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1 **Vermicomposting of municipal solid waste as a possible lever for the**
2 **development of sustainable agriculture – a review**

3

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10**Abstract:**

11Continued population growth and urbanization as well as changing consumption patterns have led to
12an explosion in the amount of waste produced, especially in cities. To feed the world, we also need to
13increase agricultural production while limiting our impact on the environment. Part of the solution
14could be to recycle the organic fraction of municipal solid waste (OFMSW) as a resource for
15agriculture near cities with techniques such as vermicomposting, which uses earthworms to recycle
16organic waste into nutrient-rich vermicompost. The objective of this review was to examine (i)
17whether vermicomposting is appropriate for recycling OFMSW, (ii) the quality of the vermicompost
18produced, and (iii) the impact of this product on crops and soil parameters. We found that
19vermicomposting can be adapted for OFMSW recovery because the process is suitable for all the types
20of OFMSW (food, paper, and green waste). The vermicompost produced is both high in organic
21carbon (18.83% to 36.01%) and a potential fertilizer (1.16 to 2.58% N, 0.42% to 1.12% P and 0.61%
22to 2.05% K). A comparison with compost from the same types of OFMSW suggested that
23vermicompost is slightly more suitable for crop production with significantly lower C/N and pH and
24higher N and P. Vermicompost was actually found to have a better effect on plant growth than
25compost, suggesting that classical chemical analyses are not always sufficient to characterize the
26potential of organic amendments/fertilizers. Indeed, the application of vermicompost in the field leads
27to an increase in carbon storage, water retention, enzymatic and microbiological activity, and soil
28fauna abundance and diversity. Finally, we found that reports on the use of vermicompost from
29OFMSW are scarce and most studies focused on the process itself. Overall, our review synthesizes
30data and the interest in this technique and proposes perspectives for future studies.

31

32

33**Keywords:** Vermicompost – Waste management – Organic Fraction of Municipal Solid Waste –
34Agronomical impact – Soil conservation

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60		

61“Figure 1”: Picture of vermicomposting windrow of urban organic waste (food) and cattle manure.



62

63

641 Introduction

65

66In the past farmers used organic waste from cities to amend soils but with the development of the
67chemical and food industry in the 20th century this waste was no longer of interest (Barles 2014). The
68link between urban organic waste and agriculture has thus largely been forgotten as a result of the
69intensification of agriculture and urbanization. Indeed, agricultural practices have become increasingly
70standardized with, for example, the use of nitrogen-phosphate-potassium (N-P-K) fertilizers
71(Kibblewhite et al. 2008). Farm specialization has also led to activities being distributed according to
72sector and region. Martin et al., (2018) noted that animal waste such as manure is concentrated in
73certain regions of the world, which can lead to potential pollution, while other agricultural areas lack
74organic matter (OM) to feed their soils. Cities are generally surrounded by "agricultural belts", which
75should make it possible to promote the valorization of the organic fraction of municipal solid waste
76(OFMSW).

77

78A World Bank study (Bhada-Tata and Hoornweg 2012), predicted that municipal solid waste will
79increase by 70% between 2012 and 2025 to reach 2.2 billion tons per year. Twenty to 30% of this
80waste is organic waste, with up to 80% of it coming from low- and middle-income regions
81(Troschinetz and Mihelcic 2009). Organic waste recovery from cities represents an enormous

82challenge for circular waste management, which aims to return OM to the soil to "close the loop" and
83thus save natural resources and reduce our impact on the environment (Ghisellini et al. 2016). To
84manage organic waste from cities in a sustainable way, it is necessary to divert it from classical
85management and treatment methods such as incineration and/or landfill. Bortolotti et al., (2018)
86showed that decentralized management of urban organic waste is a promising alternative to centralized
87industrial facilities. There are many techniques for recovering organic waste that can be adapted at
88different scales, converting it into a valuable resource. In their review, Lohri et al., (2017) classified
89these into four different categories: (i) direct use (direct land application, direct animal feed or direct
90combustion), (ii) biological treatment (composting, vermicomposting, black soldier fly treatment,
91anaerobic digestion, fermentation), (iii) physico-chemical treatment (transesterification, densification)
92and (iv) thermo-chemical treatment (pyrolysis, liquefaction, gasification). Among the products
93produced from these methods, compost (from composting and vermicomposting), black soldier fly
94residues, anaerobic digestate and biochar from pyrolysis can be used in agriculture (Lohri et al. 2017).
95

96Vermicomposting is a controlled OM degradation process based on the addition of earthworms
97upstream of decomposition to accelerate the stabilization process (Dominguez 2004; Munroe 2007;
98Lim et al. 2016). The main objective is to stabilize and degrade OM to produce a humus-like material,
99called vermicompost (Adhikary 2012; Doan et al. 2015). The degradation process is carried out at
100room temperature (mesophilic process) and stabilization is achieved through the interaction of
101earthworms, associated microorganisms and other decomposers (Gomez-Brandon et al. 2012). To
102avoid compaction and control aeration, a minimum of 2.5 kg of earthworms per m² (Munroe 2007)
103should be maintained in piles that are smaller than those for composting (1m maximum). If these
104conditions are respected, there is no need to turn the heap and the environment is conducive to
105earthworms and does not heat. The earthworm species used are generally epigeic (Blouin et al., 2013),
106which naturally remain on the soil surface and in the fresh bedding used as food. *Eisenia fetida*,
107(Savigny 1826) (Haplotaxida, Lumbricidae) is the most widely used species in vermicomposting due
108to its high waste ingestion capacity (Edwards et al. 2010). Although many variations in
109vermicomposting techniques have been developed, from low tech in windrows to high tech with fully
110automated continuous-flow vermicomposting reactor systems, (Board 2004; Edwards et al. 2010),
111there are always two major phases in the process: (i) the active decomposition phase and (ii) the
112maturation phase, (Munroe 2007; Sim and Wu 2010; Ali et al. 2015). In the active decomposition
113phase (i) earthworms (a) ingest, digest and cast organic matter; they not only improve the assimilation
114of OM (indirect effect) but also facilitate the movement of poorly mobile microorganism communities
115(direct effect) (Monroy et al. 2008); and (b) the fractionate OM. They thus allow an increase in the
116potential surface area exposed to other decomposers, especially microorganisms (Aira et al. 2007;
117Gomez-Brandon et al. 2012). Logistically, this first phase consists of setting up earthworm litter
118adapted to the quantity of waste to be recovered before applying the OM in a discontinuous (one-time

119application) or continuous (regular applications) way. Batch feeding requires more work but allows
120better control of the earthworm environment as well as pH and humidity control. To adjust these
121factors, bulking agents such as cardboard boxes, waste from green spaces or straw (for manure) are
122used. In the maturation phase (ii) earthworms migrate to new layers of fresh and undigested waste.
123Fresh OM is added in contact with the almost decomposed OM so that the hungry earthworms migrate
124to the new fresh litter. This step is essential to keep as many earthworms as possible and continue the
125process while harvesting the resulting earthworm-free vermicompost.

126

127Most of the studies on vermicomposting processes focused on adding value to animal manure and
128some rare reviews highlighted the potential of this technique for the valorization of urban organic
129waste (Sim and Wu 2010; Singh et al. 2011). In their recent review, Alshehrei and Ameen (2021)
130highlighted a growing interest in vermicomposting for the valorization of Municipal Solid Waste
131(MSW) in urban environments, particularly the organic fraction (OFMSW). Recently, the regulations
132concerning the recovery of OFMSW have been evolving with, for example, a new European mandate
133to consider this waste as an amendment resource by the end of 2023 (European Union 2018). Thus, it
134is necessary to find processes with the lowest impact on the environment but adapted to urban
135environments and all the related constraints (high density, pollution and so on...).

136

137Few studies have evaluated the agronomic potential of vermicomposts from OFMSW. However,
138studies concerning the use of vermicomposts from manures in agriculture show encouraging results
139for plant growth (Atiyeh et al. 2000; Jouquet et al. 2011), the development of beneficial bacteria for
140plants (Monroy et al. 2008; Aira et al. 2008; Adhikary 2012) and a reduction in plant diseases and pest
141attacks (Ersahin 2010; Cardoza 2011; Rowen et al. 2019). Once applied and incorporated into the soil,
142it decreases bulk density and increases porosity, increases water retention capacity and promotes
143aeration (Manivannan et al. 2009; Lim et al. 2014). In addition, a meta-analysis showed that the
144addition of vermicompost from manure increases crop yield and total biomass (Blouin et al. 2019).
145There is therefore a strong need to know more about vermicompost from OFMSW, to see if this
146product could have the same benefits to soil and crops, and thus help recycle OM (from the city to the
147field and vice versa).

148

149In this review, we first (i) define and classify the studies on vermicomposting of OFMSWs as a
150function of waste category and various other factors. Then, we characterize more precisely (ii) the
151quality of the vermicompost resulting from OFMSW to determine whether this product has interesting
152potential for the development of agriculture compared to classic compost. Finally, we evaluate (iii) the
153impact of this product on crops and the bio-physico-chemical parameters of the soil once applied to
154the field. We then discuss the outlook and future research perspectives and studies needed to better
155understand this process and its applications.

156

157

1582 **Material and methods**

159

1602.1 *Literature search*

161

162The Web Of Science (Clarivate©) was first searched for publications from 2000 to 2020 using the
163following keywords: "vermicompost*" OR "vermiculture" OR "vermitechnology". This search
164recovered a set of 3128 articles. To refine the search we then added the following keywords: AND
165"organic waste" OR "municipal solid waste" OR "urban food waste" OR "urban solid biowaste" OR
166"biowaste" OR "urban waste" OR "urban biowaste" OR "vegetable waste" OR "food waste. This
167refined search recovered 410 articles (last search on 23/10/2020). We performed the same search on
168the CABI database (CAB direct) to access national journals that often provide analysis of products
169such as vermicompost and obtained 724 articles in total. We then read the abstracts and selected those
170articles really focusing on OFMSW recycling. Here we defined OFMSW as biodegradable urban
171organic waste including non-liquid waste (thus excluding sludge) from households and small
172businesses and institutions as defined by Wilson et al., (2015). We finally obtained 96 original papers
173and 19 reviews from the Web Of Science (Clarivate(c)) and 88 additional papers and three additional
174reviews from the CABI database, for a total of 184 papers and 22 reviews. To examine how prevalent
175research on vermicomposting of OFMSW is compared to the other techniques of OFMSW recovery
176we also carried out a search with the same keywords in the Web Of Science (Clarivate(c)) and
177obtained 4,916 results with "compost*", 692 results with "methanisation" OR "digestate" and 163
178results with "black soldier fly".

179

1802.2 *Data selection*

181

182To characterize vermicomposting processes and vermicompost quality and applications we recorded
183specific information from the papers (Table 1). First, we identified the (i) categories of OFMSW in
184each study. Since we found a wide variety of organic waste (sometimes different names for the same
185waste), we chose to group it into categories: food, green waste, paper, and MSW (undefined mixture
186of municipal organic waste). Then we noted the (ii) species of earthworm used for the process and we
187found out if (iii) a pre-treatment was carried out before the process. We also noted for each of the
188studies if it was carried out in (iv) the laboratory or in the field and if it concerned the (v) process itself
189or the use of the vermicompost. Finally, we identified the (vi) country where the studies and
190experiments took place (grouped by continent) to identify the locations that are most interested in this
191process.

192

1932.3 *Data treatment*

194

195To examine the quality of the vermicompost resulting from OFMSW and determine whether this
196product has interesting potential for the development of agriculture compared to classic compost
197produced from OFMSW, we recorded data from each article/paper for the agronomically-important
198and metallic trace elements to calculate a mean and obtain a standard error according to factors. After
199analyzing the intra variability (different vermicomposts) we selected the studies that compared
200vermicomposts to composts from the same OFMSW to estimate its quality relative to a better-known
201product and we used paired tests. All analyses, tables and calculations were performed using RStudio
202software (version 1.4.17.17).

203 **Table 1:** Information retrieved from the 184 articles according to the factors studied: (i) urban organic waste categories, (ii) earthworm species, (iii) pre-
 204 treatment, (iv) laboratory (including greenhouse) or field experiment, (v) vermicomposting process or vermicompost use study and (vi) continent. In urban
 205 organic waste categories the factor “food” includes “households waste,” kitchen waste”, “food waste”, “vegetable waste”, “supermarket food waste”,
 206 “coffee” and “fruit waste”; the factor “green waste” includes “tree leaves”, “garden residues”, “sawdust”, “shaving”, “wood”, “urban green waste”, “turf
 207 grass” and “urban aquatic seed”; the factor “paper” includes “paper”, “newspaper” and “cardboard” and the factor “MSW” includes “municipal solid waste”,
 208 “solid urban waste”, “organic part of MSW”. MSW was divided into food, green waste and paper where possible according to the author's description and the
 209 replication of the same mixture with different ratios in the same publication was only counted once. In earthworm species the factor "unspecified species"
 210 indicates that in the publication the earthworm species was not specified or defined at the species level. In pre-treatment the factor “stabilization” indicates
 211 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
 212 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)	<i>Eisenia fetida</i> (116) <i>Eudrilus eugenia</i> (31) Unspecified species (28) <i>Perionyx excavatus</i> (13) <i>Eisenia andrei</i> (10) <i>Lampito mauritii</i> (10) <i>Lumbricus rubellus</i> (5) <i>Metaphire posthuma</i> (2) <i>Perionyx sansibaricus</i> (3) <i>Perionyx ceylanensis</i> (1) <i>Pheretima peguana</i> (1) <i>Allolobophora parva</i> (1) <i>Amyntus diffringens</i> (1) <i>Metaphire houlleti</i> (1) <i>Octolasion tyrtaeum</i> (1) <i>Dendrobaena veneta</i> (1) <i>Octochaetha thurstoni</i> (1) <i>Octochaetona serrata</i> (1) <i>Lumbricus terrestris</i> (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

2133 Results and discussion

214

2153.1 Suitability of vermicomposting for OFMSW recovery in urban environments

216

2173.1.1 Study Typology

218

219Our literature review found that vermicomposting is less studied than other OFMSW recovery
220processes. For example, reports on classical composting were published 10 times more frequently
221(4,916 results) than vermicomposting (410 results) during the same period on the Web Of Science
222(Clarivate(c)). The geographical origin of the studies on vermicomposting shows that it was mostly
223studied in Asia (63.6% of the studies), moderately in America (20.1%) and less in Europe (7.6%),
224Africa (7.6%) and Oceania (1.1%) (Table 1). Studies on the vermicomposting of OFMSW were still
225largely carried out in the laboratory (87%). Only 10.9% were carried out in the field and only 2.1% in
226both the laboratory and field. In addition, 67.9% of the studies focused on the vermicomposting
227process itself, 23.9% on the use of vermicompost from OFMSW and 8.2% on both (process and use).
228This suggests that vermicomposting is not thoroughly studied in outdoor conditions and that most of
229the studies focused on the understanding or optimization of the process. When the two parameters
230were crosschecked, this further confirmed that most of the research on vermicomposting is done in the
231laboratory and about processes (65.2%). Moreover, even the application of vermicompost is studied
232more in the laboratory (laboratory and use = 16.3%) than in the field (field and use = 7.1%). These
233trends can explain why this technique is not widely used to valorize OFMSW on a global scale. This
234also raises the question of whether the vermicomposting process, which is well known for waste such
235as manure, is more difficult to use on OFMSW due to the high variability of this waste, suggesting that
236further fundamental laboratory studies are required.

237

238As earthworms are fundamental to this process, we recorded the earthworm species used and their
239frequency in the articles (Table 1). As expected, *E. fetida* was the most studied species and was found
240in 50.9% of experiments. The second most used species was *Eudrilus eugenia* (13.6%) follow by
241*Perionyx excavates* (5.7%). In a relatively high percentage of studies the species was not specified
242(12.3%). This was generally in papers that only investigated the application of vermicompost. Other
243less common species were also used in Asia such as *Lampito mauritii*, which is an anecic species
244(Tripathi and Bhardwaj 2004) and *Metaphire posthuma*, which is an endogeic species (Doan et al.
2452013). It is important to note that earthworm ecological categories were defined on European species
246(Bouché, 1977) and it is difficult to use these categories for non-Lumbricidae species (Asian for
247example) while the concept itself remains controversial (Bottinelli et al. 2020). Studies that compared
248the effectiveness of different earthworm species on the decomposition of organic waste suggest that *E.*
249*fetida* more rapidly transforms OM into vermicompost (Kaviraj and Sharma 2003; Tripathi and
250Bhardwaj 2004; Rajpal et al. 2012). Other species are used because in some parts of the world *E.*

251 *fetida* is not naturally present and thus some studies focused on the potential of native and readily
252 available species (Suthar 2007, 2009; Soobhany et al. 2015a). This type of research on potential
253 earthworm species for vermicomposting also highlights the need for fundamental laboratory studies.

254

255 3.1.2 High diversity in OFMSW categories

256

257 The information found in the 184 articles (Table 1) showed that about half of the studies concerning
258 the recovery of OFMSW were based on food waste (47.3%). However, Table 1 only counts the
259 occurrence of the four keywords in the articles (food, green waste, paper and MSW) but not if the
260 studies recycled these different materials in a mixture. To define the quality of vermicompost from this
261 particular type of waste, we first listed the different types of urban waste that have been
262 vermicomposted in the 184-article dataset (Table 2). We found 256 different types of mixtures that we
263 grouped into two major groups: (i) urban waste only and (ii) urban waste + other waste. The exact
264 name of the waste (not the typology used here) and the proportion used in each study are listed in the
265 annex table 1. This classification showed that almost half of the mixtures studied (Table 2: 43.75%)
266 also contained other materials besides urban waste (OFMSW) such as agricultural waste (manure,
267 which is the preferred substrate for vermicomposting). However, vermicomposting of OFMSW is also
268 possible with green waste (Tognetti et al. 2008; Wani et al. 2013) or shredded paper and cardboard
269 (Hanc and Pliva 2013; Soobhany et al. 2015b; Mathivanan et al. 2017), which is an abundant resource
270 in cities. According to Hogg et al., (2002), paper and cardboard represent up to 37% of MSW and
271 food waste added to green waste represents up to 53% of MSW in different European countries. All
272 these wastes, which make up the majority of MSW, can be recovered through vermicomposting, which
273 would avoid having to resort to other wastes that are not necessarily easily accessible in urban areas,
274 such as agricultural wastes. OFMSW mainly includes isolated waste (food, green waste or paper only)
275 and not mixtures of several types: 43% of the studies concerned food leftovers, 9% green waste and
276 8% paper, which represented a total of 60% of the studies compared with 40% dealing with mixtures
277 of several classes (MSW are included). For the process of vermicomposting OFMSW, it is usually
278 necessary to mix different wastes such as food waste with a bulking agent such as cardboard and/or
279 paper and/or shredded wood. Studies without the use of a bulking agent were all carried out in the
280 laboratory, whereas outdoor studies (only 10/140 studies of the process) described the process with
281 mixed waste (green waste, paper with food and MSW which is a mix of organic municipal waste)
282 because they were adapted to the field reality and the constraints of the process (Singh and Sharma
283 2003; Mishra et al. 2005; Pattnaik and Reddy 2010, 2011; Agarwal and Arora 2011; Abdrabbo et al.
284 2014; Cao et al. 2016; Hanc et al. 2017; Hrebeckova et al. 2019; Dohaish 2020).

285Table 2: Classification of the 256 waste mixtures found in the 184 articles. In urban organic waste + other waste category the factor “agricultural waste”
 286includes “hay”, “straw”, “rice bran”, “sugarcane bagasse”, “biogas slurry from agriculture”, and all animal slurry, dung and manure, the factor “sewage
 287residues” includes “sewage sludge” and “biosolids”.

288

Factor studied	Urban organic waste only	Urban organic waste + other waste	Other type 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 + sewages residues (2) Food + sewages 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) - 5 g CaCO ₃ /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: <i>T. viridae</i> , <i>B. polymyxa</i> and <i>P. crysoporium</i> - 50 ml/kg (1) <i>Trichoderma harzianum</i> (1) <i>Leucaena leucocephala</i> and <i>Morus alba</i> . <i>Penicillium funiculosum</i> and <i>P. chrysogenum</i> (1) <i>Pleurotus sajor-caju</i> (fungus), <i>Trichoderma harzianum</i> (fungus) and <i>Azotobacter chroococcum</i> (1) Owinema: larvae of the nematode <i>Steinernema feltiae</i> - 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

2893.1.3 Advantages and limitations of the vermicomposting process with OFMSW in an urban context

290

291OFMSW valorization requires adapted processes that take into account the environmental stakes and
292adapt technically to an urban context. Thus in this section, we discuss the advantages (speed, reduced
293GHG, lack of odor, adaptability to different spatial scales) and disadvantages (some wastes require
294more complex pre-treatments) of vermicomposting OFMSW according to the present review of the
295subject.

296

297Ammonia (NH₃), methane (CH₄) and nitrous oxide N₂O emissions from vermicomposting are up to
298three times lower than for domestic composting (Lleo et al. 2013). Indeed, Komakech et al., (2015)
299showed with a life cycle analysis (LCA) of city biodegradable waste treatment systems that
300conventional composting (thermophilic) emitted 80.9 kg CO₂ eq.ton⁻¹ of waste compared to 17.7 for
301vermicomposting, i.e. 78% less GHG. This is mainly due to the heat produced during traditional
302composting, which produces a significant amount of GHG as 25 to 36% more N₂O and 22 to 26%
303more CH₄ than vermicomposting (Nigussie et al. 2016). Nigussie et al. (2016) showed that by
304increasing the earthworm density (1kg and 3kg per m²) and moisture content (75% and 85%) during
305the process, it was possible to further reduce GHG emissions (decreased N₂O emissions by 40% and
30623% and CH₄ emissions by 32% and 16%, with higher and lower moisture contents, respectively and
307decreased CH₄ emissions by 35% and 10% with higher and lower earthworm density, respectively
308while this density has no effect on N₂O emissions) and significantly reduced N loss by 10–20%
309compared to thermophilic composting. Based on the study by Bernstad Saraiva Schott et al. (2016),
310Nigussie et al. (2016) excluded CO₂ (including biogenic CO₂ important in the short term) in the GHG
311balance because a high emission of this gas indicates a high stabilization rate of the products as plant
312litter (humus), which is generally excluded from GHG balances. Thus when the CO₂ emitted by
313vermicomposting is omitted, the process emits less GHG than conventional composting in these
314studies. However, one study showed that vermicomposting can emit more N₂O than composting
315(Hobson et al. 2005), suggesting that the process is variable, probably depending on the type of
316material being decomposed and how well it works.

317

318One other advantage of vermicomposting to valorize OFMSW in an urban context is that it is an
319odorless process (Lleo et al. 2013). Thus it can be carried out indoors or in cellars and on several
320scales and be adapted for domestic use (Sherman and Appelhof 2011; Pirsahab et al. 2013). It can also
321be adapted for collective use or on platforms ranging from "low-tech" in windrows (Edwards 2011a;
322Hanc et al. 2017) to "high-tech" in industrial scale vermicomposters (Jain et al. 2003; Gajalakshmi et
323al. 2005; Edwards 2011b). Unlike collective vermicomposters, which aim to recycle waste close to
324where people produce it (e.g. at the bottom of buildings), platforms are defined as sites to which
325organic waste is transported and stockpiled to recycle a larger quantity of material (generally carried

326out by companies). Thus, it is possible to recycle OFMSW using vermicomposting in any available
327space, for example at individual homes, office or apartment buildings or after collection by
328professionals. Both vermicomposting and composting can be used to recycle food waste but also other
329sources of organic waste traditionally found in city. Generally, in urban composting shredded green
330waste is co-composted (Adhikari et al., 2009; Farrell and Jones, 2010; Reyes-Torres et al., 2018) to
331improve control over the process (humidity, temperature, and so on). The added value of
332vermicomposting compared to other techniques is that it is possible to replace the shredded green
333waste (bulking agent) with paper and cardboard which are abundant resources in the cities, thus
334avoiding supply problems (pressure on green waste resource in cities with other uses such as
335mulching). In addition, there is no need to turn the material over as in composting because earthworms
336naturally mix the matter, which avoids handling. However, unlike composting, vermicomposting does
337not allow for the direct recycling of waste such as meat, fish and processed products (waste from high-
338fat cooked foods or uneaten ready-made meals, for example). For this reason, studies have sought to
339optimize the vermicomposting process by adding a pre-composting stage (Frederickson et al. 1997;
340Kalamdhad et al. 2009; Varma and Kalamdhad 2016). In our review, pre-composting was often used
341(Table 1: 27%), although this pre-treatment requires a significant additional cost. In the recovery
342platform, thermophilic pre-composting allows a "safer" hygienization of this type of waste and also
343accelerates the process of stabilizing OM (Nair et al. 2006; Frederickson et al. 2007; Hanc and Pliva
3442013).

345

346Another potential limitation to the widespread use of vermicomposting is that it is more complex than
347composting and requires more skills to understand and manage the conditions necessary for a
348successful earthworm life cycle (Lohri et al. 2017). Indeed, one of the main challenges of the process
349is to maintain sufficient moisture for the development of the earthworms (Munroe 2007). For example,
350in platforms, it is necessary to use watering during periods of drought, which will be increasingly
351frequent and constraining in many parts of the world, especially in the context of global warming. In
352the case of OFMSW recovery, and more particularly food waste, it is possible to manage humidity
353with the continuous supply of this type of waste because it is mainly composed of water. Depending
354on the region, seasonality can also influence the process, which will slow down at temperatures below
35510°C or higher than 35°C (depending on the species of earthworm used) (Edwards et al. 2010). One of
356the most complicated factors to manage in the case of OFMSW recovery is the heterogeneity of the
357materials entering the process, which could potentially influence the quality of the final product.
358Finally, the low temperature of the process raises questions about the hygienization (especially at
359European standards which require heat at 70 degrees for 3 days to eliminate pathogens) and reduction
360of weeds in vermicompost.

361

3623.2. *Quality of vermicompost from OFMSW*

363

364 According to our review, vermicomposting increases the total contents of nitrogen (N), calcium (Ca),
365 phosphorus (P), potassium (K) and magnesium (Mg) and decreases organic carbon (OC) content and
366 thus the C/N ratio in relation to incoming products (Lim et al., 2015). The bibliography also shows
367 that the action of earthworms optimizes the retention of nutrients such as N (Caceres et al., 2018) by
368 10% to 20%, (according to the C:N value of the organic waste before recycling), compared to compost
369 (Nigussie et al., 2016). In addition, nutrients in vermicompost are highly available to plants compared
370 to compost (Adhikary, 2012; Samal et al., 2019), especially P and K (Hanc and Pliva, 2013). In fact,
371 earthworms help to release nutrients such as P partly due to the presence of enzyme activities in their
372 stomachs such as phosphatases (Ghosh et al., 1999).

373

374 3.2.1 Variability of vermicompost between studies

375

376 Based on the typology presented in Table 2, we estimated the quality of the different vermicompost
377 products as an organic amendment according to pH, C/N, OC, Ntot, P, K, Ca, Mg, Na, Cu, Fe, Mn,
378 Zn, Cd, Cr, Ni and Pb criteria (Annex Table 2). The results were very heterogeneous from one report
379 to another, especially regarding the metallic trace elements, which really depend on the quality of the
380 incoming waste more than on the process itself. As the standards concerning the characterization of
381 organic amendments vary from one country to another, we chose the French standard (NF U44-051
382 adapted from the European law of “Organic soil improvers — Designations, specifications and
383 marking” as the reference. This standard sets the threshold limits for metallic trace elements of As at
384 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
385 and Cr were always below the norm. Cadmium, Ni and Pb means exceeded the standard threshold
386 (annex table 2) because of only one study in which increases in the averages with three analyses above
387 50 for Cd, above 900 for Pb and above 200 mg kg⁻¹ for Ni were observed (Varma and Kalamdhad
388 2016). The mixtures concerned were generally OFMSW in which the OM had been roughly sorted,
389 which may be the cause of the high level of trace elements in this category. Indeed, due to bad waste
390 sorting, the OFMSW can contain other types of contaminant-rich waste (non-biological products e.g.,
391 plastics, glass). Overall, the products from the OFMSW appear to be in compliance with the standards
392 concerning trace elements, although further studies on this subject are needed to increase the data and
393 validate this trend.

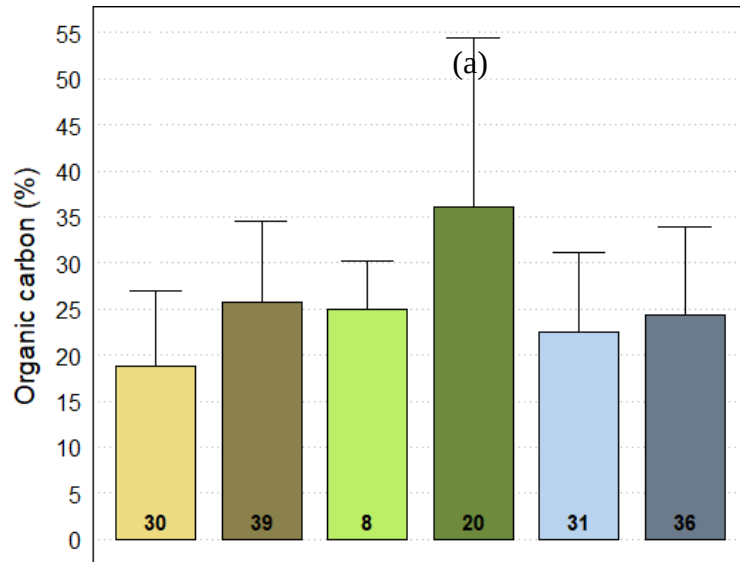
394

395 Concerning the agronomic parameters of organic amendments, the standard NF U44-051 sets
396 minimum thresholds of C/N at 8 and dry matter at 30%. For agronomic value (in % of gross), OM
397 should be at a minimum of 20%, i.e. 10% OC (OM / 2) and P, K and N must not exceed 3%. None of
398 the included studies specified the dry matter content of the final product but the C/N mean values were
399 within the correct range (Annex Table 2). The C/N ratio, which is a good indicator of nutrient intake

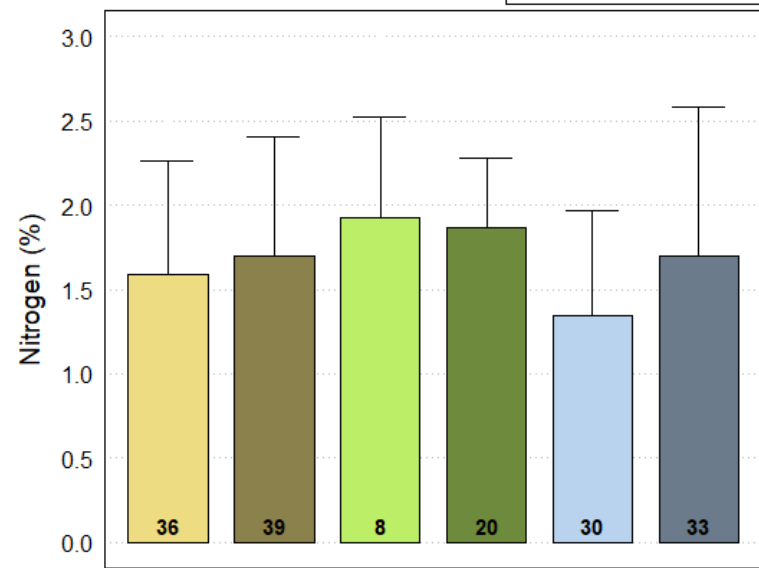
400(Diacono and Montemurro 2010), was highly variable depending on the type of waste used to make
401the vermicompost. Indeed, for C-rich waste such as paper and green waste the C/N is higher than for
402food waste (means of 17.21, 14.38 and 12.50, respectively). In a mixture of urban and agricultural
403wastes the C/N is higher, probably because of the large amount of C in this type of waste. We also
404noticed that the C/N of the various mixes was quite high with an average of 18.33 for the urban waste
405and 16.82 for the mixed urban and agricultural waste. This may be due to the heterogeneity of the
406substrate, which could complicate the process. Furthermore, the use of a bulking agent with food
407waste (paper) reduces the C/N to a mean of 10.43, a lower value than when only food was used. It
408would therefore be interesting to develop studies on the recovery of OFMSWs by mixing food waste
409and paper or waste from green spaces, which is more accessible in cities than agricultural waste such
410as manure.

411

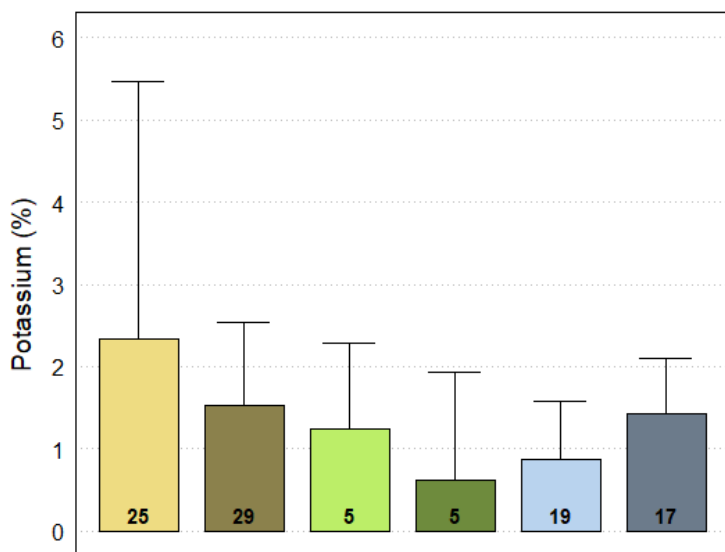
412Regarding other agronomic values (OC, N, P and K in Figure 2) it is not possible to know if the
413vermicomposts are within the NF U44-051 standard since the reported analyses were carried out on
414dry products and the moisture content was generally not specified. However, Figure 2 shows that
415vermicompost from food waste without mixing with agricultural resources is rich in N (1.59%) and P
416(1.18%), and especially in K (2.34%), but lowest in C (18.83%). In contrast, vermicomposts from
417green waste are rich in C (25%) and lower in P (0.73%) and K (1.25%). Overall the addition of
418agricultural waste increased the nutrient values in vermicompost probably due to the capacity of
419epigeic earthworms to readily degrade animal manure which in turn provided them with an optimum
420living environment (Munroe 2007; Edwards et al. 2010). In urban waste management it would be
421more interesting to combine food with green waste (or paper or both) as bulking agents because these
422resources are more available in an urban context, thus avoiding transportation of materials. In our
423review, only four studies analyzed vermicompost from food waste and green waste, and only 11 from
424food waste and paper, so we could not compute average values. The food/paper mixture increased OC
425to 28.53% and N to 2.58%, showing that a mixture of more N-rich (food) and more C-rich (paper)
426feedstock can optimize the recovery of these wastes if they are combined rather than treated
427individually. Again this may be due to the fact that appropriate mixtures create better living conditions
428for earthworms, which then optimizes vermicomposting processes.

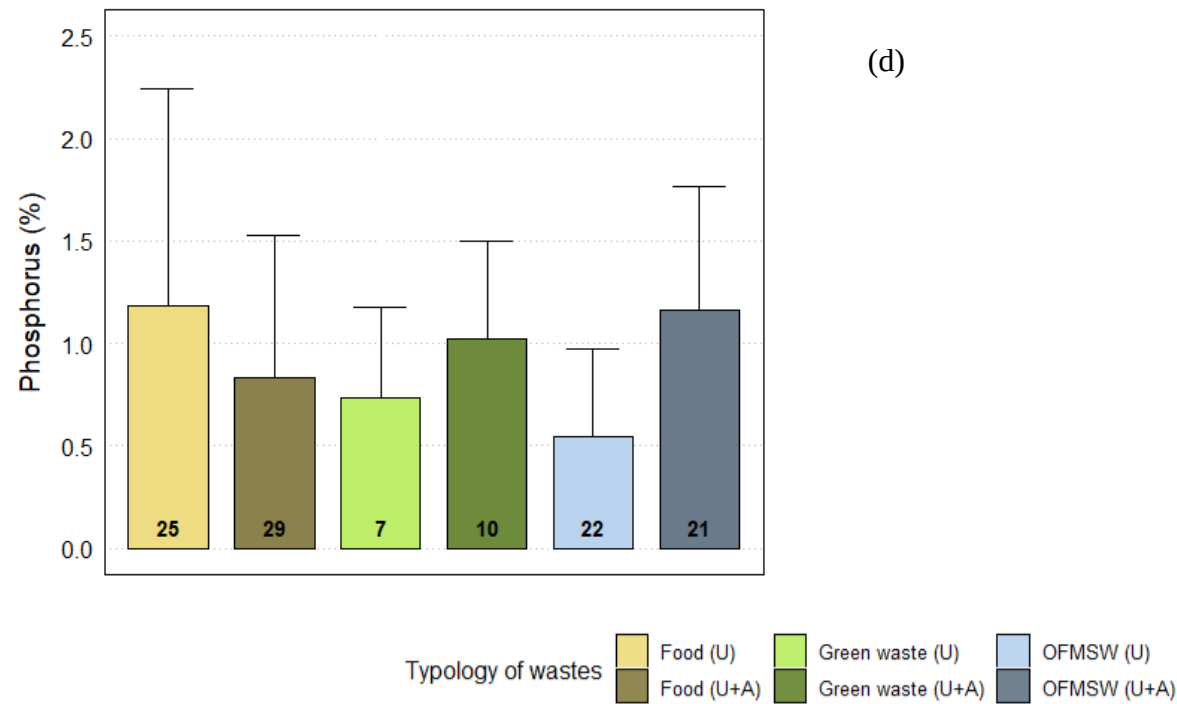


(b)



(c)





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

433

434 3.2.2 Comparison of the quality of vermicompost and compost from the same OFMSW

435

436 To better evaluate the quality of vermicompost from OFMSWs and disregard studies with variable
 437 inputs, we compared it to "classic" compost produced from exactly the same material. This issue was
 438 only addressed in 35 of the 184 articles. Table 3 shows the difference in agronomic chemical
 439 parameters between vermicompost and compost from the same wastes with the help of paired tests.
 440 There were several significant differences between the quality of compost and vermicompost from the
 441 urban waste especially for pH, which was slightly more neutral for vermicompost (7.59) than for
 442 compost (7.86), and for the C/N, which was lower for vermicompost (15.05) than compost (16.93).
 443 The vermicompost also had a higher percentage of total N and P than the compost (1.54% versus
 444 1.31% for N and 0.56% versus 0.53% for P). Organic OC and K levels were not significantly different.
 445 When compost and vermicompost of urban waste added to agricultural waste were compared, the C/N
 446 and OC of vermicompost were also significantly lower than compost (16.1 vs. 24.45 and 25.26% vs.
 447 33.22%) while total N was not significantly different in spite of a strong difference in averages (2.33%
 448 for vermicompost versus 1.49% for compost). In both types of waste (urban alone or with agricultural
 449 waste) the C/N was significantly lower for the vermicompost and the OC content was also lower

450(significantly for the mixture with agricultural waste), and the total N rates were higher (significantly
 451for the urban waste alone). According to the review, vermicomposting emits more CO₂ than
 452composting because of its higher biological activity but lower CH₄, which reduces carbon losses in
 453total C footprints and allows better N retention (less N₂O emission) (Nigussie et al. 2016, 2017). The
 454significant difference in OC from urban and agricultural wastes is certainly due to the fact that the
 455earthworms can easily degrade animal manure. According to these results, vermicompost should have
 456similar fertilizing properties to compost, although its agronomic parameters may even be slightly more
 457suitable for crop production (lower C/N, higher nutrient contents). Moreover, all these studies were
 458mostly focused on the valorization of a specific type of waste such as 100% green waste or 100% food
 459waste or a mix of OFMSW with no pre-selection of waste and only one analysis took into account a
 460mixture of food and paper wastes which, as we have seen in the previous section, would be more
 461appropriate for vermicomposting. According to Yadav and Garg (2011), it is essential to rigorously
 462select raw materials and mixtures to optimize the vermicomposting process and obtain a better quality
 463product. Also, classical chemical analyses do not take into account many other factors such as plant
 464growth regulators (PGRs), plant growth hormones (PGHs), nutrient availability, OM quality or
 465microbiological activity. All are essential factors for plants growth (Soobhany et al. 2017; Barthod et
 466al. 2018; Dominguez et al. 2019).

467

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)
	N _{tot} (%)	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)
	N _{tot} (%)	1.49 ± 0.43 ^a	2.33 ± 1.79 ^a	Student (n = 7)

468

469**Table 3:** Matched comparison of vermicomposts and composts from the same waste origin.
 470Superscript letters in bold indicate statistical differences with a p-value less than 0.05.

471

4723.3 Benefits and limitations of using vermicompost from OFMSW in agriculture soils

473

4743.3.1 Effects on crop yield

475

476In our study, we found 18 papers that assessed the impact of vermicompost from OFMSW on crop
 477yields under field conditions. All these papers found that vermicompost had a positive effect on
 478biomass and crop yield. Arancon et al., (2005, 2003a) showed improved yields for pepper, tomato and

479strawberry when vermicompost was supplemented with inorganic nitrogen fertilizers compared to
480inorganic fertilizers alone (same N dose in the different treatments). The same effect was shown for
481rice compared to the inputs of non-vermicomposted waste and a control with no inputs (Mishra et al.
4822005), and compared to the contribution of NPK alone or to NPK with farmyard manure (Sahariah et
483al. 2020). Yields also increased for ginger compared to a control (no input) and vermicompost from
484cow manure (the best yield in this study was the treatment with vermicompost from paper sludge) (Eo
485and Park 2019). Olive grove yield increased 35.5% and the nutrients in olive fruit were significantly
486different compared to the control and better than compost from MSW and sheep manure (Tejada and
487Benitez 2020). Yields also increased for bean compared to pressmud, flower waste and farmyard
488manure (Sajitha et al. 2007) and for pea compared to cattle manure (Abdrabbo et al. 2014). Pattnaik
489and Reddy, (2010, 2011) showed that vermicompost has significant results on the growth of fenugreek
490(*Trigonella foenum-graecum* L.) and tomato (*Lycopersicon esculentum* Mill.) compared to compost
491from the same OFMSW. In addition, Arancon et al. (2005, 2003a) showed that vermicompost
492(supplemented with inorganic fertilizers to equalize the initial N levels available to plants) has a
493greater impact than inorganic fertilizers (NPK) alone on marketable yield and dry shoot weight of
494pepper. The addition of NPK nutrients to vermicompost to achieve nitrogen equivalence shows that
495vermicompost has other factors that promote plant growth. According to Arancon et al. (2005, 2003a),
496it is not only the available elements such as N and P in vermicompost that enable plant growth, but
497also/rather the high biological activity and increased production of PGRs, such as humic acids, and
498PGHs.

499

500In contrast, Roberts et al., (2007) showed that vermicompost from green waste and sewage sludge,
501while increasing tomato plant germination and fruit quality, did not increase total fruit yield,
502marketable fruit yield, fruit number, fruit weight, or vitamin C concentration compared to commercial
503peat-based compost. Eo and Park (2019) found that at high doses (40 t ha⁻¹), vermicompost from
504OFMSW increased root disease in ginger (*Panax ginseng*). However, with moderate use (10 t ha⁻¹
505here) it had a positive impact on root growth. This shows that excessive inputs can lead to nutrient
506surpluses that can harm the crop and/or the environment. For example, in their experiment a 40 t ha⁻¹
507input of vermicompost is equivalent to 520 kg of N per hectare (vermicompost = 1.3% N), which is
508harmful to the crop and can also lead to pollution due to nitrogen leaching. It is therefore necessary to
509properly characterize the products before use in the field.

510

511Mishra et al. (2005) showed that the use of vermicompost increases the chlorophyll concentration in
512rice leaves. This was further corroborated by Tejada and Benitez (2020) who found an increase in
513micro and macro nutrients in olive leaves. Arancon et al. (2005, 2003a) showed that the high fulvic
514acid and protein content in vermicompost are easily degradable by soil microorganisms and
515assimilated by plants. Yardim et al. (2006) have demonstrated that a decrease in crop pests was related

516to a high dose of nitrogen in the foliage and a phenolytic compound that is stimulated by the addition
517of vermicompost.

518

519Vermicompost from OFMSW is a highly variable product (see section 3.3) and it is therefore difficult
520to generalize about its impact in the field from the few published studies. Moreover, in most of these
521studies there was no control in the strict sense of the word because vermicompost was compared to
522inorganic fertilizers (NPK) or cattle manure. It is possible to compare different products with each
523other, but without a proper control it is not possible to measure the effect compared to a treatment
524without material input. However, the findings from the application of vermicompost from OFMSW
525are consistent with the positive reports for the application of vermicompost from manure in the field
526(Tringovska and Dintcheva 2012; Guo et al. 2015; Velecela et al. 2019; Aslam et al. 2019; Tejada and
527Benitez 2020).

528

5293.3.2 *Effects in soil (bio-physico-chemical)*

530

531It is widely recognized in the literature that OM inputs of any kind, such as biochar (Atkinson et al.
5322010; Yadav et al. 2019), compost or manure (Obriot et al. 2016; Kelley et al. 2020), have positive
533effects on soil physico-chemical qualities (Diacono and Montemurro 2010; Ghosh et al. 2010; Peltre et
534al. 2017). We only found four papers that addressed the impact of vermicompost from OFMSW on the
535soil and its bio-physical-chemical parameters in the field. All these studies showed that vermicompost
536input increased soil pH (Eo and Park 2019) and carbon storage compared to the contribution of NPK
537alone or to NPK with farmyard manure (Sahariah et al. 2020). It also increased levels of the soil
538nutrients N, P, K when supplemented with inorganic fertilizers to balance fertilizer recommendations
539compared to inorganic fertilizers alone (Arancon et al., 2006b). Only Sahariah et al. (2020) studied the
540evolution of soil physical parameters and showed that vermicompost increased the soil water retention
541capacity and reduced bulk density compared to the contribution of NPK alone or to NPK with
542farmyard manure. At the same time, these authors studied soil microbiology following the application
543of vermicompost. They all observed that vermicompost increased soil microbial biomass and enzyme
544activities (dehydrogenase, urease, β -glucosidase, phosphatase and arylsulfatase) compared to MSW,
545sheep manure and control, and the enzyme-humus complex compared to the control (Tejada and
546Benitez 2020), as well as soil respiration measured by dehydrogenase activity (Arancon et al., 2006b).
547Arancon et al. (2006b) showed that increases in dehydrogenase activity and microbial biomass were
548positively correlated with increases in $\text{NH}_4\text{-N}$, $\text{NO}_3\text{-N}$ and orthophosphates. The same authors
549demonstrated that these activities promote nutrient cycling rates, the production of plant growth
550regulating materials and the accumulation of plant resistance or tolerance to pathogen attack.
551According to these authors, plant growth is stimulated not only by nutrients in the vermicompost, but
552also due to the microbiological activity and diversity of the product. This leads to improved rates of

553nutrient cycling in the soil and protection of plants against diseases through competition and
554antagonism against other pathogenic organisms. Arancon et al. (2003b) also showed that
555vermicompost allows parasite regulation at the level of soil microfauna by decreasing parasitic
556nematodes and increasing the populations of fungivorous and bacterivorous nematodes compared to
557inorganic fertilizer or a control without fertilizer. For meso and macrofauna, Gunadi et al. (2002)
558showed an increase in saprophagous arthropods (Collembola as *Isotomidae*, *Onychiuridae*,
559Sminthuridae, Acari as *Cryptostigmata* and *Symphyla*) following the addition of vermicompost
560(compared to inorganic fertilizer or compost) and also hypothesized that this could be due to the high
561microbiological activity of the product.

562

5634 Outlook and future studies

564

5654.1 Studies on the process of vermicomposting using OFMSW

566

567We found that there is a lack of research on the applications of vermicompost from OFMSW in
568agriculture. Indeed the majority of research focused on the process of vermicomposting this type of
569waste. This is justified by the great diversity of materials included in the OFMSW, which are present
570in variable proportions depending on the country and its level of development (Troschinetz and
571Mihelcic 2009). Thus, the variability of the incoming OM can lead to an additional complication in
572running waste recovery programs. However, Hanc et al. (2011) showed that in the same city, the
573composition of bio-waste (type and chemistry) over four seasons varied little in urban areas (mainly
574fruit and vegetables) but was more influenced by home garden management. Therefore, with a prior
575analysis of OFMSW, it may be possible to predict the quality of vermicomposts obtained either by
576modeling (Hosseinzadeh et al. 2020) or case-by-case studies with different bulking agents depending
577on available resources (e.g. cow manure in India).

578

579Despite a lot of research on the processes, there are still avenues for improvement to optimize the
580valorization of OFMSW by vermicomposting and improve the understanding of the fundamental
581processes related to this technique. For example, some studies looked at mixtures of earthworm
582species with different functions (Suthar and Singh 2008) or searched for native and readily available
583species (Suthar 2009) rather than *E. fetida*. On larger scales (semi-industrial platforms for example),
584the parameters necessary for the process to run smoothly (e.g. temperature, humidity, pH) are much
585harder to control, which can lead to changes in the process and increase the variability of the derived
586product.

587

5884.2 Use of vermicompost from OFMSW in the field

589

590Although we have gathered some information on the impact of vermicompost in the field, some points
591have not yet been studied. For example, in their meta-analysis, Blouin et al. (2019) showed that the
592species most receptive to vermicompost are Cucurbitaceae, Asteraceae, Fabaceae, and Poaceae. In
593addition, in our review, we found that the majority of studies using vermicompost from OFMSWs
594were focused on ornamental plants or vegetable crops and we could not find studies about cereals such
595as wheat, barley and maize.

596

597The low temperature of the process could have benefits that have been little studied such as a positive
598effect on soil biodiversity. Although most studies agree that vermicomposting increases the taxonomic
599and functional diversity of bacterial communities (Dominguez et al. 2019) as well as the functioning
600of a microdecomposer food web (Aira et al. 2008), only a few studies evaluated the impact of the
601process on meso and macrofauna abundance and diversity. However, Monroy et al., (2011) showed an
602increase in the total number of arthropods in the presence of *E. fetida* (especially springtails and
603mesostigmatid mites), suggesting that the development of large populations of soil arthropods is a
604characteristic of the initial stages of the earthworm mediated decomposition process. Of the seven
605groups of arthropods monitored (springtails; mites: astigmatids, prostigmatids, mesostigmatids and
606oribatids; psocids and spiders), only the psocids were negatively affected by the presence of *E. fetida*.
607Sampedro and Domínguez (2008) also used ^{13}C and ^{15}N to show that earthworms interact intensively
608with other detritivores such as bacteria, fungi and other soil fauna.. This work, which aimed to classify
609relative trophic positions, using pig and cow manure separately in two different systems, showed that
610the microdecomposer community was different depending on the stage of the earthworm life cycle
611(adults, hatchlings and cocoons) and resource quality. Thus, in view of its biological quality, studies
612on the impact of vermicompost, after field application, on soil macrofauna such as earthworm
613populations and mesofauna such as springtails or mites are a promising route, especially because these
614are excellent bioindicators of soil quality (Gulvik 2007; Peres et al. 2011).

615

6164.3 Comparison with other techniques and integration into OFMSW management systems

617

618Comparative studies between the different techniques for the valorization of OFMSW are missing. For
619example, Lohri et al., (2017) revealed a disparity in publications on the technology of organic waste
620recovery and a real lack of field studies and suggested that more transdisciplinary research is needed
621using real case studies. The same authors concluded that as well as studying the fundamental
622processes, more focus should be placed on systems in application. In this way, various valorization
623techniques could be compared to validate the fundamental theory on the ground (rather than in the
624laboratory) and develop the techniques for recycling biowaste while upscaling. Moreover, in order to
625choose appropriate recycling techniques, Zhang et al., (2010) showed that it is necessary to separate
626the waste streams first to optimize their recovery process. For example, in developing countries, little

627investment is made in waste separation, which can lead to contamination with pathogens and/or
628pollutants limiting or excluding the choice in OFMSW recycling techniques. On the other hand, in rich
629countries, the flows are relatively well separated which allows a more diversified selection of
630recycling systems, including vermicomposting. However, this low-tech technique is developing
631particularly well in Asia (especially in India), while few European researchers are interested in this
632process. Indeed, a small number of reports compared the life cycle of other OFMSW recovery
633techniques such as composting or methanisation with vermicomposting (Komakech et al. 2015;
634Nigussie et al. 2016) but few studies evaluated the products of these techniques at the agronomic level
635in the field. A comparison would make it possible to assess the advantages and disadvantages of each
636method and to guide regions towards an adapted management of their OFMSW according to their
637needs. Bortolotti et al. (2018) showed that decentralization of organic waste management via several
638possible scenarios could be a promising alternative to centralized industrial facilities. This type of
639management would be perfectly adapted to vermicomposting, which is particularly suitable in urban
640areas. Indeed, in a circular economy approach, some of the OFMSW could be recovered by collective
641vermicomposting in the city and some on peri-urban platforms where different techniques would allow
642the recovery of all the OM (for example pre-composting or methanisation of waste that is difficult to
643manage in vermicomposting). Thus, the vermicompost produced in cities could be used in urban
644agriculture and/or collected for use in peri-urban agriculture (reduced transport compared to the
645collection of raw OFMSW) and the products from the peri-urban platforms would be reserved for
646local agriculture.

647

6484.4. *Socio-economic issues*

649

650We found little information on the economic and social impact of the practice of vermicomposting and
651the use of vermicompost in agriculture. According to Lim et al. (2016), economic evaluations of
652vermicomposting are scarce and there are differing opinions: some activities are profitable and others
653are not, depending on the type of process used, the market value of the organic fertilizer and the
654production volume. However, vermicomposting is a feasible organic waste management strategy
655because, like composting, it is a process with lower operating costs than other waste management
656options (Ruggieri et al. 2009). As with composting systems, the economic potential of a
657vermicomposting system depends on the initial capital costs (e.g., high-tech indoor or low-tech
658outdoor windrow system) as well as the revenues from the vermicompost produced. Prices vary
659widely around the world, with a selling price of \$80 per ton of vermicompost in Uganda (Lalander et
660al. 2015) compared to \$200 to \$1000 per ton in the United States (Edwards et al. 2010) and \$200 to
661\$2500 in France depending on the type of packaging (wholesale for professionals or retail for
662individuals). The commercialization of the earthworms produced during the process can be an
663additional economic gain because they are rich in protein (65% of the dry matter) and can be used as

664meal for animal feed (Adhikary 2012; Lalander et al. 2015) or even for human consumption (Tedesco
665et al. 2019; Conti et al. 2019). Earthworms can typically sell for \$5 to \$35 per pound in the United
666States (Edwards et al. 2010). At the same time, new technologies such as worm sorters have been
667developed in recent years, which facilitate the extraction of worms from vermicompost for their
668commercialization (Lin et al. 2021). In the context of OFMSW valorization, one of the potential
669sources of income for vermicomposting activities would be directly from the collection and/or
670valorization of organic wastes from businesses and communities because in certain areas of the world
671and in particular in Europe (European Union 2018) mandates are in place for waste recovery by the end
672of 2023. To our knowledge, no study has integrated the benefits of collection/costs of recovery of
673OFMSW with a vermicomposting system. At the same time, there is a lack of policies favorable to the
674implementation of sustainable waste management practices, minimal legislation concerning waste
675recovery, and insufficient international influence from developed countries, to support the
676development of sustainable waste management in developing countries that do not have the means to
677implement the same waste management policies (Marshall and Farahbakhsh 2013). This is an
678additional constraint for the development of processes such as vermicomposting and a curb on the
679development of this technique at larger scales.

680

6815 Conclusions

682

683This review examined the value of the vermicomposting process in its entire loop/cycle, from the
684recovery of OFMSW to the application of vermicompost in the field. According to the literature
685studied, vermicomposting is perfectly adapted to the valorization of OFMSW. Indeed, earthworms can
686degrade these materials and produce a vermicompost that is beneficial for agriculture. We have shown
687that the vermicompost is an amendment with interesting fertilizing properties like compost, although
688its agronomic parameters seem to be slightly more suitable for crop production. Indeed, vermicompost
689had a greater effect on soil, plant growth and yield than compost, probably due to other parameters
690such as microbiology, mineralization potential or PGRs and PGHs. With evolving environmental
691issues and increasingly strict regulatory constraints, vermicomposting could be a suitable response to
692waste management in the context of the circular economy. However, our study also revealed a lack of
693research on vermicomposting, especially regarding field studies. These studies would provide a better
694understanding of the vermicomposting process and its applications, which in turn could accelerate
695progress in its uptake as an interesting approach for reconciling waste recovery and sustainable
696agricultural development. Vermicomposting of OFMSW is a promising solution for linking waste
697management and sustainable agriculture, but for this to happen, in-depth research on the quality of the
698vermicompost produced and its impact on agricultural soils in the long term must be developed. These
699studies could lead to a standardization, distinct from that for classical compost, so that the use of this
700technique and product becomes widespread.

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702

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707

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710

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719

720 Availability of data and material

721 All articles analyzed were previously published and are available online (on Web of Science). See also
722 Supplementary Table 1.

723

724 Code availability

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

726

727 Authors' contributions

728 Conceptualization, VD, JP, YC; Methodology, VD, JP, YC; Investigation, VD; Formal analysis, VD;
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