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REVIEW ARTICLE

Vermicomposting of municipal solid waste as a possible lever for the development of sustainable agriculture. A review

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Abstract

Continued population growth and urbanization as well as changing consumption patterns have led to an explosion in the amount of waste produced, especially in cities. To feed the world, we also need to increase agricultural production while limiting our impact on the environment. Part of the solution could be to recycle the organic fraction of municipal solid waste (OFMSW) as a resource for agriculture near cities with techniques such as vermicomposting, which uses earthworms to recycle organic waste into nutrient-rich vermicompost. The objective of this review was to examine (i) whether vermicomposting is appropriate for recycling OFMSW, (ii) the quality of the vermicompost produced, and (iii) the impact of this product on crops and soil parameters. We found that vermicomposting can be adapted for OFMSW recovery because the process is suitable for all the types of OFMSW (food, paper, and green waste). The vermicompost produced is both high in organic carbon (18.83-36.01%) and a potential fertilizer (1.16-2.58% N, 0.42-1.12% P, and 0.61-2.05% K). A comparison with compost from the same types of OFMSW suggested that vermicompost is slightly more suitable for crop production with significantly lower C/N and pH and higher N and P. Vermicompost was actually found to have a better effect on plant growth than compost, suggesting that classical chemical analyses are not always sufficient to characterize the potential of organic amendments/fertilizers. Indeed, the application of vermicompost in the field leads to an increase in carbon storage, water retention, enzymatic and microbiological activity, and soil fauna abundance and diversity. Finally, we found that reports on the use of vermicompost from OFMSW are scarce and most studies focused on the process itself. Overall, our review synthesizes data and the interest in this technique and proposes perspectives for future studies.

Keywords Vermicompost · Waste management · Organic fraction of municipal solid waste · Agronomical impact · Soil conservation

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1 Introduction

In the past, farmers used organic waste from cities to amend soils but with the development of the chemical and food industry in the twentieth century, this waste was no longer of interest (Barles 2014). The link between urban organic waste and agriculture has thus largely been forgotten as a result of the intensification of agriculture and urbanization. Indeed, agricultural practices have become increasingly standardized with, for example, the use of nitrogen-phosphate-potassium (N-P-K) fertilizers (Kibblewhite et al. 2008). Farm specialization has also led to activities being distributed according to sector and region. Martin et al. (2018) noted that animal waste such as manure is concentrated in certain regions of the world, which can lead to potential pollution, while other agricultural areas lack organic matter (OM) to feed their soils. Cities are generally surrounded by "agricultural belts," which should make it possible to promote the valorization of the organic fraction of municipal solid waste (OFMSW).

A World Bank study (Bhada-Tata and Hoornweg 2012) predicted that municipal solid waste will increase by 70% between 2012 and 2025 to reach 2.2 billion tons per year. A total of 20-30% of this waste are organic waste, with up to 80% of it coming from low-income and middle-income regions (Troschinetz and Mihelcic 2009). Organic waste recovery from cities represents an enormous challenge for circular waste management, which aims to return OM to the soil to "close the loop" and thus save natural resources and reduce our impact on the environment (Ghisellini et al. 2016). To manage organic waste from cities in a sustainable way, it is necessary to divert it from classical management and treatment methods such as incineration and/or landfill. Bortolotti et al. (2018) showed that decentralized management of urban organic waste is a promising alternative to centralized industrial facilities. There are many techniques for recovering organic waste that can be adapted at different scales, converting it into a valuable resource. In their review, Lohri et al. (2017) classified these into four different categories: (i) direct use (direct land application, direct animal feed, or direct combustion), (ii) biological treatment (composting, vermicomposting, black soldier fly treatment, anaerobic digestion, fermentation), (iii) physico-chemical treatment (transesterification, densification), and (iv) thermo-chemical treatment (pyrolysis, liquefaction, gasification). Among the products produced from these methods, compost (from composting and vermicomposting), black soldier fly residues, anaerobic digestate, and biochar from pyrolysis can be used in agriculture (Lohri et al. 2017).

Vermicomposting is a controlled OM degradation process based on the addition of earthworms upstream of decomposition to accelerate the stabilization process (Dominguez 2004; Munroe 2007; Lim et al. 2016). The main objective is to stabilize and degrade OM to produce a humus-like material, called vermicompost (Adhikary 2012; Doan et al. 2015). The degradation process is carried out at room temperature (mesophilic process) and stabilization is achieved through the interaction of earthworms, associated microorganisms, and other decomposers (Gomez-Brandon et al. 2012). To avoid compaction and control aeration, a minimum of 2.5 kg of earthworms per m^2 (Munroe 2007) should be maintained in piles that are smaller than those for composting (1 m maximum). If these conditions are respected, there is no need to turn the heap and the environment is conducive to earthworms and does not heat. The earthworm species used are generally epigeic (Blouin et al., 2013), which naturally remain on the soil surface and in the fresh bedding used as food. *Eisenia fetida* (Savigny 1826) (Haplotaxida, Lumbricidae) is the most widely used species in vermicomposting due to its high waste ingestion capacity (Edwards et al. 2010). Although many variations in vermicomposting techniques have been developed, from low tech in windrows to high tech with fully automated continuous-flow vermicomposting reactor systems (Board 2004; Edwards et al. 2010), there are always two major phases in the process: (i) the active decomposition phase and (ii) the maturation phase (Munroe 2007; Sim and Wu 2010; Ali et al. 2015) (Fig. 1). In the active decomposition phase (i), earthworms (a) ingest, digest, and cast organic matter; they not only improve the assimilation of OM (indirect effect) but also facilitate the movement of poorly mobile microorganism communities (direct effect) (Monroy et al. 2008); and (b) the fractionate OM. They thus allow an increase in the potential surface area exposed to other decomposers, especially

Fig. 1 Picture of vermicomposting windrow of urban organic waste (food) and cattle manure.

microorganisms (Aira et al. 2007; Gomez-Brandon et al. 2012). Logistically, this first phase consists of setting up earthworm litter adapted to the quantity of waste to be recovered before applying the OM in a discontinuous (one-time application) or continuous (regular applications) way. Batch feeding requires more work but allows better control of the earthworm environment as well as pH and humidity control. To adjust these factors, bulking agents such as cardboard boxes, waste from green spaces, or straw (for manure) are used. In the maturation phase (ii), earthworms migrate to new layers of fresh and undigested waste. Fresh OM is added in contact with the almost decomposed OM so that the hungry earthworms migrate to the new fresh litter. This step is essential to keep as many earthworms as possible and continue the process while harvesting the resulting earthworm-free vermicompost.

Most of the studies on vermicomposting processes focused on adding value to animal manure and some rare reviews highlighted the potential of this technique for the valorization of urban organic waste (Sim and Wu 2010; Singh et al. 2011). In their recent review, Alshehrei and Ameen (2021) highlighted a growing interest in vermicomposting for the valorization of municipal solid waste (MSW) in urban environments, particularly the organic fraction (OFMSW). Recently, the regulations concerning the recovery of OFMSW have been evolving with, for example, a new European mandate to consider this waste as an amendment resource by the end of 2023 (European Union 2018). Thus, it is necessary to find processes with the lowest impact on the environment but adapted to urban environments and all the related constraints (high density, pollution, and so on).

Few studies have evaluated the agronomic potential of vermicomposts from OFMSW. However, studies concerning the use of vermicomposts from manures in agriculture show encouraging results for plant growth (Atiyeh et al. 2000; Jouquet et al. 2011), the development of beneficial bacteria for plants (Monroy et al. 2008; Aira et al. 2008; Adhikary 2012), and a reduction in plant diseases and pest attacks (Ersahin 2010; Cardoza 2011; Rowen et al. 2019). Once applied and incorporated into the soil, it decreases bulk density and increases porosity, increases water retention capacity, and promotes aeration (Manivannan et al. 2009; Lim et al. 2014). In addition, a meta-analysis showed that the addition of vermicompost from manure increases crop yield and total biomass (Blouin et al. 2019). There is therefore a strong need to know more about vermicompost from OFMSW, to see if this product could have the same benefits to soil and crops, and thus help recycle OM (from the city to the field and vice versa).

In this review, we first (i) define and classify the studies on vermicomposting of OFMSWs as a function of waste category and various other factors. Then, we characterize more precisely (ii) the quality of the vermicompost resulting from OFMSW to determine whether this product has interesting potential for the development of agriculture compared to classic compost. Finally, we evaluate (iii) the impact of this product on crops and the bio-physico-chemical parameters of the soil once applied to the field. We then discuss the outlook and future research perspectives and studies needed to better understand this process and its applications.

2 Material and methods

2.1 Literature search

The Web of Science (Clarivate©) was first searched for publications from 2000 to 2020 using the following keywords: “vermicompost*” OR “vermiculture” OR “vermitechnology”. This search recovered a set of 3128 articles. To refine the search, we then added the following keywords: AND “organic waste” OR “municipal solid waste” OR “urban food waste” OR “urban solid biowaste” OR “biowaste” OR “urban waste” OR “urban biowaste” OR “vegetable waste” OR “food waste”. This refined search recovered 410 articles (last search on 23/10/2020). We performed the same search on the CABI database (CAB direct) to access national journals that often provide analysis of products such as vermicompost and obtained 724 articles in total. We then read the abstracts and selected those articles really focusing on OFMSW recycling. Here we defined OFMSW as biodegradable urban organic waste including non-liquid waste (thus excluding sludge) from households and small businesses and institutions as defined by Wilson (2015). We finally obtained 96 original papers and 19 reviews from the Web of Science (Clarivate(c)) and 88 additional papers and 3 additional reviews from the CABI database, for a total of 184 papers and 22 reviews. To examine how prevalent research on vermicomposting of OFMSW is compared to the other techniques of OFMSW recovery, we also carried out a search with the same keywords in the Web of Science (Clarivate(c)) and obtained 4916 results with “compost*”, 692 results with “methanisation” OR “digestate” and 163 results with “black soldier fly”.

2.2 Data selection

To characterize vermicomposting processes and vermicompost quality and applications, we recorded specific information from the papers (Table 1). First, we identified the (i) categories of OFMSW in each study. Since we found a wide variety of organic waste (sometimes different names for the same waste), we chose to group it into categories: food, green waste, paper, and MSW (undefined mixture of municipal organic waste). Then, we noted the (ii) species of earthworm used for the process and we found out if (iii) a pre-treatment was carried out before the process. We also noted for each of the studies if it was carried out in (iv) the laboratory or in the field and if it concerned the (v) process itself or the use of the vermicompost.

Table 1 Information retrieved from the 184 articles according to the factors studied: (i) urban organic waste categories, (ii) earthworm species, (iii) pre-treatment, (iv) laboratory (including greenhouse) or field experiment, (v) vermicomposting process or vermicompost use study, and (vi) continent. In urban organic waste categories, the factor "food" includes "households waste," "kitchen waste," "food waste," "vegetable waste," "supermarket food waste," "coffee," and "fruit waste"; the factor "green waste" includes "tree leaves," "garden residues," "sawdust," "shaving," "wood," "urban green waste," "turf grass," and "urban aquatic seed"; the factor "paper" includes "paper," "newspaper," and "cardboard" and the factor "MSW" includes "municipal solid waste," "solid urban waste," and "organic part of MSW". MSW was divided into food, green waste, and paper where possible according to the author's description and the replication of the same mixture with different ratios in the same publication was only counted once. In earthworm species, the factor "unspecified species" indicates that in the publication, the earthworm species was not specified or defined at the species level. In pre-treatment, the factor "stabilization" indicates that the waste was left out in the open without treatment (usually to stabilize the temperature); the factor "cut" indicates that the waste was shredded before the processes and the factor "dry" indicates that the waste was dried before the processes.

Factor studied	(i) Urban organic waste categories	(ii) Earthworm species	(iii) Pre-treatment	(iv) Laboratory (including greenhouse) or field experiment	(v) Vermicomposting process or vermicompost use study	(vi) Continent
Factor identified and its occurrence (x)	Food (150) Green waste (64) MSW (57) Paper (46)	*Eisenia fetida* (116) *Eudrilus eugenia* (31) Unspecified species (28) *Perionyx excavatus* (13) *Eisenia andrei* (10) *Lampito mauritii* (10) *Lumbricus rubellus* (5) *Metaphire posthuma* (2) *Perionyx sansibaricus* (3) *Perionyx ceylanensis* (1) *Pheretima peguana* (1) *Allolobophora parva* (1) *Amynthus diffringens* (1) *Metaphire houlleti* (1) *Octolasion tyrtaeum* (1) *Dendrobaena veneta* (1) *Octochaetha thurstoni* (1) *Octochaetona serrata* (1) *Lumbricus terrestris* (1)	Absent or undefined (80) Composting (62) Stabilization (34) Cut (33) Dry (12) Mix (9)	Laboratory (160) Field (20) Laboratory and field (4)	Process (125) Use (44) Process and use (15)	Asia (117) America (37) Europe (14) Africa (14) Oceania (2)
Total repetition of factor (*n*)	*n* = 317 because some studies used several mixtures for their experiment	*n* = 228 because some studies used several species for their experiments	*n* = 230 because some studies used several techniques of pre-treatment	*n* = 184	*n* = 184	*n* = 184

Finally, we identified the (vi) country where the studies and experiments took place (grouped by continent) to identify the locations that are most interested in this process.

2.3 Data treatment

To examine the quality of the vermicompost resulting from OFMSW and determine whether this product has interesting potential for the development of agriculture compared to classic compost produced from OFMSW, we recorded data from each article/paper for the agronomically important and metallic trace elements to calculate a mean and obtain a standard error according to factors. After analyzing the intra variability (different vermicomposts), we selected the studies that compared vermicomposts to composts from the same OFMSW to estimate its quality relative to a better-known product and we used paired tests. All analyses, tables, and calculations were performed using the RStudio software (version 1.4.17.17).

3 Results and discussion

3.1 Suitability of vermicomposting for OFMSW recovery in urban environments

3.1.1 Study typology

Our literature review found that vermicomposting is less studied than other OFMSW recovery processes. For example, reports on classical composting were published 10 times more frequently (4916 results) than vermicomposting (410 results) during the same period on the Web of Science (Clarivate(c)). The geographical origin of the studies on vermicomposting shows that it was mostly studied in Asia (63.6% of the studies), moderately in America (20.1%), and less in Europe (7.6%), Africa (7.6%), and Oceania (1.1%) (Table 1). Studies on the vermicomposting of OFMSW were still largely carried out in the laboratory (87%). Only 10.9% were carried out in the field and only 2.1% in both the laboratory and field. In addition, 67.9% of the studies focused on the vermicomposting process itself, 23.9% on the use of vermicompost from OFMSW, and 8.2% on both (process and use). This suggests that vermicomposting is not thoroughly studied in outdoor conditions and that most of the studies focused on the understanding or optimization of the process. When the two parameters were crosschecked, this further confirmed that most of the research on vermicomposting is done in the laboratory and about processes (65.2%). Moreover, even the application of vermicompost is studied more in the laboratory (laboratory and use = 16.3%) than in the field (field and use = 7.1%). These trends can explain why this technique is not widely used to valorize OFMSW on a global scale. This also raises the question of whether the vermicomposting process, which is well known for waste such as manure, is more difficult to use on OFMSW due to the high variability of this waste, suggesting that further fundamental laboratory studies are required.

As earthworms are fundamental to this process, we recorded the earthworm species used and their frequency in the articles (Table 1). As expected, *E. fetida* was the most studied species and was found in 50.9% of experiments. The second most used species was *Eudrilus eugenia* (13.6%) followed by *Perionyx excavates* (5.7%). In a relatively high percentage of studies, the species was not specified (12.3%). This was generally in papers that only investigated the application of vermicompost. Other less common species were also used in Asia such as *Lampito mauritii*, which is an anecic species (Tripathi and Bhardwaj 2004) and *Metaphire posthuma*, which is an endogeic species (Doan et al. 2013). It is important to note that earthworm ecological categories were defined on European species (Bouché, 1977) and it is difficult to use these categories for non-Lumbricidae species (Asian for example) while the concept itself remains controversial (Bottinelli et al. 2020). Studies that compared the effectiveness of different earthworm species on the decomposition of organic waste suggest that *E. fetida* more rapidly transforms OM into vermicompost (Kaviraj and Sharma 2003; Tripathi and Bhardwaj 2004; Rajpal et al. 2012). Other species are used because in some parts of the world, *E. fetida* is not naturally present and thus some studies focused on the potential of native and readily available species (Suthar 2007, 2009; Soobhany et al. 2015a). This type of research on potential earthworm species for vermicomposting also highlights the need for fundamental laboratory studies.

3.1.2 High diversity in OFMSW categories

The information found in the 184 articles (Table 1) showed that about half of the studies concerning the recovery of OFMSW were based on food waste (47.3%). However, Table 1 only counts the occurrence of the four keywords in the articles (food, green waste, paper, and MSW) but not if the studies recycled these different materials in a mixture. To define the quality of vermicompost from this particular type of waste, we first listed the different types of urban waste that have been vermicomposted in the 184-article dataset (Table 2). We found 256 different types of mixtures that we grouped into two major groups: (i) urban waste only and (ii) urban waste + other waste. The exact name of the waste (not the typology used here) and the proportion used in each study are listed in the Supplementary Table 1. This classification showed that almost half of the mixtures studied (Table 2: 43.75%) also contained other materials besides urban waste (OFMSW) such as agricultural waste (manure, which is the preferred substrate for vermicomposting). However, vermicomposting of OFMSW is also possible with green waste (Tognetti et al. 2008; Wani et al. 2013) or shredded paper and cardboard (Hanc and Pliva 2013; Soobhany et al. 2015b; Mathivanan et al. 2017), which is an abundant resource in cities. According to Hogg et al. (2002), paper and cardboard represent up to 37% of MSW and food waste added to green waste represents up to 53% of MSW in different European countries. All these wastes, which make up the majority of MSW, can be recovered through vermicomposting, which would avoid having to resort to other wastes that are not necessarily easily accessible in urban areas, such as agricultural wastes. OFMSW mainly includes isolated waste (food, green waste, or paper only) and not mixtures of several types: 43% of the studies concerned food leftovers, 9% green waste, and 8% paper, which represented a total of 60% of the studies compared with 40% dealing with mixtures of several classes (MSW are included). For the process of vermicomposting OFMSW, it is usually necessary to mix different wastes such as food waste with a bulking agent such as cardboard and/or paper and/or shredded wood. Studies without the use of a bulking agent were all carried out in the laboratory, whereas outdoor studies (only 10/140 studies of the process) described the process with mixed waste (green waste, paper with food, and MSW which is a mix of organic municipal waste) because they were adapted to the field reality and the constraints of the process (Singh and Sharma 2003; Mishra et al. 2005; Pattnaik and Reddy 2010, 2011; Agarwal and Arora 2011; Abdrabbo et al. 2014; Cao et al. 2016; Hanc et al. 2017; Hrebeckova et al. 2019; Dohaish 2020).

3.1.3 Advantages and limitations of the vermicomposting process with OFMSW in an urban context

OFMSW valorization requires adapted processes that take into account the environmental stakes and adapt technically to

Table 2 Classification of the 256 waste mixtures found in the 184 articles. In urban organic waste + other waste category, the factor “agricultural waste” includes “hay,” “straw,” “rice bran,” “sugarcane bagasse,” “biogas slurry from agriculture,” and all animal slurry, dung, and manure; the factor “sewage residues” includes “sewage sludge” and “biosolids”.

Factor studied	Urban organic waste only	Urban organic waste + other waste	Other types of material used for the process (with the ratio used)
Type of waste mixed with OFMSW and its occurrence (x)	Food (63) MSW (29) Green waste (13) Paper (12) Food + green waste + paper (9) Food + paper (8) MSW + green waste (6) Food + green waste (4)	Food + agricultural waste (45) Green waste + agricultural waste (16) MSW + agricultural waste (14) Food + green waste + agricultural waste (9) Food + paper + agricultural waste (7) Paper + agriculture waste (5) Food + green waste + paper + agricultural waste (4) Paper + green waste + agricultural waste (1) MSW + sewage residues (6) MSW + agricultural waste + sewage residues (2) Green waste + sewage residues (2) Food + sewage residues (1)	Products: Biochar (2) – 10% maximum Red mud (1) – 15 % Ash (1) – 15 % Zeolite (1) – 10% maximum Urea (1) – to adjust C/N ratio Lime (1) Lumbricidae 5 g CaCO3/kg Mussorie rock phosphate (1) Saw dust (1) Dry neem (1) Nutrient (iron, manganese, zin, copper, molybdenum, boron) (1) Butter milk Jaggery (1) Vermiwash (1) Microbial inoculants: *T. viridae*, *B. polymyxa*, and *P. crysoporium* – 50 ml/kg (1) *Trichoderma harzianum* (1) *Leucaena leucocephala* and *Morus alba. Penicillium funiculosum* and *P. chrysogenum* (1) *Pleurotus sajor-caju* (fungus), *Trichoderma harzianum* (fungus) and *Azotobacter chroococcum* (1) Owinema: larvae of the nematode *Steinernema feltiae* – 50 × 10^{6} larvae m^{-2} (1)
Total repetition of factor (*n*)	*n* = 144	*n* = 112 with agricultural waste (*n* = 101); sewage residues (*n* = 11)	*n* = 18

an urban context. Thus, in this section, we discuss the advantages (speed, reduced GHG, lack of odor, adaptability to different spatial scales) and disadvantages (some wastes require more complex pre-treatments) of vermicomposting OFMSW according to the present review of the subject.

Ammonia (NH_3), methane (CH_4), and nitrous oxide N_2O emissions from vermicomposting are up to three times lower than for domestic composting (Lleo et al. 2013). Indeed, Komakech et al. (2015) showed with a life cycle analysis (LCA) of city biodegradable waste treatment systems that conventional composting (thermophilic) emitted 80.9 kg CO_2 eq.ton^{-1} of waste compared to 17.7 for vermicomposting, i.e., 78% less GHG. This is mainly due to the heat produced during traditional composting, which produces a significant amount of GHG as 25-36% more N_2O and 22-26% more CH_4 than vermicomposting (Nigussie et al. 2016). Nigussie et al. (2016) showed that by increasing the earthworm density (1 kg and 3 kg per m^{2}) and moisture content (75% and 85%) during the process, it was possible to further reduce GHG emissions (decreased N_2O emissions by 40% and 23% and CH_4 emissions by 32% and 16%, with higher and lower moisture contents, respectively and decreased CH_4 emissions by 35% and 10% with higher and lower earthworm density, respectively while this density has no effect on N_2O emissions) and significantly reduced N loss by 10–20% compared to thermophilic composting. Based on the study by Bernstad Saraiva Schott et al. (2016), Nigussie et al. (2016) excluded CO_2 (including biogenic CO_2 important in the short term) in the GHG balance because a high emission of this gas indicates a high stabilization rate of the products as plant litter (humus), which is generally excluded from GHG balances. Thus, when the CO_2 emitted by vermicomposting is omitted, the process emits less GHG than conventional composting in these studies. However, one study showed that vermicomposting can emit more N_2O than composting (Hobson et al. 2005), suggesting that the process is variable, probably depending on the type of material being decomposed and how well it works.

One other advantage of vermicomposting to valorize OFMSW in an urban context is that it is an odorless process (Lleo et al. 2013). Thus, it can be carried out indoors or in cellars and on several scales and be adapted for domestic use (Sherman and Appelhof 2011; Pirsaheb et al. 2013). It can also be adapted for collective use or on platforms ranging from “low tech” in windrows (Edwards 2011a; Hanc et al. 2017) to “high tech” in industrial scale vermicomposters (Jain et al. 2003; Gajalakshmi et al. 2005; Edwards 2011b). Unlike collective vermicomposters, which aim to recycle waste close to where people produce it (e.g., at the bottom of buildings), platforms are defined as sites to which organic waste is transported and stockpiled to recycle a larger quantity of material (generally carried out by companies). Thus, it is possible to recycle OFMSW using vermicomposting in any available space, for example at individual homes, office, or apartment buildings or after collection by professionals. Both vermicomposting and composting can be used to recycle not only food waste but also other sources of organic waste traditionally found in city. Generally, in urban composting, shredded green waste is co-composted (Adhikari et al., 2009; Farrell and Jones, 2010; Reyes-Torres et al., 2018) to improve control over the process (humidity, temperature, and so on). The added value of vermicomposting compared to other techniques is that it is possible to replace the shredded green waste (bulking agent) with paper and cardboard which are abundant resources in the cities, thus avoiding supply problems (pressure on green waste resource in cities with other uses such as mulching). In addition, there is no need to turn the material over as in composting because earthworms naturally mix the matter, which avoids handling. However, unlike composting, vermicomposting does not allow for the direct recycling of waste such as meat, fish, and processed products (waste from high-fat cooked foods or uneaten ready-made meals, for example). For this reason, studies have sought to optimize the vermicomposting process by adding a pre-composting stage (Frederickson et al. 1997; Kalamdhad et al. 2009; Varma and Kalamdhad 2016). In our review, pre-composting was often used (Table 1: 27%), although this pre-treatment requires a significant additional cost. In the recovery platform, thermophilic pre-composting allows a “safer” hygienization of this type of waste and also accelerates the process of stabilizing OM (Nair et al. 2006; Frederickson et al. 2007; Hanc and Pliva 2013).

Another potential limitation to the widespread use of vermicomposting is that it is more complex than composting and requires more skills to understand and manage the conditions necessary for a successful earthworm life cycle (Lohri et al. 2017). Indeed, one of the main challenges of the process is to maintain sufficient moisture for the development of the earthworms (Munroe 2007). For example, in platforms, it is necessary to use watering during periods of drought, which will be increasingly frequent and constraining in many parts of the world, especially in the context of global warming. In the case of OFMSW recovery, and more particularly food waste, it is possible to manage humidity with the continuous supply of this type of waste because it is mainly composed of water. Depending on the region, seasonality can also influence the process, which will slow down at temperatures below 10°C or higher than 35°C (depending on the species of earthworm used) (Edwards et al. 2010). One of the most complicated factors to manage in the case of OFMSW recovery is the heterogeneity of the materials entering the process, which could potentially influence the quality of the final product. Finally, the low temperature of the process raises questions about the hygienization (especially at European standards which require heat at 70° for 3 days to eliminate pathogens) and reduction of weeds in vermicompost.

3.2 Quality of vermicompost from OFMSW

According to our review, vermicomposting increases the total contents of nitrogen (N), calcium (Ca), phosphorus (P), potassium (K), and magnesium (Mg) and decreases organic carbon (OC) content and thus the C/N ratio in relation to incoming products (Lim et al., 2016). The bibliography also shows that the action of earthworms optimizes the retention of nutrients such as N (Caceres et al., 2018) by 10-20% (according to the C:N value of the organic waste before recycling), compared to compost (Nigussie et al., 2016). In addition, nutrients in vermicompost are highly available to plants compared to compost (Adhikary, 2012; Samal et al., 2019), especially P and K (Hanc and Pliva, 2013). In fact, earthworms help to release nutrients such as P partly due to the presence of enzyme activities in their stomachs such as phosphatases (Ghosh et al., 1999).

3.2.1 Variability of vermicompost between studies

Based on the typology presented in Table 2, we estimated the quality of the different vermicompost products as an organic amendment according to pH, C/N, OC, Ntot, P, K, Ca, Mg, Na, Cu, Fe, Mn, Zn, Cd, Cr, Ni, and Pb criteria (Supplementary Table 2). The results were very heterogeneous from one report to another, especially regarding the metallic trace elements, which really depend on the quality of the incoming waste more than on the process itself. As the standards concerning the characterization of organic amendments vary from one country to another, we chose the French standard (NF U44-051) adapted from the European law of “Organic soil improvers—designations, specifications and marking” as the reference. This standard sets the threshold limits for metallic trace elements of As at 18, Cd at 3, Cr at 120, Cu at 300, Hg at 2, Ni at 5.55, Pb at 180, and Se at 12 mg kg^{-1}. The levels of Cu and Cr were always below the norm. Cadmium, Ni, and Pb means exceeded the standard threshold (Supplementary Table 2) because of only one study in which increases in the averages with three analyses above 50 for Cd, above 900 for Pb, and above 200 mg kg^{-1} for Ni were observed (Varma and Kalamdhad 2016). The mixtures concerned were generally OFMSW in which the OM had been roughly sorted, which may be the cause of the high level of trace elements in this category. Indeed, due to bad waste sorting, the OFMSW can contain other types of contaminant-rich waste (non-biological products e.g., plastics, glass). Overall, the products from the OFMSW appear to be in compliance with the standards concerning trace elements, although further studies on this subject are needed to increase the data and validate this trend.

Concerning the agronomic parameters of organic amendments, the standard NF U44-051 sets minimum thresholds of C/N at 8 and dry matter at 30%. For agronomic value (in % of gross), OM should be at a minimum of 20%, i.e., 10% OC (OM/2) and P, K, and N must not exceed 3%. None of the included studies specified the dry matter content of the final product but the C/N mean values were within the correct range (Supplementary Table 2). The C/N ratio, which is a good indicator of nutrient intake (Diacono and Montemurro 2010), was highly variable depending on the type of waste used to make the vermicompost. Indeed, for C-rich waste such as paper and green waste, the C/N is higher than for food waste (means of 17.21, 14.38, and 12.50, respectively). In a mixture of urban and agricultural wastes, the C/N is higher, probably because of the large amount of C in this type of waste. We also noticed that the C/N of the various mixes was quite high with an average of 18.33 for the urban waste and 16.82 for the mixed urban and agricultural waste. This may be due to the heterogeneity of the substrate, which could complicate the process. Furthermore, the use of a bulking agent with food waste (paper) reduces the C/N to a mean of 10.43, a lower value than when only food was used. It would therefore be interesting to develop studies on the recovery of OFMSWs by mixing food waste and paper or waste from green spaces, which is more accessible in cities than agricultural waste such as manure.

Regarding other agronomic values (OC, N, P, and K in Fig. 2), it is not possible to know if the vermicomposts are within the NF U44-051 standard since the reported analyses were carried out on dry products and the moisture content was generally not specified. However, Fig. 2 shows that vermicompost from food waste without mixing with agricultural resources is rich in N (1.59%) and P (1.18%), and especially in K (2.34%), but lowest in C (18.83%). In contrast, vermicomposts from green waste are rich in C (25%) and lower in P (0.73%) and K (1.25%). Overall the addition of agricultural waste increased the nutrient values in vermicompost probably due to the capacity of epigeic earthworms to readily degrade animal manure which in turn provided them with an optimum living environment (Munroe 2007; Edwards et al. 2010). In urban waste management, it would be more interesting to combine food with green waste (or paper or both) as bulking agents because these resources are more available in an urban context, thus avoiding transportation of materials. In our review, only four studies analyzed vermicompost from food waste and green waste, and only 11 from food waste and paper, so we could not compute average values. The food/paper mixture increased OC to 28.53% and N to 2.58%, showing that a mixture of more N-rich (food) and more C-rich (paper) feedstock can optimize the recovery of these wastes if they are combined rather than treated individually. Again this may be due to the fact that appropriate mixtures create better living conditions for earthworms, which then optimizes vermicomposting processes.

3.2.2 Comparison of the quality of vermicompost and compost from the same OFMSW

To better evaluate the quality of vermicompost from OFMSWs and disregard studies with variable inputs, we compared it to "classic" compost produced from exactly the same material. This issue was only addressed in 35 of the 184 articles. Table 3 shows the difference in agronomic chemical parameters between vermicompost and compost from the same wastes with the help of paired tests. There were several significant differences between the quality of compost and vermicompost from the urban waste especially for pH, which was slightly more neutral for vermicompost (7.59) than for compost (7.86), and for the C/N, which was lower for vermicompost (15.05) than compost (16.93). The vermicompost also had a higher percentage of total N and P than the compost (1.54% versus 1.31% for N and 0.56% versus 0.53% for P). Organic OC and K levels were not significantly different. When compost and vermicompost of urban waste added to agricultural waste were compared, the C/N and OC of vermicompost were also significantly lower than compost (16.1 vs 24.45 and 25.26% vs 33.22%) while total N was not significantly different in spite of a strong difference in averages (2.33% for vermicompost versus 1.49% for compost). In both types of waste (urban alone or with agricultural waste), the C/N was significantly lower for the vermicompost and the OC content was also lower (significantly for the mixture with agricultural waste), and the total N rates were higher (significantly for the urban waste alone). According to the review, vermicomposting emits more CO_2 than composting because of its higher biological activity but lower CH_4, which reduces carbon losses in total C footprints and allows better N retention (less N_2O emission) (Nigussie et al. 2016, 2017). The significant difference in OC from urban and agricultural wastes is certainly due to the fact that the earthworms can easily degrade animal manure. According to these results, vermicompost should have similar fertilizing properties to compost, although its agronomic parameters may even be slightly more suitable for crop production (lower C/N, higher nutrient contents). Moreover, all these studies were mostly focused on the valorization of a specific type of waste such as 100% green waste or 100% food waste or a mix of OFMSW with no pre-selection of waste and only one analysis took into account a mixture of food and paper wastes which, as we have seen in the previous section, would be more appropriate for vermicomposting. According to Yadav and Garg (2011), it is essential to rigorously select raw materials and mixtures to optimize the vermicomposting process and obtain

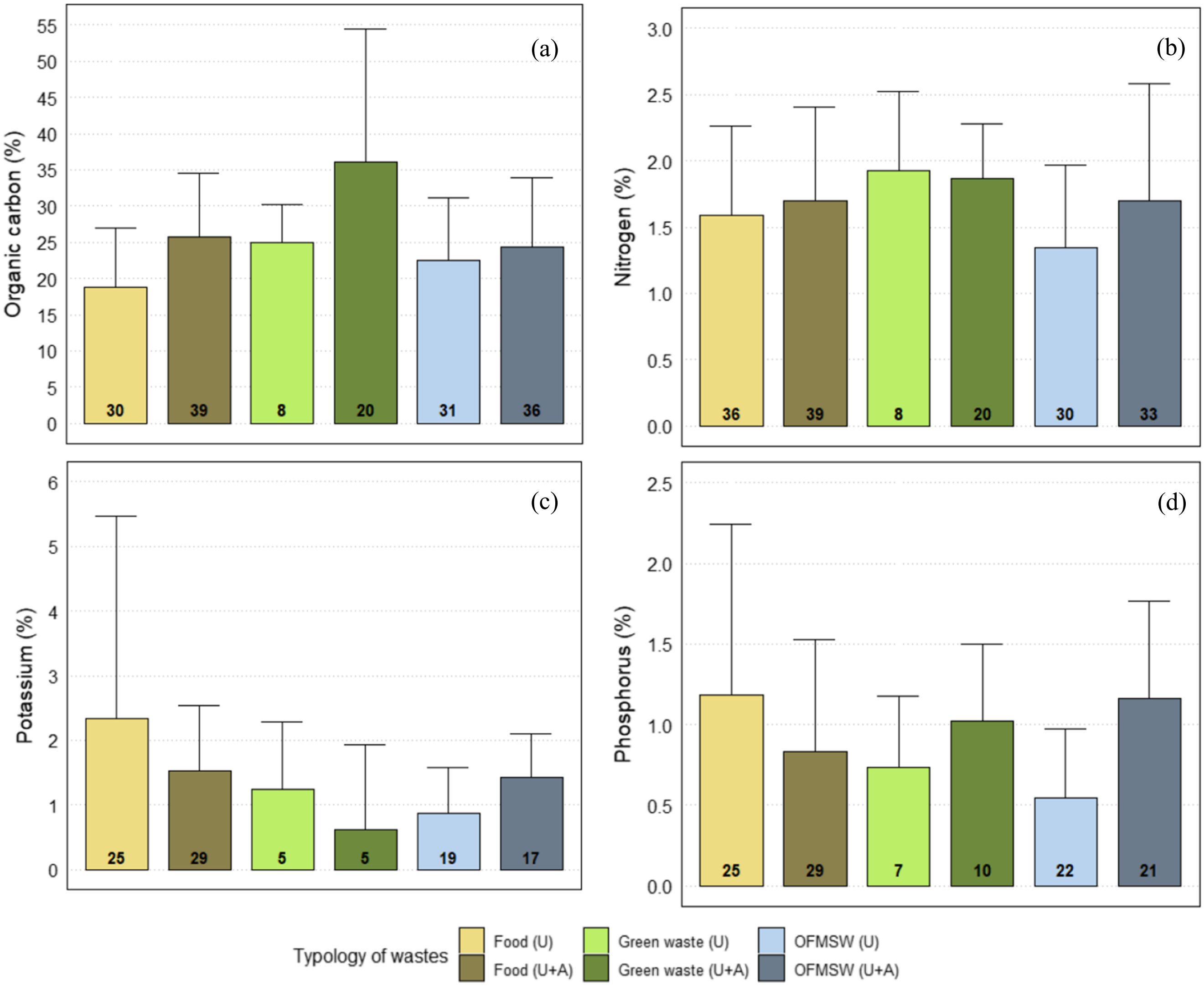

Fig. 2 Means and standard deviations of the organic carbon content (**a**), nitrogen content (**b**), potassium (**c**), and phosphorus content (**d**). The number in bold in the barplots is the number of repetitions for calculating means. The letter (U) corresponds to the average for urban waste only and the letters (U+A) correspond to the average for urban and agricultural waste.

a better quality product. Also, classical chemical analyses do not take into account many other factors such as plant growth regulators (PGRs), plant growth hormones (PGHs), nutrient availability, OM quality, or microbiological activity. All are essential factors for plant growth (Soobhany et al. 2017; Barthod et al. 2018; Dominguez et al. 2019).

Table 3 Matched comparison of vermicomposts and composts from the same waste origin. Superscript letters in bold indicate statistical differences with a *p*-value less than 0.05.

Type of organic waste	Chemical factor	Compost	Vermicompost	Test with repetition
Urban wastes only	pH	7.86 ± 0.75^{a}	7.59 ± 0.71^{b}	Student (*n* = 21)
	C/N	16.93 ± 5.71^{a}	15.05 ± 5.46^{b}	Wilcoxon (*n* = 18)
	OC (%)	24.54 ± 9.04^{a}	23.04 ± 7.44^{a}	Student (*n* = 18)
	Ntot (%)	1.31 ± 0.74^{b}	1.54 ± 0.65^{a}	Wilcoxon (*n* = 25)
	P (%)	0.53 ± 0.51^{b}	0.56 ± 0.37^{a}	Wilcoxon (*n* = 22)
	K (%)	1.23 ± 0.94^{a}	1.26 ± 0.8^{a}	Wilcoxon (*n* = 16)
Urban and agricultural wastes	C/N	24.45 ± 7.75^{a}	16.11 ± 5.05^{b}	Student (*n* = 7)
	OC (%)	33.22 ± 2.32^{a}	25.26 ± 7.62^{b}	Student (*n* = 7)
	Ntot (%)	1.49 ± 0.43^{a}	2.33 ± 1.79^{a}	Student (*n* = 7)

Superscript letters indicate statistical differences with a *p*-value less than 0.05.

3.3 Benefits and limitations of using vermicompost from OFMSW in agriculture soils

3.3.1 Effects on crop yield

In our study, we found 18 papers that assessed the impact of vermicompost from OFMSW on crop yields under field conditions. All these papers found that vermicompost had a positive effect on biomass and crop yield. Arancon et al. (2005, 2003a) showed improved yields for pepper, tomato, and strawberry when vermicompost was supplemented with inorganic nitrogen fertilizers compared to inorganic fertilizers alone (same N dose in the different treatments). The same effect was shown for rice compared to the inputs of non-vermicomposted waste and a control with no inputs (Mishra et al. 2005), and compared to the contribution of NPK alone or to NPK with farmyard manure (Sahariah et al. 2020). Yields also increased for ginger compared to a control (no input) and vermicompost from cow manure (the best yield in this study was the treatment with vermicompost from paper sludge) (Eo and Park 2019). Olive grove yield increased 35.5% and the nutrients in olive fruit were significantly different compared to the control and better than compost from MSW and sheep manure (Tejada and Benitez 2020). Yields also increased for bean compared to pressmud, flower waste, and farmyard manure (Sajitha et al. 2007) and for pea compared to cattle manure (Abdrabbo et al. 2014). Pattnaik and Reddy (2010, 2011) showed that vermicompost has significant results on the growth of fenugreek (*Trigonella foenum-graecum* L.) and tomato (*Lycopersicum esculentum* Mill.) compared to compost from the same OFMSW. In addition, Arancon et al. (2005, 2003a) showed that vermicompost (supplemented with inorganic fertilizers to equalize the initial N levels available to plants) has a greater impact than inorganic fertilizers (NPK) alone on marketable yield and dry shoot weight of pepper. The addition of NPK nutrients to vermicompost to achieve nitrogen equivalence shows that vermicompost has other factors that promote plant growth. According to Arancon et al. (2005, 2003a), it is not only the available elements such as N and P in vermicompost that enable plant growth, but also/rather the high biological activity and increased production of PGRs, such as humic acids, and PGHs.

In contrast, Roberts et al. (2007) showed that vermicompost from green waste and sewage sludge, while increasing tomato plant germination and fruit quality, did not increase total fruit yield, marketable fruit yield, fruit number, fruit weight, or vitamin C concentration compared to commercial peat-based compost. Eo and Park (2019) found that at high doses (40 t ha^{-1}), vermicompost from OFMSW increased root disease in ginger (*Panax ginseng*). However, with moderate use (10 t ha^{-1} here), it had a positive impact on root growth. This shows that excessive inputs can lead to nutrient surpluses that can harm the crop and/or the environment. For example, in their experiment, a 40 t ha^{-1} input of vermicompost is equivalent to 520 kg of N per hectare (vermicompost = 1.3% N), which is harmful to the crop and can also lead to pollution due to nitrogen leaching. It is therefore necessary to properly characterize the products before use in the field.

Mishra et al. (2005) showed that the use of vermicompost increases the chlorophyll concentration in rice leaves. This was further corroborated by Tejada and Benitez (2020) who found an increase in micro and macro nutrients in olive leaves. Arancon et al. (2005, 2003a) showed that the high fulvic acid and protein content in vermicompost are easily degradable by soil microorganisms and assimilated by plants. Yardim et al. (2006) have demonstrated that a decrease in crop pests was related to a high dose of nitrogen in the foliage and a phenolytic compound that is stimulated by the addition of vermicompost.

Vermicompost from OFMSW is a highly variable product (see Section 3.3) and it is therefore difficult to generalize about its impact in the field from the few published studies. Moreover, in most of these studies, there was no control in the strict sense of the word because vermicompost was compared to inorganic fertilizers (NPK) or cattle manure. It is possible to compare different products with each other, but without a proper control, it is not possible to measure the effect compared to a treatment without material input. However, the findings from the application of vermicompost from OFMSW are consistent with the positive reports for the application of vermicompost from manure in the field (Tringovska and Dintcheva 2012; Guo et al. 2015; Velecela et al. 2019; Aslam et al. 2019; Tejada and Benitez 2020).

3.3.2 Effects in soil (bio-physico-chemical)

It is widely recognized in the literature that OM inputs of any kind, such as biochar (Atkinson et al. 2010; Yadav et al. 2019), compost, or manure (Obriot et al. 2016; Kelley et al. 2020), have positive effects on soil physico-chemical qualities (Diacono and Montemurro 2010; Ghosh et al. 2010; Peltre et al. 2017). We only found four papers that addressed the impact of vermicompost from OFMSW on the soil and its bio-physical-chemical parameters in the field. All these studies showed that vermicompost input increased soil pH (Eo and Park 2019) and carbon storage compared to the contribution of NPK alone or to NPK with farmyard manure (Sahariah et al. 2020). It also increased levels of the soil nutrients N, P, and K when supplemented with inorganic fertilizers to balance fertilizer recommendations compared to inorganic fertilizers alone (Arancon et al., 2006). Only Sahariah et al. (2020)

studied the evolution of soil physical parameters and showed that vermicompost increased the soil water retention capacity and reduced bulk density compared to the contribution of NPK alone or to NPK with farmyard manure. At the same time, these authors studied soil microbiology following the application of vermicompost. They all observed that vermicompost increased soil microbial biomass and enzyme activities (dehydrogenase, urease, β-glucosidase, phosphatase, and arylsulfatase) compared to MSW, sheep manure and control, and the enzyme-humus complex compared to the control (Tejada and Benitez 2020), as well as soil respiration measured by dehydrogenase activity (Arancon et al., 2006). Arancon et al. (2006) showed that increases in dehydrogenase activity and microbial biomass were positively correlated with increases in NH_4-N, NO_3-N, and orthophosphates. The same authors demonstrated that these activities promote nutrient cycling rates, the production of plant growth regulating materials, and the accumulation of plant resistance or tolerance to pathogen attack. According to these authors, plant growth is stimulated not only by nutrients in the vermicompost, but also due to the microbiological activity and diversity of the product. This leads to improved rates of nutrient cycling in the soil and protection of plants against diseases through competition and antagonism against other pathogenic organisms. Arancon et al. (2003b) also showed that vermicompost allows parasite regulation at the level of soil microfauna by decreasing parasitic nematodes and increasing the populations of fungivorous and bacterivorous nematodes compared to inorganic fertilizer or a control without fertilizer. For meso and macrofauna, Gunadi et al. (2002) showed an increase in saprophagous arthropods (Collembola as *Isotomidae*, *Onychiuridae*, *Sminthuridae*, Acari as *Cryptostigmata* and *Symphyla*) following the addition of vermicompost (compared to inorganic fertilizer or compost) and also hypothesized that this could be due to the high microbiological activity of the product.

4 Outlook and future studies

4.1 Studies on the process of vermicomposting using OFMSW

We found that there is a lack of research on the applications of vermicompost from OFMSW in agriculture. Indeed, the majority of research focused on the process of vermicomposting this type of waste. This is justified by the great diversity of materials included in the OFMSW, which are present in variable proportions depending on the country and its level of development (Troschinetz and Mihelcic 2009). Thus, the variability of the incoming OM can lead to an additional complication in running waste recovery programs. However, Hanc et al. (2011) showed that in the same city, the composition of biowaste (type and chemistry) over four seasons varied little in urban areas (mainly fruit and vegetables) but was more influenced by home garden management. Therefore, with a prior analysis of OFMSW, it may be possible to predict the quality of vermicomposts obtained either by modeling (Hosseinzadeh et al. 2020) or case-by-case studies with different bulking agents depending on available resources (e.g., cow manure in India).

Despite a lot of research on the processes, there are still avenues for improvement to optimize the valorization of OFMSW by vermicomposting and improve the understanding of the fundamental processes related to this technique. For example, some studies looked at mixtures of earthworm species with different functions (Suthar and Singh 2008) or searched for native and readily available species (Suthar 2009) rather than *E. fetida*. On larger scales (semi-industrial platforms for example), the parameters necessary for the process to run smoothly (e.g., temperature, humidity, pH) are much harder to control, which can lead to changes in the process and increase the variability of the derived product.

4.2 Use of vermicompost from OFMSW in the field

Although we have gathered some information on the impact of vermicompost in the field, some points have not yet been studied. For example, in their meta-analysis, Blouin et al. (2019) showed that the species most receptive to vermicompost are Cucurbitaceae, Asteraceae, Fabaceae, and Poaceae. In addition, in our review, we found that the majority of studies using vermicompost from OFMSWs were focused on ornamental plants or vegetable crops and we could not find studies about cereals such as wheat, barley, and maize.

The low temperature of the process could have benefits that have been little studied such as a positive effect on soil biodiversity. Although most studies agree that vermicomposting increases the taxonomic and functional diversity of bacterial communities (Dominguez et al. 2019) as well as the functioning of a microdecomposer food web (Aira et al. 2008), only a few studies evaluated the impact of the process on meso and macrofauna abundance and diversity. However, Monroy et al. (2011) showed an increase in the total number of arthropods in the presence of *E. fetida* (especially springtails and mesostigmatid mites), suggesting that the development of large populations of soil arthropods is a characteristic of the initial stages of the earthworm-mediated decomposition process. Of the seven groups of arthropods monitored (springtails; mites: astigmatids, prostigmatids, mesostigmatids, and oribatids; psocids and spiders), only the psocids were negatively affected by the presence of *E. fetida*. Sampedro and Domínguez (2008) also used ^{13}C and ^{15}N to show that earthworms interact intensively with other detritivores such as bacteria, fungi, and other soil fauna. This work, which aimed to classify relative trophic positions, using pig and cow manure separately in two different systems, showed that the microdecomposer community was different depending on the stage of the earthworm life cycle (adults, hatchlings, and cocoons) and resource quality. Thus, in view of its biological quality, studies on the impact of vermicompost, after field application, on soil macrofauna such as earthworm populations and mesofauna such as springtails or mites are a promising route, especially because these are excellent bioindicators of soil quality (Gulvik 2007; Peres et al. 2011).

4.3 Comparison with other techniques and integration into OFMSW management systems

Comparative studies between the different techniques for the valorization of OFMSW are missing. For example, Lohri et al. (2017) revealed a disparity in publications on the technology of organic waste recovery and a real lack of field studies and suggested that more transdisciplinary research is needed using real case studies. The same authors concluded that as well as studying the fundamental processes, more focus should be placed on systems in application. In this way, various valorization techniques could be compared to validate the fundamental theory on the ground (rather than in the laboratory) and develop the techniques for recycling biowaste while upscaling. Moreover, in order to choose appropriate recycling techniques, Zhang et al. (2010) showed that it is necessary to separate the waste streams first to optimize their recovery process. For example, in developing countries, little investment is made in waste separation, which can lead to contamination with pathogens and/or pollutants limiting or excluding the choice in OFMSW recycling techniques. On the other hand, in rich countries, the flows are relatively well separated which allows a more diversified selection of recycling systems, including vermicomposting. However, this low-tech technique is developing particularly well in Asia (especially in India), while few European researchers are interested in this process. Indeed, a small number of reports compared the life cycle of other OFMSW recovery techniques such as composting or methanisation with vermicomposting (Komakech et al. 2015; Nigussie et al. 2016) but few studies evaluated the products of these techniques at the agronomic level in the field. A comparison would make it possible to assess the advantages and disadvantages of each method and to guide regions towards an adapted management of their OFMSW according to their needs. Bortolotti et al. (2018) showed that decentralization of organic waste management via several possible scenarios could be a promising alternative to centralized industrial facilities. This type of management would be perfectly adapted to vermicomposting, which is particularly suitable in urban areas. Indeed, in a circular economy approach, some of the OFMSW could be recovered by collective vermicomposting in the city and some on peri-urban platforms where different techniques would allow the recovery of all the OM (for example pre-composting or methanisation of waste that is difficult to manage in vermicomposting). Thus, the vermicompost produced in cities could be used in urban agriculture and/or collected for use in peri-urban agriculture (reduced transport compared to the collection of raw OFMSW) and the products from the peri-urban platforms would be reserved for local agriculture.

4.4 Socio-economic issues

We found little information on the economic and social impact of the practice of vermicomposting and the use of vermicompost in agriculture. According to Lim et al. (2016), economic evaluations of vermicomposting are scarce and there are differing opinions: some activities are profitable and others are not, depending on the type of process used, the market value of the organic fertilizer, and the production volume. However, vermicomposting is a feasible organic waste management strategy because, like composting, it is a process with lower operating costs than other waste management options (Ruggieri et al. 2009). As with composting systems, the economic potential of a vermicomposting system depends on the initial capital costs (e.g., high-tech indoor or low-tech outdoor windrow system) as well as the revenues from the vermicompost produced. Prices vary widely around the world, with a selling price of $80 per ton of vermicompost in Uganda (Lalander et al. 2015) compared to $200 to $1000 per ton in the USA (Edwards et al. 2010) and $200 to $2500 in France depending on the type of packaging (wholesale for professionals or retail for individuals). The commercialization of the earthworms produced during the process can be an additional economic gain because they are rich in protein (65% of the dry matter) and can be used as meal for animal feed (Adhikary 2012; Lalander et al. 2015) or even for human consumption (Tedesco et al. 2019; Conti et al. 2019). Earthworms can typically sell for $5 to $35 per pound in the USA (Edwards et al. 2010). At the same time, new technologies such as worm sorters have been developed in recent years, which facilitate the extraction of worms from vermicompost for their commercialization (Lin et al., 2021). In the context of OFMSW valorization, one of the potential sources of income for vermicomposting activities would be directly from the collection and/or valorization of organic wastes from businesses and communities because in certain areas of the world and in particular in Europe (European Union 2018), mandates are in place for waste recover by the end of 2023. To our knowledge, no study has integrated the benefits of collection/costs of recovery of OFMSW with a vermicomposting system. At the same time, there is a lack of policies favorable to the implementation of sustainable waste management practices, minimal legislation concerning waste recovery, and insufficient international influence from developed countries, to support the development of sustainable waste management in developing countries that do not have the means to implement the same waste management policies (Marshall and Farahbakhsh 2013). This is an additional constraint for the development of processes such as vermicomposting and a curb on the development of this technique at larger scales.

5 Conclusions

This review examined the value of the vermicomposting process in its entire loop/cycle, from the recovery of OFMSW to the application of vermicompost in the field. According to the literature studied, vermicomposting is perfectly adapted to the valorization of OFMSW. Indeed, earthworms can degrade these materials and produce a vermicompost that is beneficial for agriculture. We have shown that the vermicompost is an amendment with interesting fertilizing properties like compost, although its agronomic parameters seem to be slightly more suitable for crop production. Indeed, vermicompost had a greater effect on soil, plant growth, and yield than compost, probably due to other parameters such as microbiology, mineralization potential, or PGRs and PGHs. With evolving environmental issues and increasingly strict regulatory constraints, vermicomposting could be a suitable response to waste management in the context of the circular economy. However, our study also revealed a lack of research on vermicomposting, especially regarding field studies. These studies would provide a better understanding of the vermicomposting process and its applications, which in turn could accelerate progress in its uptake as an interesting approach for reconciling waste recovery and sustainable agricultural development. Vermicomposting of OFMSW is a promising solution for linking waste management and sustainable agriculture, but for this to happen, in-depth research on the quality of the vermicompost produced and its impact on agricultural soils in the long term must be developed. These studies could lead to a standardization, distinct from that for classical compost, so that the use of this technique and product becomes widespread.

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Code availability The code used in this article is available from the corresponding author upon reasonable request.

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Declarations

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