. Their presence in composts and digestates can make these products unsuitable for agricultural use [31]. As post-collection separation of these impurities is difficult, their presence in food waste must be greatly reduced at source. Contaminants such as pesticide residues, persistent organic pollutants, terpenes, aldehydes and ketones and heavy metals may also be present in bio-waste, although their concentrations are low following the ban on hazardous chemicals. Given their impact, it would seem necessary to have additional statistical data on the type and quantity of contamination in bio-waste in order to reduce it effectively.

As it is difficult to improve what we do not measure correctly, there is an urgent need to develop a common strategy for acquiring, sharing and using reliable data about bio-waste flows. In the same line, throughout the bio-waste recovery chain, understanding and optimizing the system requires bio-waste to be characterized according to a variety of indicators (typological, physical, chemical, biological, and also sociological representation). The difficulty lies in the complexity of these indicators and the challenge of sampling the bio-waste. In agreement with operators, researchers should thus advise the minimum indicators that should be

measured on field at an acceptable cost to determine bio-waste flows and quality.

A Resource with a Strong Societal Impact

Bio-waste: An Urgent Challenge Lacking Concerted Governance

The revision of the European Waste Framework Directive [2] in 2018 made compulsory for all European countries to introduce source separation and recovery of bio-waste, for all types of producers (households and activities) since the 1st January 2024. In countries like France, where the obligation has been traduced in the law against food waste and for circular economy [7], as the bio-waste sorting was still not largely implemented, the time for the first trials of sorted bio-waste collection will overlap with the obligatory rollouts. The implementation of the law obligation will involve a lot of stakeholders as households, local authorities, businesses, future “customer-farmers” and SSE (Social and Solidarity Economy) players, among others. Trade-offs are going to be increasingly crucial, and need to be thought through systemically between the roles of each player and the priorities for recovery. For example, the ways in which bio-waste can be recycled will have an impact on the relationship between town and countryside, where interdependencies are becoming increasingly complex [32]. Trade-offs therefore need to be debated collectively, at an inter-territorial level (from regional to micro-urban) and with a forward-looking vision at local authority level, as part of urban renewal projects and the creation of new neighborhoods. However, urban professionals, developers, urban planners and architects are not yet sufficiently aware of these issues and of the challenges posed by bio-waste and its impact on the dynamics of urban and regional development.

These factors show that the governance of bio-waste management currently lacks a systemic approach shared by all the players involved, whatever their role in the value chain. All stakeholders involved in bio-waste management, i.e. institutions (involved in defining environmental standards, urban planning, policy orientations, development financing, communication), citizens (participation in decision-making), NGOs (community mobilization, communication), private operators (implementation of actions), scientists (decision support) and the media (communication) need to work together to make decisions, implement and monitor actions that will enable sound management of bio-waste, with a long-term vision that optimizes resource allocation.

Food-Waste: A “dirty” Waste Among Bio-waste?

When it comes to bio-waste, food waste constitutes a specific stream. Users’ social perceptions about food waste are

largely linked to eating habits, consumption patterns and attitudes to health issues. It is often perceived as ‘dirtier’ than other waste and is associated more with the notion of elimination than with that of recycling a resource. As a result, sorting food waste is not a small ecological gesture to be adopted, like turning off the tap water. The special characteristics of food waste mean that it needs to be managed differently in the home, with daily attention, dedicated and adequate storage space, more frequent disposal, etc. The routine involved in sorting food waste and more generally bio-waste is not unique and univocal over the course of a lifetime, due to the ups and downs of people’s lives (acquiring a home, forming a couple, births, separations, etc.). It would therefore be necessary to put in place high-quality communication and training on sorting, as well as a system for qualifying products in order to overcome this reputation as “dirty” waste.

Beyond the challenges of characterization and quantification, bio-waste is thus also a specific biomass in terms of its social significance and the number of players involved in its management. This dynamic social ecosystem, which needs to be properly identified, cannot be ignored in the decision-making process for bio-waste recovery systems.

How does the Unique Nature of Bio-waste Affect the Technical Steps of Its Management Systems?

The Choice of Collection System must Consider Diversity of Local and Regional Contexts

The diversity of situations and contexts encountered in a given territory calls for a variety of bio-waste management solutions. For collection, voluntary drop-off points and door-to-door collection must complement each other to offer solutions that are adapted to the types of areas, sources of bio-waste, existing facilities and future outlets, considering economic efficiency, environmental impacts and social acceptance. While door-to-door collection tends to achieve a higher recovery rate and higher quality than the drop-off point, it has higher operating costs. Handling different waste streams in the same lorry (e.g. some towns in Wales, UK) could decrease this cost. The effectiveness of a voluntary drop-off system depends mainly on the density of the equipment installed and the distance that residents have to travel. However, a drop-off point may not be limited to the collection of bio-waste, as tested in Milan, but may also include equipment for the selective collection of several streams (bio-waste bin, glass bin, etc.), making the journey more cost-effective for the user. The choice of collection method also strongly depends on population density [33, 34]. From these considerations, it is obvious that the diversity and

complexity of the influencing factors make the choice of a bio-waste collection strategy a complex one, which opens up new research needs. To date, researchers have focused mainly on optimizing collection rounds [35], locating the processing site [36], the drop-off point [37] or evaluating different management scenarios linked to an increase in the quantity of bio-waste [38]. However, no study has really analyzed the deployment of a new bio-waste collection system in a city using a multi-criteria approach. New research in this area will be able to draw on more numerous and diversified data since collection and management systems are increasingly equipped with identification cards [39].

It is Crucial to Ensure that the Bio-waste Collected is Sorted Properly

The aim of sorting bio-waste is to maximize the collection of high-quality bio-waste that is free from contaminants, particularly when targeting recovery for agricultural purposes. Advanced sorting techniques used in centralized platforms have good potential for eliminating impurities, but are not sufficient to guarantee the required product quality. They also mean greater complexity in the processing chain and higher costs. For these reasons, reducing contamination at source is by far the most desirable approach. Policies aimed at maximizing bio-waste collection under increasingly complex socio-technical conditions could, in the absence of sufficient feedback on performance, lead to a high degree of contamination of raw materials [40]. It will therefore be necessary to study the limits of mass collection of bio-waste in order to maintain high product quality.

Many factors influence sorting behavior and the resulting quality, as listed below:

- Clarity of collection strategy. The types of bio-waste accepted and undesirable materials must be perfectly identified by citizens and producers. All the containers (bins, bags, etc.) and the surrounding urban context are relevant vectors for incentive communication to raise awareness of the issue of sorting quality. In addition, sanitary quality must be ensured, as shown by a German study [41].
- Make sorting comfortable for citizens and professionals [42]. The size, weight, design (ventilated bins or not, with bag or not), maintenance, location and handling of containers must be optimized on a set of criteria simultaneously. The design of new buildings must also take better account of waste management [43].
- Raising awareness by adapting to the target audience [44]. An information strategy tailored to the target group must be adopted, with information repeated over time, translated into several languages and using a variety of appropriate media. It should be noted that the method of

raising awareness is not easily transferable from one site to another or from one country to another, as it depends heavily on the level of education and cultural and social aspects. Citizens and producers should be better informed about the consequences of poor sorting on the bio-waste management system. Surveys have shown that linking bio-waste to a 'return to the earth' and the idea of nature is a way of mobilizing the general public [45]. The innovative concept of Know-as-you-throw (KAYT) should be applied to continuously inform the citizen about his sorting performance [46].

- Incentives, charges and pricing. These are key actions to make citizens and producers more responsible [47]. Incentives such as the Pay-as-you-throw tariff scheme (PAYT) appear to be more effective than taxation in improving sustainable consumption and sorting behavior [48]. Penalties can be effective but should be progressive. Reducing anonymity by accurately allocating waste containers to citizens in buildings by installing radio frequency identification (RFID) systems or an individual card to access the containers seems to be a relevant approach [49]. Regular inspection of the containers and measurement of the impurity content should be systematized [19] and the information should then be communicated to the citizen, for example by means of a label affixed to the container. The consistency of the entire waste management system must also be ensured. For example, residual waste should be subject to a much higher tax than bio-waste in order to motivate citizens to sort their waste at source.

All these points show that multi-criteria research is necessary to help implementing a good combination of technical, communication and incentive means. Moreover, as it will take time to adjust the sorting process with the quality objective, the mechanical sorting technologies mentioned above could be used as transitional tools during this training period.

Choosing the Appropriate Recovery Routes

Currently, the most common treatment in Europe is composting (30.5 million tons treated per year), followed by anaerobic digestion (12.4 million tons treated per year) and the combination of these two processes (4.4 million tons treated per year) [50]. These techniques meet the objectives of returning waste to the soil and producing renewable energy (anaerobic digestion also called methanization). In sparsely populated areas, home composting and community composting reduce the volume of food waste and green waste to be collected and therefore greatly reduce the cost of treating bio-waste. However, the risks of poor process control leading to GHG emissions [51], with a particular focus

on nitrous oxide, microbiological risks [4] and the risks of spreading compost on non-productive areas need to be better assessed and minimized. Urban agriculture can also offer an attractive solution for compost recovery in cities.

Methanization is considered to be an economic activity that should make a significant contribution to mitigating climate change in the short and long term [52]. If methane leaks are controlled, it therefore appears to be the most climate-friendly option, albeit at a slightly higher cost than composting [53]. The choice between these technologies is therefore closely linked to population density, the nature and quality of the raw material, and the existence of facilities and an outlet for the products (gas, heat, digestate, compost). In France, bio-waste is still not widely used, accounting for just 3% of the quantity of material entering anaerobic digestion in 2020 [54]. However, supplying bio-waste from urban areas to methanization units run by farmers in outlying rural areas seems to be a convincing model, promoting the resilience of methanization units and strengthening the town/country link. The most virtuous projects could be encouraged by local authority decisions based on the choice of outlets (agricultural projects promoting agro-ecology and organic farming, for example).

Several other recovery alternatives are being investigated: (1) the biological production of ethanol, volatile fatty acids (which can be converted into polyhydroxyalkanoates), lactic acid, hydrogen, biopesticides and insects; (2) the production of solid or gaseous products from thermal processes (pyrolysis, gasification, hydrothermal carbonization); (3) the use of green waste to produce molecules or as fuel; (4) direct use of food waste as animal feed [5]. The main challenges for biological processes are related to the economic balance and environmental impact of the production chain, which depend heavily on the recovery stages for the targeted molecules or products [55]. Research should therefore systematically consider these stages and demonstrate a lower environmental impact than competing solutions. The link with anaerobic digestion and/or composting for the recovery of residues should be systematically considered in order to complete the nutrient cycles. For thermal processes, in addition to production costs, technologies need to be improved, in particular to manage the heterogeneity of bio-waste.

Regulatory barriers to the marketing of products derived from bio-waste have also been identified. These need to be simplified and adapted to new challenges, while maintaining high health standards. The feasibility and profitability of processing chains depend on dedicated flows and their regularity. In terms of the circular economy, these chains are at the top of the recycling hierarchy, but they need to demonstrate their results in terms of effective and efficient material recycling. Consequently, given the high level of investment required to set up a value chain, holistic research should be carried out to help choose, on a multi-criteria basis, which

recovery routes are feasible and preferable for a given territory and context.

Intrinsically Improving Processing Technologies

While the choice of recovery route is of prime importance, the fact remains that improved processes are needed to adapt to the specific characteristics of bio-waste and to spatial and temporal variations in flows.

Due to the multiplicity of sources and the variability of their characteristics and the objectives pursued, different physical, mechanical, thermal, chemical, biological or enzymatic pre-treatments can be applied to bio-waste [56, 57]. The main challenges of bio-waste pre-treatment are (1) optimizing transport and resource conservation [58, 59], (2) reducing environmental [60] and health risks [61], including odor management [62], (3) removal of unwanted fractions [63], (4) optimization of subsequent biological conversion and (5) optimization of product recovery [64]. The issue of impurity removal is crucial [63, 65, 66], but few works study the performance of deconditioning technologies. Difficulties in meeting the European target for high-quality composts have been reported [67], especially when shredding was initially applied. Finally, deconditioning may require the addition of water [68], limiting subsequent biological treatment. Establishing an appropriate combination of pre-treatments for deconditioning, hygienization and biotreatment optimization therefore remains a challenge, as little information is available on the transferability of processes and procedures in real cases, on scale effects and on environmental impacts.

Even if composting appears to be a mature, adaptable and mastered technology, some specific challenges remain when applied to bio-waste. Being very moist and fermentable, food waste requires the systematic addition of a co-substrate (green waste, for example). Physical limitations to aeration, liquid and gas emissions (CO_2 , N_2O , CH_4 and odors) and undesirable fauna must be minimized. While hygienization conditions are well established (example of the French decree on animal by-products –ABP– decree of 2018 [69]) via the establishment of adequate temperature/time couples (55 °C/14 days, 60 °C/7 days or 65 °C/ 3 days), very few studies address microbiological risks for composting on an individual and community scale [70–72]. Better consideration of social, socio-geographic and political aspects seems necessary in the composting field. For example, the conditions for implementing sorting instructions with prohibitions (meat products, uncrushed eggshells, citrus fruit remains, etc.) that redirect this organic matter to incineration or landfill need to be studied. The multi-functionality of collective composting—waste management, urban sociability, relationship with nature, learning about democracy and governance—should also be the subject of further research.

Methanization technologies can be considered mature, but their application to food waste faces various obstacles. In 2018, an insufficient number (47) of methanization facilities with sanitary approval for ABP of third category were listed in France [26]. This represents a major challenge for the development of the sector [73]. Security of raw material supply is another point of vigilance, as is control of input characteristics (green waste, grease, salinity, abrasive materials, etc.), which have a major impact on digestibility, product quality in terms of composition, dehydratability, etc., and process operation. Given the characteristics of bio-waste, co-digestion with optimized recipes should be favored. [30]. For anaerobic digestion, research challenges should focus on process efficiency (ex: reducing water consumption), with better knowledge for optimizing solid processes [74], and on digestate management, which is a key issue for the viability of the sector. Nutrient recovery and the re-growth of post-hygiene microorganisms are key issues in this latter area [75].

A Holistic, Forward-Looking Approach to Bio-waste Recovery: Recommendation for System Conception

Because of its unique properties, bio-waste presents challenges at every stage of the production-recovery chain, whose global efficiency, assessed as technical, social, environmental and economic performance, then depends on multiple interacting factors, beyond technical solutions. Indeed, the bio-waste value chain results from the combination of the territorial context, the stakeholders' behavior, the available operational solutions and the regulatory framework (Fig. 1, colored rectangles). Such a complex system calls for a holistic design and management approach, including waste prevention promotion.

Bio-waste: Thinking About Reduction Throughout the Food Value-Chain Before Conceiving Recovery

Whereas green waste mainly depends on geographical and climate context, losses leading to food-waste occur throughout the food production and consumption chain. They represent about 10 Mt/year in France, i.e. 150 kg/year/person, costs €16 billion and emits 15 million tons of CO₂ equivalent, i.e. 3% of greenhouse gas emissions from national activity [76]. Prevention targets primarily the consumer,

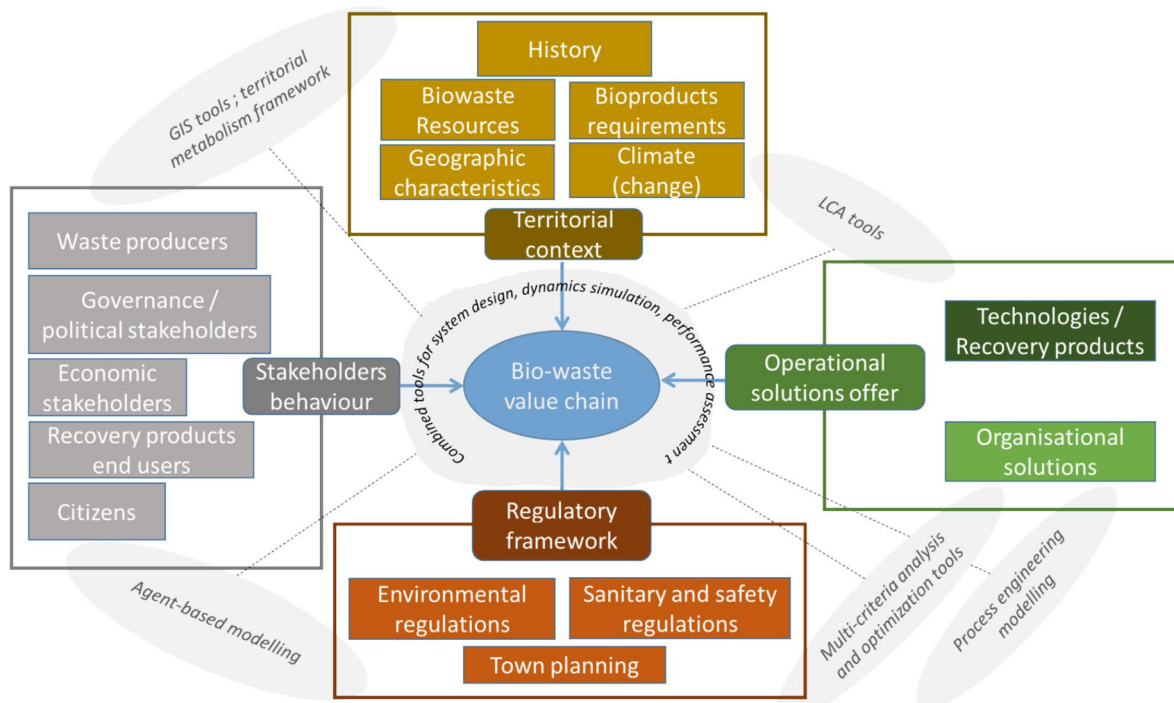


Fig. 1 Factors influencing the design of bio-waste recovery systems (colored rectangles) and the current tools available to model and assess it (grey clouds)

who accounts for 30% of food waste production. However, we must not ignore other sources of bio-waste production. Launched ten years ago with the National Pact to Combat Food Waste, France's legislative arsenal has been steadily strengthened over the years to reduce food waste, based on the classic hierarchy of prevention, recovery and recycling. National and local initiatives combine awareness-raising, tax incentives for food donations and the development of networks and partnerships between players in the food production and supply chain. However, the supply model is still based on a plethora of processed and standardized food products, which inevitably leads to major losses that are totally invisible to consumers [77]. The conditions for relaxing the constraints linked to use-by dates and the absolute need for standardized products could be studied to determine how to act without creating a health risk. Furthermore, we need to avoid any contradictions in our vision of the circular economy: the introduction of solutions for recovering food waste must not make the prevention of surpluses less incentive. This is why priority must be given to reducing food waste and losses. Feedback shows that sorting at source can raise awareness of food waste and bring about a change in behavior, leading to a reduction in losses and improved sorting. Researches on this lever for action should be the amplified through multidisciplinary even interdisciplinary approaches.

The Need for System Conception Tools Based on Multi-criteria and Dynamic Approaches

As Fig. 1 illustrates, it is essential to take into account the multiplicity of interacting factors when proposing effective value chains for bio-waste management. Economic and social considerations must be taken into account at least as much as technological constraints. A complex network of stakeholders, requiring in-depth analysis, influences bio-waste management. Recent work on urban metabolism [78] could provide useful insights in this area.

Moreover, the dynamic context surrounding bio-waste (changing bio-waste flows, urbanized areas, policies, etc.) calls for adaptive management systems to ensure their continued relevance. As previously discussed, food waste prevention is a crucial component. Assessing the evolution of household food waste flows in the medium term remains uncertain, raising challenges for the sizing of treatment facilities. Indeed, facilities dedicated solely to bio-waste treatment can be inefficient if they are not correctly sized.

Consequently, the development of modelling tools to design bio-waste management systems must be based on multi-criteria analysis to respond to this diversity of considerations [79]. The tools should consider: (1) the location of the existing infrastructure and the urban planning of the territory, the use of geographic information tool is

thus necessary (GIS); (2) the evolution in time of the bio-waste production and new facilities of treatment; (3) the impact of political decision on the fraction of bio-waste collected, for instance communication effort or change in collection; (4) but also the link between the stakeholders and how the market will react to political incentive. The tools should be able to assess the system based on (i) the economic viability for all stakeholders (ii) environmental impact, (iii) social indicators for instance the number of jobs created.

Currently many types of models exist, each dealing with one part of the above-mentioned goals (Fig. 1, grey clouds). For instance, geographic information system (GIS) models have been already used to optimize the location of facilities and voluntary drop-off points [37, 53, 80] or to optimize the transport. However, they are not considering evolving collection rate. System dynamics must be taken into account to study how the management system can be transformed over time [81]. Agent-based models have been used to explore the impact of policy on the use of composting or anaerobic digestion facilities [82]. These studies are interesting to understand how the market will respond to a new regulation or political decision. Agent-based models have the advantage of modelling each stakeholder with its own objective. Thus, it is possible to analyze the economic viability of all stakeholder and the decision of each type of stakeholder. Life cycle assessments (LCA) are used to compare different scenarios of management at a certain time of deployment from an environmental point of view. LCA is based on a macro scale simulation, and needs a description of the modelled system. To reach an efficient multi-criteria decision tools, it is necessary to consolidate these modelling approaches within a single modelling platform. In this sense, the hybrid simulation tool developed by Ding et al. [83] for demolition waste is promising because it compiles a geographic information system (GIS) and a hybrid simulation system comprising system dynamics (SD), agent-based modelling (ABM) and even discrete event simulation (DES) to predict the fate of a stockpile of demolition waste over time as a function of the regulations applied to specific stakeholders. In addition, the use of artificial intelligence and machine learning, fed by local data, could improve these tools. The creation of shared databases on local experiences also represents a major challenge to be met in order to be able to validate each modelling block.

However, we can see that most of the design and assessment tools proposed in scientific studies lack a truly interdisciplinary and multi-stakeholder approach enabling them to be fully adopted by local authorities. We thus recommend that whatever the chosen modelling tools the design of bio-waste recovery systems must include close collaboration with local authorities in order to be adapted to the specific needs of each context.

The Evolving Context of Bio-waste Calls for Adaptable Management Systems Based on Diversity of Solutions and Cooperation Between Stakeholders

As above mentioned, the dynamic context on bio-waste requests a system highly adaptable to an evolving amount and quality of collected bio-waste. Such an adaptability could be reached through the diversity, flexibility and modularity of the technical and organizational solutions forming the bio-waste management system. Hence, if co-treatment of bio-waste in multi-stream facilities, such as agricultural or territorial anaerobic digestion, can offer a resilient solution, decentralized management is another adaptable approach, offering greater flexibility to respond to temporary variations [84]. Decentralized composting, particularly in Italy, has demonstrated its efficiency and cost-effectiveness [53, 85]. Although some authors attest to environmental benefits [86, 87], further studies are needed to fully assess the environmental and economic advantages of decentralized solutions. More likely, an approach combining centralized and decentralized management, considering local characteristics and existing infrastructures could prove optimal. It is therefore imperative to develop methods for designing solutions tailored to each territory, considering the different aspects of the socio-technical system involved in bio-waste management and exploring a diversity of solutions.

However, even with a sophisticated multi-criteria decision tool, the challenges of bio-waste management remain complex, particularly the mobilization of stakeholders, which is essential. In this latter domain, the concretization of actions remains questionable. To overcome these difficulties, since 2018 the French National Environment Agency has introduced the ConcerTO method to work with territories on their organic waste management strategies by mobilizing stakeholders [88]. However, its effectiveness remains uneven, as demonstrated by its application in five territories since early 2024. Other research, such as the BEECOME project [89], is examining the factors influencing the transition to better bio-waste management, to better define the levers for action.

One of the major remaining problems is that no optimal form of governance has been yet established to coordinate local stakeholders, including citizens, initiatives. Sharing experiences between all players, particularly at local level, is crucial to avoid pitfalls and promote best practices. Researchers have thus a key role to play in collaborating with local authorities to evaluate co-construction solutions and identify success factors or obstacles to their implementation.

Conclusion

The management of bio-waste requires an integrated approach, from consideration of the root causes of its production to its recovery.

Thus, it is firstly crucial to tackle the causes of over-production and overconsumption of foodstuffs, and not to overshadow them with a capacity to recycle the bio-waste produced. In this view, relaxing the constraints linked to use-by dates and promoting less standardized products should be encouraged. Moreover, prevention methods such as the concept of Know-as-you-throw should be further implemented. For unavoidable bio-waste, priority should be given to material and agronomic recovery, with the aim of achieving circularity. This means combating impurities at source. Moreover, comparisons between different management methods must anticipate the requested quality of the final products. Various sorting incentive and pricing measures need to be assessed, as well as new methods for characterizing sorting quality, such as photo-coding combined with artificial intelligence.

While the quality of recovery products is essential, other issues and questions need also to be better addressed by research. For example, improving the quantification of bio-waste flows, and the associated methods, is essential when targeting the design of flexible collection and treatment solutions adapted to local characteristics. In addition, behavioral sciences are essential for effectively mobilizing the players involved.

Finally, the organizational stakes, integrating economic, social, political and environmental considerations, are major, and require a trans-disciplinary approach based on close collaboration between research, operational staff, private sector, NGOs, media and decision-makers. This calls for the development of powerful scenario assessment tools based on shared field data and feedback and integrating at least LCA and multi-criteria decision analysis. Moreover, the conditions for creation of interaction and governance spaces adapted to bio-waste management, along the lines of water management systems, should be studied.

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Authors and Affiliations

Tremier Anne^{1,6}  · Barrault Julia^{2,6} · Bayard Rémy^{3,6} · Berger Sylvaine^{4,6} · Besson Mathilde^{5,6} ·
Vivière Bevan Manon^{2,6} · Zdanevitch Isabelle⁶ · Paul Etienne^{5,6}

✉ Tremier Anne
anne.tremier@inrae.fr

¹ INRAE, UR OPAALE, Rennes, France

² SUEZ, R&D Centre LyRE, Bordeaux, France

³ Laboratoire DEEP, INSA, Lyon, France

⁴ SOLAGRO, Toulouse, France

⁵ TBI, Université de Toulouse, CNRS, INRAE, INSA,
Toulouse, France

⁶ Member of Bio-Waste Prospective Working Group, ASTEE,
Courbevoie, France