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Article

Carbon Footprint of Composting and Vermicomposting of Household Biowaste: A Decision-Making Factor for Regional Biowaste Recovery Policies?

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Abstract: Since 1 January 2024, French local authorities will be required to offer householders a means of recovering biowaste, either as a soil improver or as an energy source. Several criteria influence their choice: cost, availability of operators and equipment, social facilitation, etc. However, greenhouse gas (GHG) emissions are rarely taken into account in the decision-making process. This article compares the emissions of four biowaste recovery systems, differentiated by their process (composting or vermicomposting) and management type (community or industrial). It is based on the carbon footprint method defined by the French Agency for Ecological Transition (ADEME). The assumptions and emission factors come from two sources: a field survey of composting and vermicomposting companies and associations in the Lyon area and a review of the literature on GHG emissions from the decomposition of organic matter. The carbon footprint of the processes was determined by estimating the CO₂ equivalent per ton of composted biowaste. The results show that industrial composting emits the most carbon (CO₂). Depending on whether biogenic carbon is taken into account or not, the ranking of the other three processes changes. When biogenic CO₂ is taken into account, it is the process that has the greatest influence on the result; on the other hand, when biogenic CO₂ emissions are not taken into account, the type of management determines the ranking. These results are discussed in relation to the methodological limitations of the comparison, other biowaste management options and the reduction of biowaste-related emissions. For example, by studying the agricultural use of biowaste compost, the carbon balance could be refined by including the emissions avoided from the production of nitrogen fertiliser. However, environmental assessment is only one of a number of decision-making factors (social, economic, agricultural, etc.) in waste management.

Keywords: carbon footprint; biowaste; greenhouse gases; composting; vermicomposting; carbon sequestration



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1. Introduction

The irreversible consequences of climate change are one of the greatest challenges facing society today. Since the Industrial Revolution, human activities have led to a steady increase in GHG emissions, particularly carbon dioxide (CO₂) [1]. In response to the effects of climate change, various measures have been taken to reduce GHG emissions into the atmosphere [2].

Urban waste management is a significant source of GHG emissions [3,4]. Organic waste from green waste, agriculture, food industry, household consumption and catering is of particular interest. Firstly, it is of significant quantity: it is estimated that one-third of the food produced in the world is thrown away, accounting for over 40% of total solid waste [5,6]. Secondly, the decomposition of organic waste in open landfills is responsible for 20% of global anthropogenic methane (CH₄) emissions [7]. Finally, organic waste can be converted into potential resources such as energy [8,9] and soil amendments or plant fertilisers [10,11].

1.1. Composting and Vermicomposting Household Biowaste

Given the enormous volume of organic waste, four treatment methods are commonly used: incineration, methanisation, composting and vermicomposting. In France, the volume of composted waste has increased significantly over the last 15 years [12], while incineration and methanisation have shown little change. Vermicomposting remains mainly a domestic or experimental practice.

This study focuses on composting and vermicomposting as these are the methods promoted by municipalities for the recovery of household biowaste. It examines the GHG emissions generated during the transformation of biowaste into compost or vermicompost, in particular CO₂, CH₄ and nitrous oxide (N₂O). The assessment considers direct emissions associated with the biochemical transformation process as well as emissions associated with waste collection.

This article focuses on biowaste as defined in Article L. 541-1-1 of the French Environmental Code. In practice, the household biowaste considered here is kitchen waste (vegetable peelings, fruit residues, etc.) and plate waste (leftovers, meat residues, etc.). The particularities of household biowaste are the seasonal heterogeneity of its composition, which reduces its potential use for biogas production [13]. Because of the diffuse nature of its production (produced by each household), the active participation of residents is essential to mobilize this source.

1.2. Composting and Vermicomposting Biowaste: A Little Studied Subject

Biowaste composting is an ancient practice. It involves the decomposition of biowaste by microorganisms under aerobic conditions. The result is a stable, nutrient-rich organic product (compost) [14,15] that improves soil structure and fertility [16].

So far, the scientific literature has mainly examined composting from the perspective of local initiatives and their social and educational externalities [17,18], as well as their integration into more global collective experiments (e.g., food, education) [19–21]. Few biochemical studies have examined pathogen survival during different composting processes (domestic, industrial) [22–26] or nutrient inputs to soil and plants [27,28]. In most cases, compost is studied after sowing, which leads to the integration of soil-related variables, making it difficult to compare results taking into account specific soil characteristics. Belgium is an exception in Europe, as composting has long been included in discussions on its importance for agricultural and economic transition [29,30].

Vermicomposting (or worm composting) is relatively new and not well-developed in France. Local vermicomposting is still experimental and has been promoted by the Eisenia association in the Lyon area [31]. It gained popularity in the 1980s through a 'pyramid' commercial system in which earthworm breeders provided a starting stock and instructions for reproduction [32] and through Marcel Bouché's work on the role of earthworms in soil activity [33]. Although it was the subject of several publications in the 1980s and 1990s, vermicomposting of urban biowaste is currently under-researched in France [34,35]. Some French research looks at vermicomposting in Mexico, describing its origins in an

alternative agroecosystem in Indigenous communities [36] and its relative normalisation in schools [37]. Outside of French studies, vermicomposting research includes case studies in Canada [38], Senegal [39], Madagascar [40], and Vietnam [41,42].

1.3. Biochemistry of the Composting and Vermicomposting Processes

The basic principle of composting is to treat organic waste according to three main principles.

- Principle 1: Alternating between wet nitrogenous waste (household biowaste) and dry carbonaceous materials (green waste, wood, dead leaves, cardboard). Nitrogenous waste, which is rich in organic matter, often comes from our meals, vegetable peelings and grass. The balance between these two types of waste is essential to obtain a mixture that promotes decomposition, creating a favourable environment for the microorganisms that facilitate the composting process.
- Principle 2: Regular aeration of the compost. This step ensures a constant supply of oxygen, a vital element for the aerobic microorganisms responsible for decomposing the waste. It promotes air circulation within the compost, helping to maintain optimum conditions for the biological reactions needed to convert organic waste into compost.
- Principle 3: Carefully monitor the moisture content of the compost. While the presence of water is essential for the survival of microorganisms, excess moisture can compromise the process. Compost that is too moist runs the risk of lowering the temperature, thereby disrupting the necessary thermophilic dynamics. Maintaining the right balance of moisture helps to create an optimal environment for microorganisms and promotes the efficient decomposition of organic waste.

Vermicomposting differs from traditional composting in that it uses earthworms to accelerate the decomposition of organic matter and improve soil conditions. The worms increase the surface area exposed to microorganisms, speeding up the process [43]. Unlike composting, vermicomposting is a mesophilic process (occurring at ambient temperatures), stabilised by interactions between worms, microorganisms and other composting agents [44] (Table 1). Suitable vermicomposting worms must have high rates of organic matter consumption, tolerance to environmental stress, high reproductive rates and rapid growth [45]. The most commonly used species are *Eisenia fetida* and *Eisenia Andrei* [46].

Table 1. Stages of composting and vermicomposting.

Composting	Vermicomposting
<p>The composting process is made up of four phases: the mesophilic phase, the thermophilic phase, the cooling phase and the maturing phase. The mesophilic phase, at the beginning of the process, is characterised by a high proliferation of mesophilic bacteria [47,48]. This is followed by the thermophilic phase, during which there is a significant increase in temperature over a short period of time. The thermophilic phase is where most biodegradation takes place. It is considered to be the most active phase. This is followed by the cooling phase, during which the temperature drops, and finally, the maturing phase, which can last up to 6 months and during which the temperature drops even further [3].</p>	<p>The process of vermicomposting is made up of two phases: the active decomposition phase and the maturing phase. Earthworms ingest and break down organic matter, which is then biochemically degraded by microorganisms during the active decomposition phase [43]. Earthworms both increase the ability to assimilate organic matter and help move less mobile microbial communities [48]. Maturation does not directly involve earthworms. It is characterised by the final decomposition of organic matter by microorganisms. At this stage, the earthworms need to be separated from the organic matter, a process known as migration, which is achieved by adding fresh waste elsewhere to attract the earthworm community [49].</p>

1.4. The Carbon Footprint: A Tool for Local Policy Guidance and Evaluation

Many French municipalities are not yet in compliance with the 2020 AGEC law, which requires them to offer biowaste recycling solutions to every household. GHGs are rarely considered in territorial biowaste management strategies. Comparing the carbon footprints of composting and vermicomposting provides information that can influence local public policy decisions.

The carbon footprint is a tool for calculating the GHG emissions of a public or private organisation. Since the Grenelle 2 law of 2010, it has become a tool for guiding and evaluating local public policies. For example, local climate and energy plans are based on carbon footprints, which have become mandatory for certain companies, public institutions and local authorities. More specifically, they are required to draw up a carbon footprint, publish it and update it every three years (article 75 of the Grenelle 2 law).

However, few of these structures are in compliance (compliance rate of 35% in 2021) [50]. When the data are published, they are often not very detailed and truncated for Scope 3 (optional from a regulatory perspective), which is often the most emissive. In addition to the strategic and political issues faced by these organisations, there are methodological and financial challenges to conducting a carbon audit, particularly in terms of identifying emission factors and collecting data. The availability of local data on carbon emissions and sequestration is therefore an important issue for local public policy.

2. Methodology

The carbon footprint assesses the amount of GHGs emitted into the atmosphere when processing 1 metric ton of biowaste for each biowaste recovery sector. Two choices are essential in the methodology: the scope of the emissions to be counted and the data to be included.

2.1. Presentation of the Biowaste Recovery Systems

The carbon footprint compares four biowaste recovery systems that differ in terms of decomposition process (composting and vermicomposting) and management (community management and industrial management).

Community management is a management method based on the participation of households (sorting, voluntary collection, turning of compost piles, etc.). Community composting and vermicomposting take place in collective bins managed by associations near housing estates in dense urban fabric. Industrial composting is carried out on a platform on which a large volume of shredded biowaste is decomposed. The processes differ in terms of the space required, the type of facilities and the way they are managed.

Industrial composting involves several stages: sorting to eliminate unwanted waste, shredding, adding pruning waste (shredded woody green waste such as tree branches) and maturing. After 6 or 8 months of decomposition, the compost is sieved to remove the last undesirable elements (source: interviews). Table 2 shows the four systems assessed.

Table 2. Biowaste recovery processes studied.

	Community Management	Management of Industrial Composting
Composting	Community composting	Industrial composting
Vermicomposting	Community vermicomposting	Windrow vermicomposting

Community composting and vermicomposting take place in wooden bins located near residential buildings. They require no energy to operate. In contrast, management of industrial composting requires energy during the process, which has an impact on indirect

GHG emissions. In fact, industrial composting management involves the collection of a significant volume of biowaste (by truck) and the mechanical turning of rotting biowaste. Industrial composting is carried out on concrete slabs to avoid infiltration of the 'juices' into the soil, which can pollute the soil at high levels. Industrial vermicomposting is carried out in windrows directly on agricultural soils. So, unlike composting, there is a question mark over the massive infiltration of "juice" into agricultural soils, with a potential risk of contamination.

2.2. Principles of Carbon Accounting: Gases Studied and Units of Measurement

The carbon balance methodology used is that defined by Ademe in France [51]. It is regulated by law. Emissions must be expressed in ton of carbon dioxide equivalent (art. R. 229-45, Environmental Code) and are based on conversion factors. The GHGs considered in the carbon footprint are CH₄, N₂O, CO₂, carbon monoxide and fluorinated gases. GHG emissions are divided into three scopes according to their proximity to the activity studied: direct emissions from biowaste recovery processes (Scope 1), indirect emissions related to energy demand (Scope 2) and other indirect emissions (Scope 3).

Establishing GHG inventories requires taking into account a choice of components linked to the six main gases mentioned in the Kyoto Protocol. In order to carry out the inventory in France, the ADEME relies on the two international standards [52,53] as well as the European directives in force [54] and other national standards [55].

The exhaustive list of GHGs covered includes carbon dioxide (CO₂), nitrous oxide (N₂O), methane (CH₄), sulphur hexafluoride (SF₆), hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs). This reflects a concern about capturing the largest emissions with the greatest potential impact on climate change. CO₂, as the main GHG resulting from the combustion of fossil fuels, represents the direct carbon footprint of human activities. N₂O and CH₄, produced by agricultural and industrial activities, add an important dimension to the sources of emissions, being associated with soil management and organic decomposition processes, respectively. SF₆, HFCs and PFCs are more specific but no less important gases. Their inclusion highlights the need to consider emissions from specific sectors and, thus, the importance of understanding the specific sources contributing to the accumulation of these gases in the atmosphere.

2.3. Application of the Carbon Footprint Method to Composting and Vermicomposting

The sources of emissions to be taken into account in the carbon footprint were adapted to the specific composting and vermicomposting processes based on a field survey of stakeholders in the Lyon agglomeration, where three of the studied processes were established: community composting, vermicomposting and industrial composting [31]. Ten interviews and three site visits were carried out with institutional actors in biowaste management, companies and composting associations. The study identified and quantified the sources of indirect emissions (Scope 2 and 3) depending on the type of composting (community or industrial): collection by lorry and its energy (diesel, electricity, mechanical or manual turning of biowaste, building lighting, energy consumed by sorting machines, etc.). An analysis of the scientific literature was then used to obtain data on emission factors related to biochemical degradation processes (Scope 1).

Scopes 1, 2, and 3 emissions are calculated for each biowaste recovery system studied, as well as avoided emissions. Scope 1 includes direct emissions of CO₂, CH₄ and N₂O from the analysed process and direct emissions from combustion engine-driven mobile sources in the case of facility processes. The assessment takes into account the addition of carbonaceous materials during the process of the four systems (pruning waste, cardboard,

etc.). Scope 2 includes indirect emissions related to the consumption of electricity, steam, heat or cooling.

Given the differences in processes between community management and the industrial management of biowaste, it is important to include the third (optional) scope in the carbon footprint in order to include the emissions associated with waste collection and the composting processes. Scope 3 includes, for community composting and vermicomposting, the purchase of products or services and the end-of-life of products sold; for composting and windrow composting, the purchase of products or services, waste, investments, downstream transport of goods, the use of products sold, the end-of-life of products sold and business travel. Table 3 shows the activities that emit GHGs included in the carbon footprint for each scope for composting and vermicomposting.

Table 3. Details of the activities taken into account in the study.

Scope 1 Direct Emissions	Scope 2 Indirect Emissions	Scope 3 Indirect Emissions from Upstream and Downstream Activities
Stationary combustion sources		
Mobile combustion sources (energy from biowaste collection)	Electricity consumption	Upstream Energy
Non-energy processes Addition of carbonaceous materials	Steam, heat and cooling consumption	Purchases of goods and services
Biomass (soil and forests)		Buying products and services
		Inbound freight Outbound freight
		Transporting visitors and customers Commuting
		Waste End of life of products sold
		Use of products sold

2.4. Inclusion of Biogenic Carbon in Process Emission Factors

Biogenic carbon is defined in the ADEME carbon database as “the carbon contained in biomass of agricultural or forest origin that is emitted during its combustion or decomposition, as well as that contained in soil organic matter”. In other words, fossil carbon and biogenic carbon are both emitted into the atmosphere, but biogenic carbon is subsequently absorbed by nature through the process of photosynthesis, thus creating a cycle. Biogenic carbon, derived from organic matter, is inherent in many activities and processes and plays an important role in the natural balance of the carbon cycle.

There is a scientific debate on the potential carbon neutrality of biogenic CO₂ [56–59], particularly for the composting of biowaste, considering their organic origin [3,60]. In political decision-making, there is currently a consensus in France and several other countries that biogenic CO₂ should not be included in the calculations, as carbon is of natural, non-fossil origin and is therefore part of a cycle [61].

However, biogenic carbon has a climate impact: before being captured by biomass growth, CO₂ molecules remain in the atmosphere and contribute to global warming [56]. There is therefore a time lag between the flux of emissions and the sequestration of biogenic CO₂ in the biosphere and anthroposphere. The term “rotation period” is used to describe the time it takes for a plant to grow before it is used as bioenergy [56]. Therefore, 1 unit of biocarbon stored over a time horizon is not always equivalent to 1 unit of CO₂eq [62]. The time lag varies with vegetation type [62] and decomposition conditions (temperature, humidity) [63]. Adetona and Layzell (2023) [63] identified biomass decomposition profiles based on a criterion of material and duration: biowaste corresponds to the rapid decomposition of agricultural residues. This is the profile that releases carbon into the atmosphere the fastest, releasing up to 90% of its carbon into the atmosphere in the first year of decomposition.

Biogenic carbon is not taken into account in Ademe’s carbon balance methodology (Documentation Base Carbone), which is justified by the capacity of French forests to absorb biogenic CO₂. We have chosen to include biogenic carbon among the GHGs emitted during the process. Although biogenic carbon is less harmful than fossil carbon, its emissions are still harmful to the environment and contribute to the greenhouse effect. There is no guarantee that the carbon sequestered by photosynthesis will offset this effect. The impact of biogenic carbon on the carbon balance results of the sectors studied is crucial: excluding this component is tantamount to eliminating carbon dioxide emissions altogether. Such an omission would undoubtedly be an aberration in a robust and scientifically based environmental analysis. Omitting them from the emissions calculation would mean ignoring an essential dimension of the carbon footprint, thereby distorting the reality of the environmental impacts associated with a given entity or activity.

2.5. Choice of Emission Factors

Emissions were calculated using reference units from the Base Carbone[®] and scientific literature, as well as variables from the field survey. The field survey provided data not widely available in the literature, such as the rate of carbon addition, which varies from sector to sector.

For community composting, the values from Nordahl et al. [64] were used, as they refer to the same type of waste and come from a relatively recent study from 2023. For industrial composting, CH₄ and N₂O emission factors were taken from ADEME, as these are the official data used in France [65]. CO₂ was estimated using data from UpCycle and the scientific literature [66]. The range used is between 15 and 25 kg/t of waste. However, there is no scientific consensus on emission factors for vermicomposting, as they depend on the type of waste processed and various factors such as temperature, humidity, ventilation, etc. We therefore decided to use the emission factors reported in the literature. We decided to use the data from Nigussie et al. [67] because, although it is a less recent study, the data are presented as a percentage of composting, which makes it easier to compare the four processes. We cross-referenced these data with the review carried out by Zhang et al. [68].

The emission factors for community vermicomposting are calculated on the basis of those for community composting, and the emission factors for windrow vermicomposting are calculated on the basis of those for industrial composting. In addition, as there are different values in the scientific literature, we have constructed a range of values and chosen an average scenario. Table 4 shows the emission factors used. Tables 5 and 6 specify the minimum, maximum and average data for each biowaste recovery system.

Table 4. Average emission factors for the four composting processes (kg/metric ton of biowaste).

	Gas	Composting Process			
		Industrial Composting [65,66]	Windrow Vermicomposting [67]	Community Composting [60,64,68,69]	Community Vermicomposting [63,68,69]
GHG	CO ₂	20.00	24.08	56.30	66.72
	CH ₄	3.10	2.36	0.88	0.67
	N ₂ O	0.06	0.04	0.07	0.05

Table 5. Construction of emission factor for windrow vermicomposting.

Emission from Industrial Composting [65,66] Kg/t Waste		Emission Factors for Windrow Composting [67] Kg/t Waste		
		Min (+11%)	Moy	Max (+26%)
[15–25]	CO ₂	16.65	24.08	31.50
3.10	CH ₄	2.29	2.36	2.42
0.063	N ₂ O	0.04	0.044	0.047

Table 6. Construction of emission factor for community vermicomposting.

Emission Factor for Community Composting [64] Kg/t Waste		Emission Factor for Community Vermicomposting [65–68] Kg/t Waste		
		Min (+11%)	Moy	Max (+26%)
56.30	CO ₂	62.49	66.72	70.94
0.88	CH ₄	0.65	0.67	0.69
0.07	N ₂ O	0.044	0.047	0.051

3. Results

The carbon footprint analysis assesses and compares the GHG emissions of different composting and vermicomposting methods. The results suggest that the biochemical transformation process has less impact on emissions than the type of management (community or industrial).

Figure 1 compares the CO₂ equivalent emissions of the different processes, taking into account biogenic carbon. Industrial composting appears to be the solution with the highest emissions. Total emissions by the composting method (Figure 1) are calculated on the basis of an average.

Vermicomposting processes have lower emissions than composting processes, which is consistent with the results obtained by Komakech et al. (2014) [70] and Lleó et al. (2013) [60]. This can be explained by the Scope 1 direct emissions, which are lower for vermicomposting for all three gases (CO₂, CH₄ and N₂O). In addition, the CH₄ and N₂O emission factors considered are lower for vermicomposting than for composting (Table 4), so it is natural that their direct emissions are lower for the former case. However, direct CO₂ emissions are lower for vermicomposting despite its higher emission factor. This is due to the fact that vermicomposting uses less bulking materials (0.4 metric ton of shredded material for 1 metric ton of biowaste compared to 1 metric ton of shredded material for 1 metric ton of biowaste in composting), which increases the direct emissions of composting by about 40% compared to the direct emissions of vermicomposting. There is no precise information in the literature on the amount of shredded material that should be used in the composting and vermicomposting processes. The proportions used in this article were estimated on the basis of interviews with stakeholders in the Lyon area. The results could therefore vary if these proportions were changed.

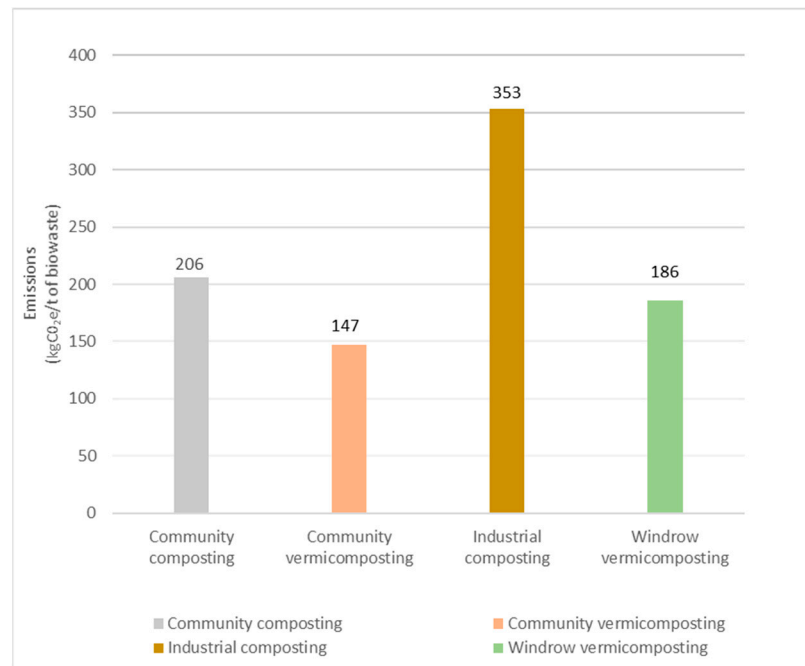


Figure 1. Total emissions from the four composting processes (including biogenic carbon).

According to the literature, the reduction in GHG emissions from vermicomposting compared to composting can be explained by two main factors. First, earthworms increase air circulation in the compost, which maintains aerobic conditions and therefore reduces emissions [71]. Another explanation is that vermicomposting is a process that takes place at ambient temperature, unlike traditional composting, which is a thermophilic process. Chukwudi et al. [16] analysed the composting process and found that the rate of CO₂ and CH₄ emissions was directly proportional to temperature.

Emissions by scope are very uneven across all sectors (see Figure 2). Scope 1 accounts for the majority of emissions. There are very few Scope 2 GHG emissions. Community management (composting and vermicomposting) generates very few Scope 3 emissions.

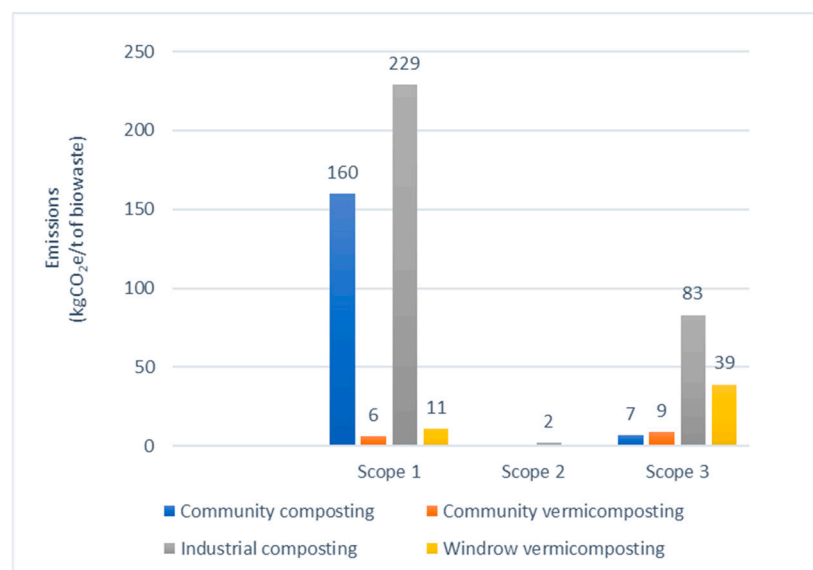


Figure 2. Comparing the four composting systems by scope.

GHG emissions vary according to the solution (see Figure 3). Community processes (composting and vermicomposting) emit more biogenic carbon, almost three times more.

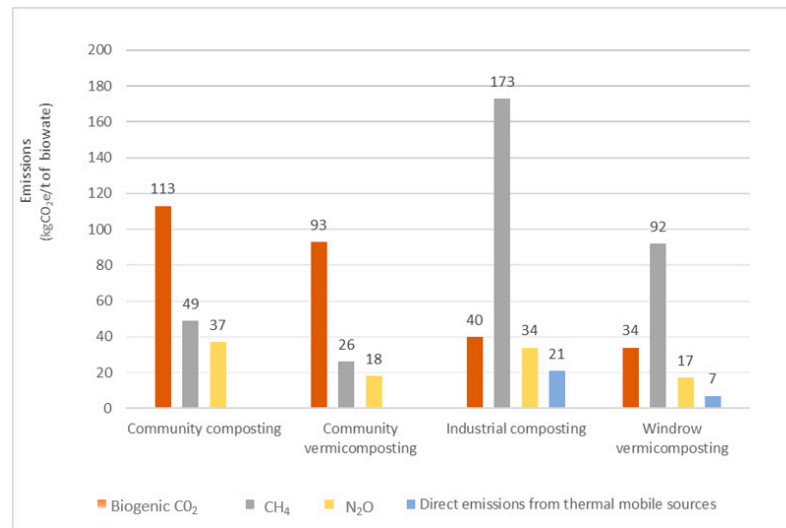


Figure 3. Comparison of Scope 1 GHG emissions by sector.

If biogenic carbon is included in the emissions, industrial composting is the highest emitting process compared to community composting and windrow vermicomposting (see Figure 4). If biogenic carbon is excluded, the order from highest to lowest emitter is industrial composting, windrow vermicomposting, community composting and community vermicomposting. When biogenic CO₂ is included, Scope 1 emissions are higher for all processes, with composting processes emitting more than vermicomposting processes, both for industrial and community processes. On the other hand, if biogenic CO₂ emissions are not taken into account, Scope 1 emissions are reduced and Scope 3 becomes more important. The result is the industrial or community nature of the processes: industrial processes emit more than community processes.

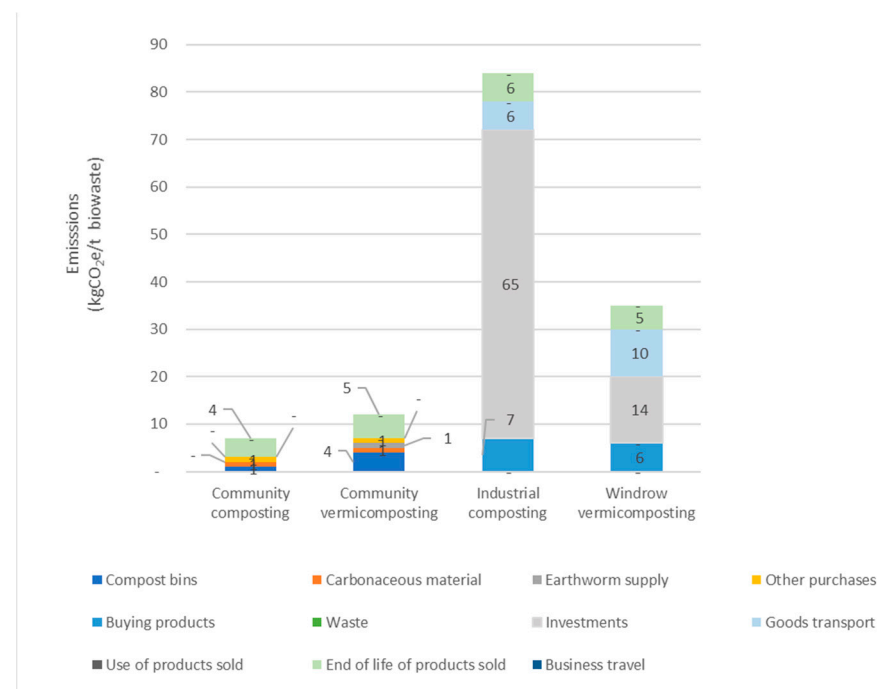


Figure 4. Comparing the origin of Scope 3 emissions by sector.

4. Discussion

Finally, we compare the carbon footprint results with emissions reported in the scientific literature. We discuss the potential for incorporating carbon footprints into local waste management policies, as well as local climate change adaptation and agricultural development policies.

4.1. Compare and Contrast the Results with the Scientific Literature

Our results are based on average emissions and tend to support the view that overall GHG emissions from vermicomposting are lower [71]. Industrial composting is probably the biowaste recovery process that emits the most GHGs due to the high temperature of the process and its large-scale mechanisation [49,65].

The main gas emitted during composting and vermicomposting is CO₂, and these emissions occur mainly at the beginning of the process, which may be related to high temperatures [3,72,73]. Although CO₂ emissions are higher, their global warming potential is about 273 and 28 times lower than that of N₂O and CH₄, respectively, making the emissions of these two gases quite significant [3,74].

There is no consensus in academic circles on the comparison between composting and vermicomposting in terms of GHG emissions. For example, Komakech et al. (2015) [70] conducted a life cycle assessment study with municipal biowaste and found that vermicomposting emitted approximately 78% less CO₂eq than conventional composting. Lleó et al. (2013) [60] also found that vermicomposting emits less, reducing NH₃, CH₄ and N₂O emissions by up to three times compared to composting.

Nigussie et al. (2016) [67] found that vermicomposting emitted 25–26% less N₂O and 22–26% less CH₄ than traditional composting but 3–14% more CO₂. A study by Lv et al. (2018) [72] analysed emissions from both processes using sewage sludge waste and found that vermicomposting emitted less CH₄ and more N₂O than composting, with no significant difference in CO₂ emissions between the two processes. On the other hand, Zhang et al. (2023) [69] analysed N₂O emissions from composting and vermicomposting of biowaste and found that there was no significant difference between the emission rate of the two processes.

4.2. Discussing Emission Factors

In order to consider the GHG emissions of biowaste management systems, it is first necessary to ensure that the methodological conditions for comparing recovery systems are in place. Comparison is difficult because the emission factors produced in the scientific literature vary widely, reflecting the different conditions under which they were produced.

As far as our research is concerned, the diversity of information available in the literature is a major limitation. The lack of a standard reference makes it difficult to compare our results with previous work and highlights the need to define a common protocol for each recovery method. There is a relative consensus that vermicomposting is more likely to emit CO₂ than composting [75–78]. Hobson et al. (2005) [79] showed that vermicomposting emits less CH₄ than composting due to the aeration effect of earthworms in biowaste compost heaps. These results are shared by Chan et al. (2011) [77], Lubbers et al. (2013) [80], Nigussi et al. (2016) [67] and Dume et al. (2021) [78]. However, the literature diverges for N₂O emissions. Chan (2011) [77], Wang et al. (2014) [81] and Nigussi et al. (2016) [67] found that the presence of earthworms would reduce N₂O emissions. Conversely, several studies have found a much higher emission rate from vermicomposting [77–79]. Many factors affect N₂O emissions. For example, the gut of earthworms contains denitrifying bacteria that affect the nitrogen/carbon ratio of the substrate [80,82]. Vermicomposting conditions also play an important role in N₂O emissions. Climatic conditions and maturation time

vary the moisture content of the substrate [82]. N₂O emissions from vermicomposting are therefore difficult to control [82].

4.3. Methodological Limitations of the Comparison

In addition to the methodological construction of the carbon footprint, there are difficulties in the comparison due to the unequal conditions under which the processes were set up.

The data vary according to factors related to the nature of the biowaste and the composting process. The composition of biowaste varies according to urban location, season and weather conditions; its moisture content varies, which has an impact on Scope 1. Composting processes also have a significant impact on Scope 1 emissions: aeration practices and the addition of carbonaceous materials, as well as ambient temperature [3,65]. Finally, biowaste management policies influence Scopes 2 and 3 (e.g., collection methods). Measuring the moisture content of the compost produced by companies and associations in Lyon would have reduced the uncertainties in this carbon footprint. Unfortunately, only industrial composting companies carry out controls as they comply with the NFU-44051 standard [83]. Products from community composting and community vermicomposting have not been tested.

Community composting, vermicomposting and industrial composting are not equivalent recovery solutions. Although vermicomposting has a lower carbon footprint than composting, these results need to be put into perspective, given the differences between the two systems. There are significant technical challenges to implementing vermicomposting, requiring a thorough understanding of the life cycle of earthworms and the optimum conditions to keep them healthy. Another limiting factor is the sensitivity of earthworms to certain types of food [84]. These organisms are intolerant of waste products such as dairy products, meat and fish offal, fats and oils, and foods rich in salt or vinegar. This restriction may limit the variety of waste that can be effectively processed by vermicomposting.

Another major challenge is the lack of standards for vermicomposting, unlike composting, which is standardised. The lack of hygiene increases the risk of microbes (*Aspergillus*) and bacteria (*Salmonella*, *Escherichia coli*) developing: this problem is one of the disadvantages of implementing vermicomposting on an industrial scale" [80]. It also makes vermicomposting particularly difficult to implement, especially for agricultural uses where regulations are often more restrictive. These technical and regulatory limitations, combined with the specific requirements of earthworms, make vermicomposting less practical to implement on a large scale.

4.4. Soil Carbon Capture, Storage and Release

If biogenic carbon is included in emissions, it is interesting to place the issue in the context of agricultural practices, in particular (1) the need for inputs to fertilise crops and amend soils and (2) carbon sequestration by soils.

The production of compost from biowaste has a potential impact on agricultural practices. Farmers need inputs to nourish their crops and soils. Biowaste compost, if standardised, can be used for this purpose and can increase yields three times compared to untreated crops [85]. This avoids the emissions associated with the production of chemical nitrogen fertilisers [86] and reduces the use of livestock effluent, which has high emissions [87].

The agricultural sector has great potential for carbon sequestration by soils and biomass, i.e., the absorption of atmospheric CO₂ by plants and the storage of carbon in soil organic matter [88]. Most agricultural emissions are nitrous oxide and methane [79],

mainly associated with the livestock sector [87]. Soil absorbs carbon from the atmosphere through plant photosynthesis and stores it in the form of organic matter [89].

Since the creation of the PCAETs in 2016, local and regional authorities have been responsible for public policies on soil carbon. They have at their disposal a tool (Aldo) that allows them to estimate the storage capacity of agricultural soils and the emissions to the atmosphere associated with the artificialisation of soils or changes in land use [90]. It is based, in particular, on standard values (developed by Ademe) for variations in storage capacity per hectare as a function of agricultural activity.

The logic of sequestering and storing carbon in the soil implies changing agricultural practices, in particular ploughing, which releases the sequestered carbon, and promoting practices that store it, such as planting grass and hedges, crop species and fertilisation regime [74,82]. Local and regional climate policies cannot be developed without involving the agricultural sector.

4.5. An Opportunity for the Development of Local Policies in the Field of Agriculture, Food and Biowaste?

The carbon balance proposes an analysis of composting processes in terms of GHG emissions, but other criteria could be used to evaluate the processes (social, educational, energy, economic, agricultural, etc.).

The collection and processing of biowaste is often considered from the perspective of a territorial biowaste cycle through energy or agricultural recovery of compost or vermicompost. The aim would be to treat biowaste locally and turn it into a resource for the local area, either energy produced by methanisation, soil improver or fertiliser for the fields. Initial studies have shown the beneficial effects of compost and vermicompost as soil improvers or fertilisers. Ducasse (2023), who carried out studies and comparative measurements on the use of compost and vermicompost as soil improvers and fertilisers, concluded that vermicompost is more beneficial than compost [49]. However, the agricultural use of compost and vermicompost depends on economic conditions (selling price, local use to reduce transport costs), social conditions (social acceptance of agricultural use of household biowaste), agricultural conditions (type and age of crops, farming practices) and regulatory conditions (hygiene) [91]. Currently, the regulatory framework does not allow vermicompost to be used for agricultural purposes (in the community or in windrows) because these processes do not guarantee that the compost produced is safe. As far as industrial compost is concerned, if biowaste is to be used in agriculture, support measures need to be put in place, for example, by setting up a network for discussions with farmers and composting facilities.

However, community management of composting and vermicomposting provides the conditions for social facilitation and the teaching of environmental and educational issues [17,18]. This is why some municipalities opt for a mixed management policy, combining different mechanisms in order to benefit from their complementary externalities. In the Lyon metropolitan area, several measures have been implemented: the support for local associative composting for approximately ten years, the installation of composting bins in public spaces for two years and experimentation with community vermicomposting in “urban policy” districts for several years.

4.6. Environmental Assessment of Biowaste Management

The carbon footprint of composting facilities is a first step in the environmental assessment of biowaste management. It allows the GHG emissions of each process to be compared by estimating the equivalent CO₂ per ton of biowaste treated. However, it could be refined to include the emissions avoided by reducing the amount of waste incinerated (as biowaste is wet, the energy consumption is higher than for other wastes). Industrial composting

emits fewer GHGs than landfilling but can be as polluting as incineration [92,93]. Composting and vermicomposting are environmentally beneficial waste treatment processes compared to traditional methods (landfilling, incineration).

Indeed, the combustion of biowaste results in an instantaneous release of CO₂ (pulse) into the atmosphere [56,63]. Cherubini et al. (2011) [56] proposed the formula of “global warming potential of biogenic CO₂ (GWP_{bCO₂})” to describe the impact of burning biomass for energy compared to burning fossil fuels. For rapidly decomposing biomass from agricultural residues, the GWP_{bCO₂} is approximately 0.014 g CO₂e/g bCO₂.

In addition, the field study provided information on the agricultural use of compost from the industrial process [91], which reduces emissions associated with the production of nitrogen fertilisers [86] and reliance on high-emission livestock manure [93]. The reuse of biowaste in agriculture through composting appears to be a lever for regional policies that rethink waste as a resource, thereby reducing emissions associated with the production of new resources.

Furthermore, biowaste management is not only an environmental issue. The creation of scenarios for reducing emissions associated with biowaste management, as can be achieved in health policy [94], would need to take into account the social and economic orientations of the local authority, as well as its resources in terms of equipment, funding and skills.

5. Conclusions

In France, the AGECL law encourages local authorities to set up biowaste collection systems, particularly for households. While these systems have been studied in terms of their efficiency, location of bins and management systems, few studies have been concerned with the issue of carbon impacts. One of the main drawbacks of these systems is the emission of GHGs: CO₂, CH₄ and N₂O.

The analysis carried out in this article proposes a carbon balance for biowaste based on a combination of two biowaste decomposition processes (composting and vermicomposting) and a management criterion (community or industrial management). The results obtained using the Ademe carbon balance methodology show that emissions by scope are very uneven across all sectors, with the majority of emissions falling under Scope 1. There are very few Scope 2 GHG emissions. Community management (composting and vermicomposting) also generates very few Scope 3 emissions.

However, these results need to be put into perspective. The amount of GHGs emitted during the composting and vermicomposting process is highly dependent on several factors: type of waste processed and its composition, aeration, moisture content, temperature, carbon/nitrogen ratio, pH, blowing agents, etc.

Further research is needed to broaden the analysis criteria to include variables related to the specificities of the processes used by operators (e.g., rate and nature of bulking materials) and changes in treatment conditions during the year (e.g., weather, composition of biowaste, etc.). This would provide local authorities with a more informed view so that they can make informed environmental choices about biowaste management solutions.

Biowaste management is not only a question of environmental criteria. For example, the sorting behaviour of households, the spatial configuration of housing, contracts linking local authorities and private operators, and the hygienic quality of compost (standardisation) are all parameters that can influence the choice of biowaste management methods.

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