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Management of organic waste materials in a territory with a circular economy approach: issues and challenges[1]

Olivier Schoefs
Full Professor at Université de Technologie de Compiègne (UTC), Director of the Department of Chemical Engineering and member of the "Integrated Transformations of Renewable Matter" research unit, Compiègne, France
olivier.schoefs@utc.fr

Nomena Ravoahangy
PhD student at Université de Technologie de Compiègne (UTC), Compiègne, France
Polytechnique Montréal, Montréal, Canada
nomena.ravoahangy@utc.fr

Guillaume Majeau-Bettez
Professor at Polytechnique Montréal, member of the Department of Chemical Engineering and member of the CIRAIG research group, Montréal, Canada
guillaume.majeau-bettez@polymtl.ca

Frédéric Huet
Professor at Université de Technologie de Compiègne (UTC), member of the Department of Technology, Societies, Humanities and member of the "Knowledge, organization and technical system" research unit, Compiègne, France
frederic.huet@utc.fr

SUMMARY

Municipal bio-waste can be recovered through various technologies. Some may be industrial-scale, others may be neighborhood-scale or even individual. Moreover, geographical, demographic and socio-economic characteristics present a high degree of territorial variability. The intersection of these technological and socio-economic diversities leads us to define two meta-scenarios for the management of these bio-waste: either decentralized management that avoids costly collection but leads to low added value co-products, or centralized management that requires collection and transport of bio-waste to an industrial recovery unit but leads to higher added value co-products. Both meta-scenarios reveal environmental and economic tensions, coupled with social considerations. Finally, pending a circular economy, it is necessary to verify the circularity of economic and material flows within the territory. As a result, the management scenarios must be adapted to the specific characteristics of the territory and assessed environmentally, economically and socially. The life cycle analysis provides a comprehensive assessment of these impacts. In the context of a circular economy, it is also necessary to analyze and review the economic models of the sector and the structural relationships between players. These objective elements of analysis are intended to help decision-makers choose the appropriate system for managing municipal bio-waste on a territory in a logic of circular economy.

KEYWORDS: Biowaste. Territory. Valuation technologies. Life cycle analysis. Circularity.

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INTRODUCTION

Every year, more than 2 million tons of municipal waste are produced worldwide according to the World Bank, 44% of which is organic (KAZA *et al.*, 2018). Moreover, it is estimated that food waste is between 30% and 45% of these residual materials. The management of such bio-waste[1] is therefore a concern for all countries. They put in place regulatory mechanisms to reduce the quantities generated and to recover the residual materials. For example, France has adopted laws to reduce the amount of bio-waste in a logic of circular economy and green growth. In particular, they foresee that all individuals will have a practical solution for the sorting at source and recovery of their bio-waste before 2025. This dynamic presents a real challenge to waste managers in the territories to find a sustainable solution, that is to say, one that is livable, viable and equitable. The objective of this article is to present the challenges of organic waste management, taking into account economic, environmental and social impacts, and in a logic of circular economy. Our contribution aims to clarify the possible link between the above statements and the implementation of coherent solutions in the territories to achieve the best management and recovery of this bio-waste.

METHODOLOGY

The work presented here is based on a field study currently being conducted within the ARC agglomeration (Agglomération de la Région de Compiègne, in the French region of Hauts de France). It has more than 70,000 inhabitants, and is characterized by a wide variety of situations both geographically (urban and rural habitats) and socio-demographically (inequalities within the territory).

The methodology used consists, first of all, in identifying existing technologies for the recovery of bio-waste. Secondly, the various possible management systems will be formalized in terms of meta-scenarios, which will make it possible, in a third stage, to highlight the tensions that may exist between the various management systems at environmental, economic and social levels and in a circular economy logic. In a fourth step, it will set out the basic principles to be followed in identifying alternative scenarios to be compared. Finally, in a fifth step, a methodology for analyzing scenarios aiming at assisting decision-making in the choice of the most satisfactory scenario will be presented.

RESULTS AND DISCUSSIONS

Municipal organic waste recovery technologies

Several proven technologies exist for the recovery of organic waste materials (NAYAK and BUSHAN, 2019). They can be divided into three main categories: biological, (thermo-)physico-chemical and thermal technologies. The most common biological technologies are composting and anaerobic digestion.

Composting is a process for the biological decomposition and stabilization of putrescible residues under thermophilic aerobic conditions (HAUG, 2018). It produces compost that can be used as an organic soil amendment in green spaces or in the horticultural industry. Anaerobic digestion (also called methanization) involves the conversion of organic matter into biogas composed mainly of methane and carbon dioxide by a microbial consortium operating anaerobically (MOLETTA, 2008). In addition to generating an energy-recoverable biogas, anaerobic digestion produces a nutrient-rich digestate that can be used as a fertilizer for agriculture or, after stabilization by composting, in green spaces or in the horticultural industry. Biological processes may also include processes involving enzymatic hydrolysis, the purpose of which is to produce molecules of interest. However, these processes must be coupled with other biological or thermal processes to recover the remaining material after extraction of these molecules of interest.

(Thermo-)physico-chemical processes, which consist in extracting bio-waste from high added value molecules, are still marginal processes and specific to certain types of bio-waste. Furthermore, they must be coupled to another biological or thermal process to recover the remaining material after extraction.

Thermal processes include incineration, pyrogasification and hydrothermal liquefaction/carbonization. Incineration, as a method of waste disposal, involves burning waste at high temperatures (800-1000ºC) in ovens with an excess of oxygen to reduce its volume (McKENDRY, 2002). The energy produced during the process can be used to supply an urban heat network, to produce electricity or both (cogeneration). Incineration also generates a co-product called coke that can be used in the construction and public works industry. Pyro-gasification involves bringing waste to medium or high temperatures (400-900ºC) and in the absence of oxygen. The solid and liquid phases obtained during this first phase are then converted into a synthesis gas, called syngas, by the addition of an oxidizing agent. (OKOLIE *et al.*, 2022). The syngas produced, rich in hydrogen and carbon dioxide, can be steam reformed to form methane. The solid phase generated, called biochar, rich in carbon, can be used in the horticultural industry. Hydrothermal liquefaction/carbonization involves treating bio-waste with subcritical or supercritical water at high pressure (greater than 20 MPa) and temperatures between 180ºc and 260ºC. This process produces a structured charcoal, called hydrochar, which can be used as a fuel or organic amendment for the horticultural industry for example (OKOLIE *et al.*, 2022). These biological, thermal and thermo-physicochemical processes may optionally be coupled to optimize the conversions (KASSIM *et al.*, 2022).

Each of these technologies can potentially be deployed at different scales: industrial, neighborhood (area defined by the concentrated presence of several households) or individual (corresponding to one household). However, as much as the composting process and, to a lesser extent, the process of methanization can be implemented at the three scales, the thermal processes are deployed only on an industrial scale mainly due to investment cost considerations.

Table 1 associates the main biological and thermal processes with their specificities in terms of co-product generation and adaptability to the three major scales (industrial, neighborhood and individual). It is noted, on one hand, that all technologies generate valuable co-products and, on the other hand, that only biological technologies can be applied on all three scales.

Table 1 Main processes for the recovery of municipal organic waste.

Technology	Category	Co-products	Scales
Composting	Biological	Compost	Industrial Neighborhood Individual
Methanization (anaerobic digestion)	Biological	Biogas Digestate	Industrial Neighborhood Individual
Incineration	Thermal	Coke	Industrial
Pyro-gasification	Thermal	Syngas Biochar	Industrial
Hydrothermal liquefaction/carbonization	Thermal	Hydrochar	Industrial

Municipal organic waste management systems

Municipal organic waste is generated by citizens. Their distribution, in quantity and quality, in a territory therefore depends on variations in population density and socio-demographic profile in that territory (DUPRÉ, 2013). Given that some technologies can be deployed at the industrial, neighborhood, and individual scales, two extreme meta-scenarios can be imagined. In a first scenario, hereinafter referred to as the decentralized scenario, bio-waste is sorted but not collected. They must therefore be treated by technologies that can be adapted to individual or neighborhood levels. In a second scenario, hereinafter referred to as the centralized scenario, the bio-waste is sorted, collected and transported to an industrial recovery unit. In this case, all the technologies presented in Table 1 can be used. In a given territory, between these two extreme meta-scenarios, hybrid scenarios can be considered by bringing together decentralized and centralized management systems according to the variations in population density and socio-demographic profile in that territory. The two meta-scenarios thus defined are illustrated in Figure 1.

(a)

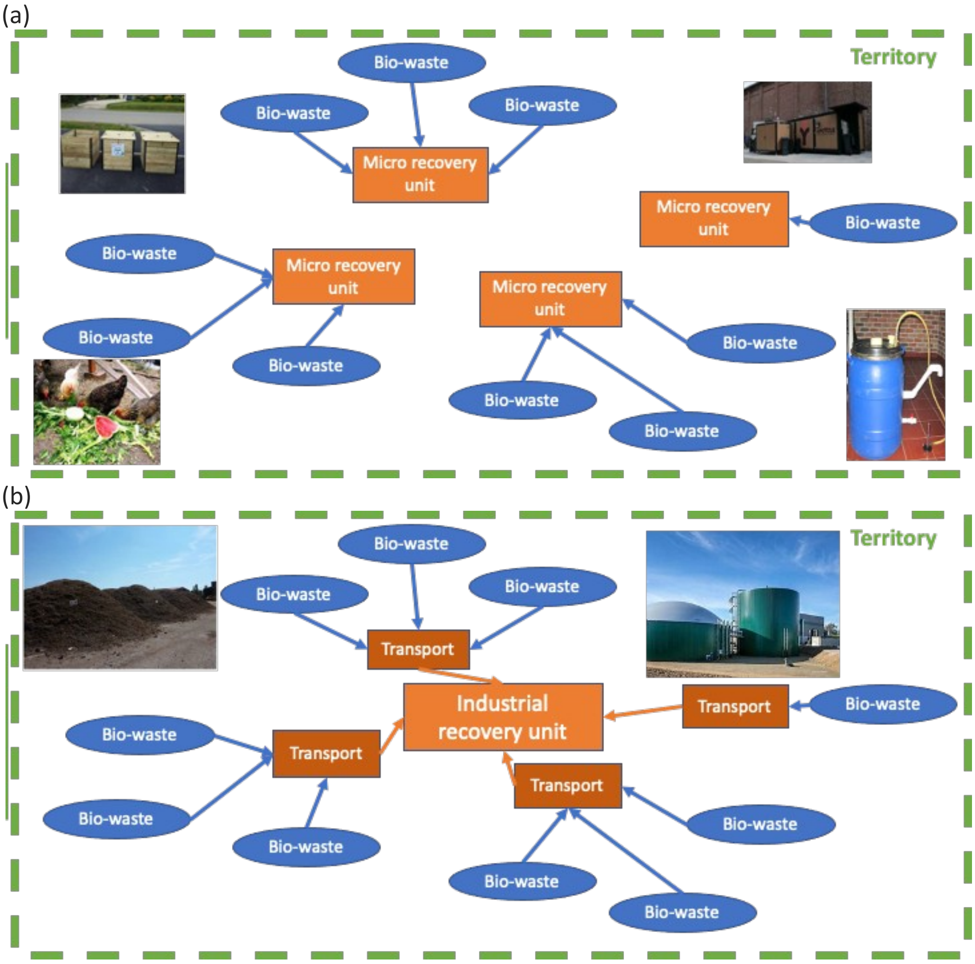

Figure 1 Illustration of the two meta-scenarios for municipal bio-waste management: (a) decentralized and (b) centralized.

Tensions between the two meta-scenarios for municipal bio-waste management

In a context of decision-making regarding the choice of the management system to be implemented, these meta-scenarios reveal tensions in their ability to reconcile the environmental, economic and social dimensions. There are also some questions about the circularity of scenarios.

On one hand, the decentralized management system makes it possible to avoid collecting and transporting costs economically and environmentally. However, co-products generated by individual or neighborhood technologies have low quality due to the presence of contaminants (plastics, metals, etc.) or the suboptimal operation of the process (absence of thermophilic phase or poor aeration for composting, poor temperature control for methanization, for example). In summary, this decentralized scenario, the most sober, is the one that allows the least control for the recovery of organic waste.

On the other hand, the centralized management system must bear the economic and environmental cost of transporting bio-waste, equipment and infrastructure. However, the industrial process can guarantee better quality of co-products by introducing a pre-treatment step to remove the contaminants from the bio-waste or by optimizing the operating process parameters (forced aeration systems and temperature control for example). These co-products can thus integrate a market (for example, organic compost amendments, energy for purified biogas and fertilizer for digestate). In summary, this centralized industrial scenario offers the best potential for organic waste recovery, but generates a higher economic and environmental cost than the decentralized scenario.

The definition of the scenarios must therefore take into account not only the environmental impacts (use of natural resources and emissions into the environment) throughout the life cycle of the biowaste recovery chain but also the economic model of this sector.

The economic and environmental considerations can be complemented by a social study. Indeed, in the chain of municipal bio-waste recovery, the citizen is the first link. Regardless of the meta-scenario, its performance and implementation will be influenced by the behavior of the citizen. It is thus possible to anticipate heterogeneous behavior as regards the use of an individual composter, the sorting of bio-waste before collecting, both qualitatively and quantitatively, the deposit of bio-waste in a voluntary point of supply, and the degree of appropriation and motivation according to the possible benefit that the citizen would derive from his effort. Moreover, decentralized management systems can lead to odor nuisance due to poor operation of the micro-process or public health problems due to the proliferation of rodents for example.

In terms of circularity, the two meta-scenarios also stand out. Indeed, in a decentralized management system, it is very likely that all co-products remain in the territory or are used in the territory, thus respecting the economic circularity of chemical atoms (i.e. matter), in particular carbon, nitrogen and phosphorus. By contrast, in a centralized system, co-products enter a global market and can therefore leave the territory altering the economic circularity of atoms in that territory, which potentially implies a loss of control and regulatory oversight as well as transport-related environmental impacts. Moreover, in the decentralized scenario, each citizen has the "burden" of finding a utility for the compost he produces. One can even imagine situations where there is no relevant utility nearby (no vegetable garden or green spaces, etc.). On the contrary, collectivization/centralization of co-products would facilitate access to more relevant markets in the territory to some extent. As a result, the ways in which co-products are valued in a circular economy logic involve reviewing the economic models of the players involved (new values attached to products and processes, new cost and remuneration structures, etc.) and the structural buying/selling relationships in a territory.

Finally, management systems are defined at a given point in time according to demographic, sociological and economic situations. However, these situations can change over time: increase in the population of the territory, development of the urban plan, establishment of new economic activities, etc. From this point of view, although the industrial recovery units benefit from significant economies of scale, their sustainability depends on the ability of local authorities to anticipate the quantitative and qualitative development of the organic waste to be treated. Faced with demographic or sociological changes, industrial facilities may become undersized or oversized. Also, changes in dietary behavior could affect the production of bio-waste. The micro-recovery units have the other side of the coin: a large adaptive capacity with installations that can easily be added or removed, but much less effective in terms of economies of scale, and thus the costs of production of the recovery service. There is therefore a potential for a sort of temporality conflict between the volatility of user behavior and the longer-term commitments involved in setting up a system for the recovery of bio-waste. This raises the specific issue of the ability of local authorities to anticipate or appreciate these behavioral changes when choosing solutions.

It follows that the choice of a system for the management of municipal organic waste materials in a territory under a circular economy logic is not a matter of optimization but rather of seeking a satisfactory solution, of collective compromise, from an economic, environmental and social point of view.

Identification of alternative scenarios for bio-waste management systems

Given the tensions highlighted in the previous section, it is important to break down these meta-scenarios into more precise and contextualized scenarios. Scenario identification consists of choosing between centralized or decentralized management systems, defining key parameters (routes and frequencies of collection tours, quantity and location of neighborhood recovery units, quantity and location of individual composters, etc.) and choosing recovery technologies.

Hybrid scenarios involving individual solutions, neighborhood solutions in certain areas or centralizing collection in certain others according to their specificities may, for example, be recommended. Furthermore, taking into account the variations in population density, socio-demographic profile and the typography of the areas (urban or rural) on the territory must make it possible to better understand the quantities and qualities of the residual materials available and the ways in which the citizen appropriates the scenarios on each area of that territory. This mapping makes it possible to optimize certain key parameters of the scenarios, such as the routes and frequencies of collection tours, or the location of the neighborhood recovery units, or even the way in which they are financed.

In the choice of technologies, it is important to take into account the quantity and quality of bio-waste (in terms of organic composition and contamination) to be recovered in order to properly size processes and model environmental performance and impacts, reducing uncertainty as much as possible. In the context of a circular economy, it is also important to understand the markets within or outside the territory in order to make economic use of the process co-products (compost, biogas, digestate, coke, biochar, etc.) and to define the economic model(s) over the whole sector or territorial ecosystem.

Analysis of municipal organic waste management scenarios

The assessment of the economic, environmental and social dimensions of these bio-waste management scenarios can be based on various impact measurement tools. This multi-faceted mobilization of tools could reflect an empirical difficulty in bringing together multiple questions. However, this plurality could be valuable in order to appreciate the problem in its complexity (previously mentioned) and to avoid an incoherent reductionism facing the nature of the stated problem.

From an environmental perspective, life cycle analysis (LCA) is recognized as the reference method for systematically quantifying the various types of environmental impacts (multiple criteria) caused directly and indirectly by a technological choice, in order to avoid displacement of impacts (JOLLIET et al., 2017).

From an economic point of view, the analysis of the flows of money and value production over the life cycle also makes it possible to quantify the economic impacts of a scenario.

From the point of view of social impact assessment, Social Product Life Cycle Assessment (S-LCA) is the recommended methodology. In 2009, the United Nations Environment Program (UNEP) issued guidelines for the social life cycle assessment of products, which were updated in 2020 (BENOIT NORRIS et al., 2020).

Joint environmental, economic and social life cycle analyzes constitute the life cycle sustainability assessment as illustrated in Figure 2.

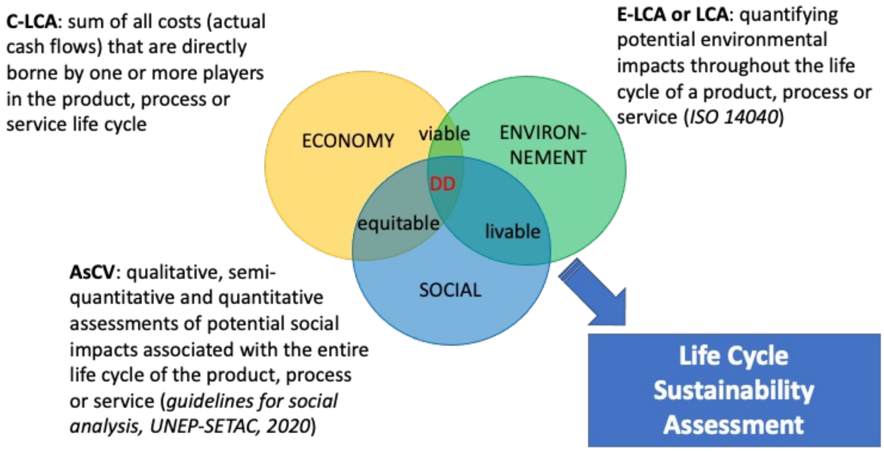

Figure 2 Components of Life Cycle Sustainability Assessment.

In a circular economy, these analyzes must be supplemented by analyzes of economic flows and of imported and exported materials flows at the territory level in order to characterize the economic and atome circularity. It is, of course, important that the interpretation of the results be made in the light of possible imports of materials used for food into the territory and therefore for the generation of bio-waste.

FINAL CONSIDERATIONS

Defining a municipal waste management system on a territory is a complex subject. All of the following elements must be taken into account, and in their interdependencies:

- the effectiveness of recovery technologies
- local and global markets for co-products of recovery processes
- the variability in the quantities and quality of bio-waste generated in the territory
- variability in population density
- the variability of the socio-economic profile
- the business models of the biowaste recovery chain

The study of the tensions between the different possible meta-scenarios showed that a unique management system cannot be implemented to answer all territory situations. It is therefore necessary to consider several relevant alternative scenarios and compare them on the basis of environmental, economic and social life-cycle analyzes and of an analysis of imported and exported economic and materials flows at the territorial level in a circular economy logic. These objective elements of analysis will help decision-makers and/or stakeholders to choose the most appropriate system for the management of residual materials in a territory in a circular economy logic and to help communicate choices.

NOTES

[1] In the article the term 'bio-waste' will be used as a synonym for 'organic waste' to facilitate reading.

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Correspondência: