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REVIEW ARTICLE

Optimizing the vermicomposting of organic wastes amended with inorganic materials for production of nutrient-rich organic fertilizers: a review

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Abstract

Vermicomposting is a bio-oxidative process that involves the action of mainly epigeic earthworm species and different micro-organisms to accelerate the biodegradation and stabilization of organic materials. There has been a growing realization that the process of vermicomposting can be used to greatly improve the fertilizer value of different organic materials, thus, creating an opportunity for their enhanced use as organic fertilizers in agriculture. The link between earthworms and micro-organisms creates a window of opportunity to optimize the vermi-degradation process for effective waste biodegradation, stabilization, and nutrient mineralization. In this review, we look at up-to-date research work that has been done on vermicomposting with the intention of highlighting research gaps on how further research can optimize vermi-degradation. Though several researchers have studied the vermicomposting process, critical parameters that drive this earthworm–microbe-driven process which are C/N and C/P ratios; substrate biodegradation fraction, earthworm species, and stocking density have yet to be adequately optimized. This review highlights that optimizing the vermicomposting process of composts amended with nutrient-rich inorganic materials such as fly ash and rock phosphate and inoculated with microbial inoculants can enable the development of commercially acceptable organic fertilizers, thus, improving their utilization in agriculture.

Keywords Biodegradation fraction · Microbial inoculants · Vermi-degradation · Nutrient enrichment · Rock phosphate · Fly ash

Introduction

The rapidly growing world population has increased food demand leading to intensification of agricultural and industrial activities to meet this demand. This intensification of agriculture and industrial activities has resulted in generation of huge quantities of organic and inorganic waste, with most of these wastes being inappropriately disposed into landfills and other places. These inappropriately and indiscriminately disposed waste products carry health (Gomez-Brandon et al. 2013) and environmental hazards (Usmani et al. 2017; Das et al. 2016a, b); risking deposition of toxic trace metals, salts, and pathogens into the soil (Bhattacharya and Kim 2016; Lazcano et al. 2008). These challenges associated with waste production have made researchers to look into environmentally friendly technologies that can convert these wastes into potential nutrient sources in agriculture such as vermicomposting (Das et al. 2016a, b; Dominguez 2011). The end products of technologies such as vermicomposting are nutrient-rich and environmentally friendly with many potential uses in agriculture as soil conditioners (Usmani et al. 2017; Mupambwa et al. 2017; Das et al. 2016a, b; Gomez-Brandon and Dominguez 2014). Coupled to this has been the growing realization of the advantages of organic fertilizers to soil health such as improved soil carbon sequestration, balanced pH, increased cation–anion retention, and micro-nutrient supply, compared to inorganic fertilizers (Mupambwa et al. 2017, Singh et al. 2011).

Due to the potential of vermicomposting in improving the nutrient fertilizer value of waste materials, studies have been undertaken focusing on understanding earthworm and nutrient

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dynamics during vermicomposting (Atiyeh et al. 2000; Aira et al. 2006; Lazcano et al. 2008; Gupta and Garg 2009; Gomez-Brandon et al. 2013; Mupambwa and Mnkeni 2015). As indicated by Gomez-Brandon and Dominguez (2014), the vermicomposting process involves synergy between earthworms and microbes and requires a balanced supply of mainly carbon, nitrogen, and phosphorus, which are the main elements required in protein formation, energy generation, and reproduction in every living organism (Bernal et al. 2009; Ndegwa and Thompson 2000). Due to the link between C, N, and P to the vermicomposting process, it is likely that processes like nutrient mineralization, bio-stabilization, and earthworm development will be compromised if these are not balanced during the vermicomposting process (Chang and Chen 2010). Several researchers have used different organic materials for vermicomposting such as cow dung (Lazcano et al. 2008), pig manure (Aira et al. 2006), chicken manure (Ravindran and Mnkeni 2016), household wastes (Frederickson et al. 2007), sewage sludge (Maboeta and Van Rensburg 2003), and waste paper (Gupta and Garg 2009). Though these studies are numerous, very few of these have tried to initially optimize these different organic materials before vermicomposting to allow for effective vermi-degradation. Similarly, the stocking density and type of earthworm species during vermicomposting are also very important as they affect the growth and reproduction of earthworms thus, directly influencing the biochemical processes taking place within the vermicompost (Mupambwa and Mnkeni 2016). Though it is widely accepted that stocking density and earthworm species directly influence the vermi-degradation process, several researchers have reported vermicomposting research under different earthworm stocking densities and using different species (Mupambwa and Mnkeni 2016; Dominguez and Edwards 2011b; Ndegwa et al. 2000).

The growing realization of the negative impacts of inorganic fertilizers to soil health and their economic impact on agriculture has stimulated interest in the use of soil health-compatible organic nutrient sources like vermicomposts (Arancon et al. 2004, 2008). However, the low macronutrient concentrations relative to inorganic fertilizers have been among the major limitations to the sustained use of organic fertilizers like vermicomposts in agriculture. Among all macro-nutrients, phosphorus (P) is the least mobile and least available, with its soil bioavailability being a major bottleneck in crop production (Gichangi et al. 2009). In organic-based soil fertility management, improving the availability of soil phosphorus has been reported to be critical (Edwards et al. 2010); hence, it receives considerable attention in this review.

The economic and environmental challenges associated with the agronomic use of inorganic P fertilizers such as eutrophication and diminishing P reserves have resulted in renewed interest in sustainable alternative sources of P, such as phospho-composts (Alamgir et al. 2012). Recently, inclusion of inorganic materials with very high total concentrations of P has gained momentum as an opportunity to improve P nutrition of organic fertilizers (Mupambwa et al. 2015; Busato et al. 2012; Unuofin and Mnkeni 2014). It is believed that the action of earthworms and microbes during vermicomposting can be used to enhance mineralization of the P bound in the inorganic materials thus, generating a phosphorus-rich vermicompost. This review seeks to summarize up-to-date research information on the vermicomposting process, nutrient enrichment of organic vermicomposts, and the opportunities available to enhance the vermi-degradation process. The following questions will guide this review:

1. What are the most optimum conditions for the vermicomposting process to yield the most stabilized and nutrient-rich fertilizer over the shortest period?
2. What opportunities are available for improving the vermicomposting process in terms of nutrient composition and biodegradation?
3. What is the practical potential of vermicomposts as soil amendments in agriculture?

The vermicomposting process

The term *vermi* in vermicomposting is derived from the Latin word "vermis" which means a worm. However, vermicomposting refers to a composting process that is done by epigeic, anecic or endogeic earthworm species which have a natural ability to colonize and degrade organic wastes (Bhat et al. 2017; Das et al. 2016a, b). According to Gomez-Brandon and Dominguez (2014), vermicomposting has thus been defined as "bio-oxidative process in which detrivorous earthworms interact with microorganisms and other fauna within the decomposer community, thus accelerating the stabilization of organic matter (OM) and greatly modifying its physical and biochemical properties." Though there are more than 4000 known species of earthworms classified according to the three groups, only a few belonging to the epigeic class have been shown to be effective for the vermicomposting process mainly due to their high feed consumption rates, high reproduction rates, and high tolerance to a wide range of environmental conditions (Bhat et al. 2017; Dominguez and Edwards 2011a, b). Among the widely used for vermicomposting are earthworm species which belong to the epigeic earthworm class include *Eisenia fetida*, *E. andrei*, *Eudrilus eugeniae*, and *Perionyx excavates* (Mupambwa et al. 2016; Atiyeh et al. 2000; Ravindran et al. 2015; Khwairakpam and Bhargava 2009a). Also, though having a low vermicomposting potential, endogeic species *Metaphire posthuma* and *Drawida barwelli* (Das et al. 2016a, b; Bhat et al. 2017) together with anecic species *Lampito mauritii*, *Apporrectodea trapezoids*, and *L. terrestris* (Bhat et al. 2017; Anbalagan and Manivannan 2012) have also been used for vermicomposting.

Earthworms have been shown to enhance the composting process directly by mechanically breaking down larger organic wastes using their gizzards thus, increasing the substrate surface area and consequently altering microbial activity, in processes that have been collectively called gut-associated processes (Swati and Hait 2017; Gomez-Brandon and Dominguez 2014). Therefore, apart from the mechanical action of the earthworms, the micro-organisms within the earthworm gut and the compost are then responsible for producing various bio-compounds like enzymes and organic acids which are responsible for accelerating the biodegradation and nutrient mineralization within vermicomposts (Dominguez et al. 2010; Aira et al. 2007), as schematically shown in Fig. 1. According to Dominguez et al. (2010), micro-organisms are the most abundant and diverse members of the vermi-degradation food web, with the earthworms being secondary higher level consumers existing together with micro-organisms which feed and disperse the microbes. The crucial link between earthworms and microbes during the vermicomposting process has driven several researchers into trying to deliberately modify the microbial composition of vermicomposts by inoculating vermicomposts with specialized microbial cocktails such as effective micro-organism (EM), phosphate-solubilizing microbes (PSM), and N_2-fixing bacteria (Mupambwa et al. 2016; Busato et al. 2012; Kumar and Singh 2001). Such microbial cocktails are believed to play a crucial role in cast-associated processes (CAPs) which take place during aging of the vermicompost, following transportation of the organic materials through the earthworms' gut.

During the vermicomposting process and mainly in the CAPs, low molecular weight organic acids which include oxalic, formic, citric, and acetic acids are produced (Busato et al. 2012). These organic acids have been observed to play a crucial role in nutrient mineralization during vermicomposting, but have however received limited research attention (Bolan et al. 1994; Kumari et al. 2008). Though these organic acids are not produced directly by the earthworms, the earthworm–microbe-driven process of organic decomposition during vermicomposting produces these organic acids which are crucial in nutrient mineralization particularly in releasing inorganically bound nutrients (Busato et al. 2012). These organic acids have been reported to cause this mineralization via three processes which include competition for adsorption sites, dissolution of adsorbents, and changes in the surface charges of adsorbents (Bolan et al. 1994). So, nutrient release during vermicomposting can be viewed from both a biological and chemical perspective. However, much of the research has focused on the biological aspects of vermicomposting on nutrient mineralization, with limited attention having been given to how changes in other chemical properties like organic acids influences nutrient mineralization.

Critical parameters that drive optimal vermi-degradation

Carbon, nitrogen, and phosphorus

Due to the vermicomposting process being directly driven by living organisms, it cannot take place in the absence of organic materials which act as the primary energy sources for the organisms. Several researchers have reported vermicomposting results based on the use of different organic materials which include cow dung and pig manure (Aira and Dominguez 2009), rabbit manure (Gomez-Brandon et al. 2013), fish offal (Laos et al. 2002), sewage sludge (Khwairakpam and Bhargava 2009b), tannery waste (Ravindran et al. 2013), poultry manure (Ravindran and Mnkeni 2016), rice straw, water hyacinth and saw dust (Das et al. 2016a, 2016b), and food waste (Chang and Chen 2010). In all these studies, different organic sources were used during the vermicomposting process; however, very few researchers took into consideration the critical chemical parameters required for effective vermicomposting. The factors affecting the vermicomposting process can be divided into chemical and physical properties, with C, N, and P playing a critical role on composting optimization (Bernal et al. 2009; Brown et al. 1998; Enriquez et al. 1994). The vermicomposting process as previously defined is driven by micro-organisms, and these need more carbon than nitrogen as they use nitrogen for building cell materials only but need carbon as a source of energy and for cell development. However, if there is too much carbon relative to nitrogen available during vermicomposting, decomposition is slowed down as there will be less N, which is required for protein synthesis by the microbes, resulting in gradual death of the micro-organisms (Tuomela et al. 2000). For proper nutrition of both earthworms and micro-organisms, it is of paramount importance that carbon and nitrogen be present at the appropriate ratio (Ndegwa and Thompson 2000).

Though it is widely agreed that the C/N ratio directly affects vermicomposting, very few researchers have attempted to balance the C/N ratio during the vermicomposting process, with others not even reporting the C/N ratio of the materials used (Mupambwa and Mnkeni 2015). Using cow manure, Lazcano et al. (2008) used a C/N ratio of 17, Aira et al. (2008) used pig manure with a C/N of 18.95, Khwairakpam and Bhargava (2009) used sugar cane waste (filter mud) with a C/N ratio of 24, Gupta and Garg (2009) used paper waste and cow dung with an initial C/N ratio ranging from 60 to 120, to mention a few. However, among other researchers, Ndegwa and Thompson (2000) and Mupondi (2010) using cow dung

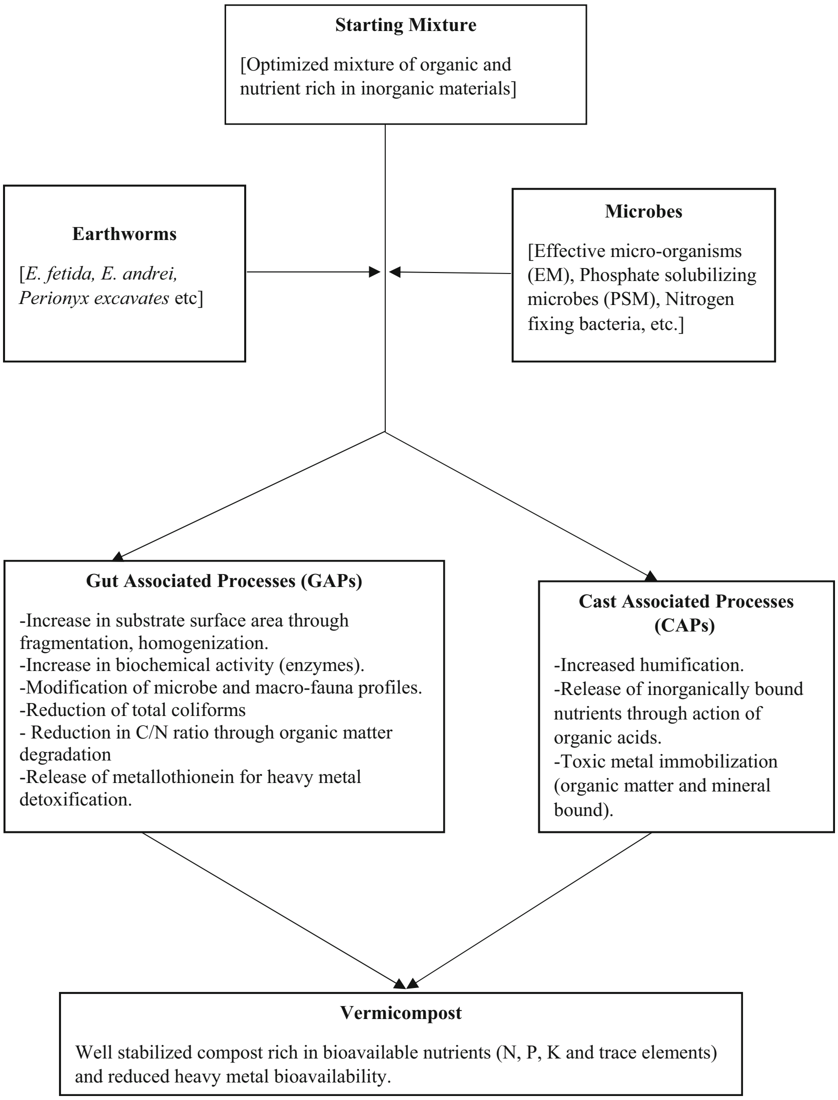

Fig. 1 Schematic representation of earthworm and microbe roles during vermicomposting of organic materials enriched with inorganic materials

and Nayak et al. (2013) using sewage sludge established that for an effective vermicomposting, a C/N ratio of between 25 and 30 was most appropriate, supporting the general idea that detrivorous organisms require 30 parts C per unit of N (Bernal et al. 2009). As illustrated in Fig. 2, an initially high C/N ratio above 30 in most organic materials will result in high final C/N ratio above 20, indicating a vermicompost that has not yet matured, relative to those whose starting C/N ratio is around 30. Though most of the research on vermicomposting reported positive results even without optimization of the chemical parameters like C/N ratio, it is possible that better results could be obtained if the C/N ratios of the materials were optimized to achieve maximum earthworm–microbe activities, which are the drivers of the vermi-chemistry and biology.

On another note, the influence of quality of materials used as carbon (organic) sources during vermicomposting could also play a critical role in influencing the efficiency of vermi-degradation and ultimately nutrient mineralization. Chandler et al. (1980) as cited by Komilis and Ham (2003) investigated the influence of complex lignocellulosic carbon substrates like lignin on the biodegradation of organic materials under aerobic environments. Using various organic substrates including animal manure, newsprint, straw, and leaves, a mathematical correction for biodegradability of an organic substrate based on the overall lignin content has been developed (Richard 1996; Komilis and Ham 2003) as shown in Eq. 1 below:

$$\text{Biodegradation fraction} = 0.83-\left(\text{lignin}_{\%\text{VS}}\right) \qquad (1)$$

where $\text{lignin}_{\%\text{VS}}$ is the initial lignin content as a percentage of volatile solids.

It is, therefore, possible that organic materials can have the same C/N ratio as measured by the dry combustion method but have different biodegradation fractions. According to Richard (1996), differences in the biodegradable fractions of different materials could affect their rate of vermi-degradation. In a recent study, Ravindran and Mnkeni (2016), using poultry

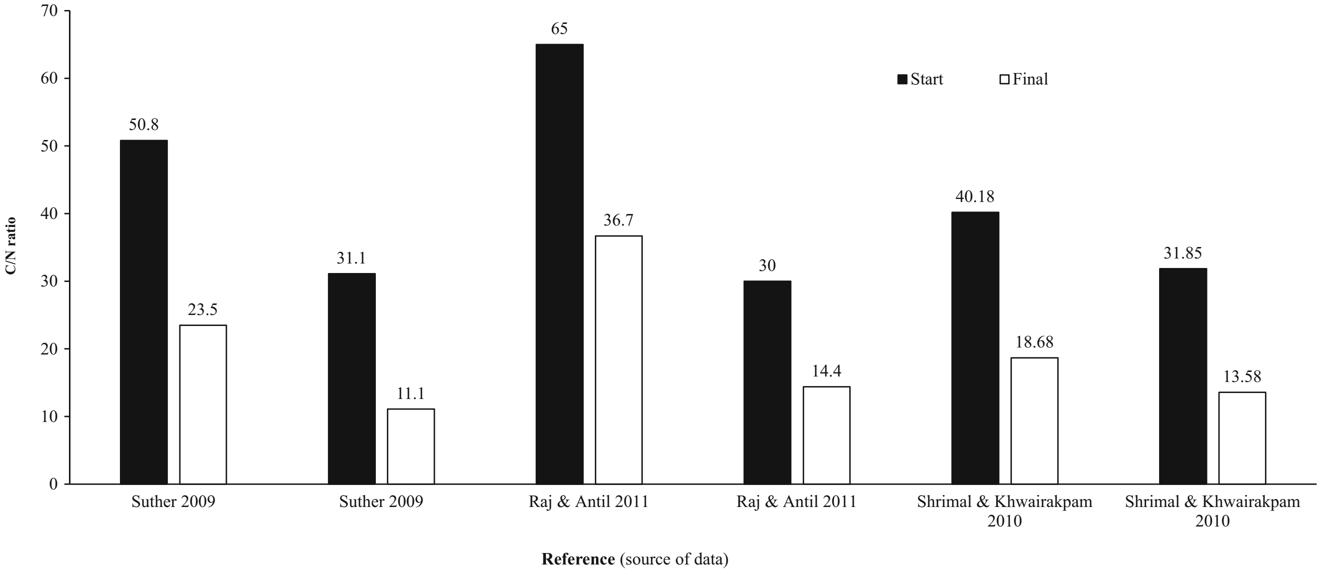

Fig. 2 Influence of starting C/N ratio on compost maturity as indicated by final C/N ratio. (Data extracted from the cited references to create the figure). According to Bernal et al. (2009) and Raj and Antil (2011), a C/N ratio of between 15 and 10 indicates a fully mature vermicompost

manure amended with waste paper to achieve different C/N ratios, reported that a C/N ratio of 40 was most appropriate for poultry manure vermicomposting. In another study, Raj and Antil (2011) evaluated biodegradation of different composts to which the initial C/N ratios of the composts had been set to 30. After 120 days, they observed that significant differences in the final C/N ratios of the composts were possibly due to the differences in their biodegradable fractions. The contribution of the biodegradation fraction of the organic matter to the vermi-degradation process is thus an area that requires more research to provide further basis for optimizing the vermicomposting of different materials.

The C to phosphorus (C/P) ratio has also been pointed out by some researchers as having an impact on biodegradation. Enriquez et al. (1994) pointed out that microbial growth efficiency measured as the fraction of C allocated to cell growth, decreased with an increase in C/N and C/P ratios, suggesting that materials with higher N and P contents are more likely to vermi-degrade faster. Brown et al. (1996), working with municipal waste sludge with different C/P ratios from 60:1 to 500:1 during composting, observed that a C/P ratio of between 120 and 240:1 is necessary for optimal biodegradation when the C/N ratio was 30:1. In another study, Mupondi (2010) amended cow dung–waste paper mixtures with different levels of phosphorus from 0 to 8% during vermicomposting. In this study, Mupondi (2010) found out that a P level of at least 2% was necessary for speedy vermi-degradation relative to the control with no P added. Optimizing the C/P ratio could thus be as critical as optimizing the C/N ratio, particularly during vermi-degradation of P-deficient materials. More work on the role of P in vermi-degradation is needed in order to further optimize the vermi-degradation process.

Earthworm species and stocking density

The earthworm stocking density has been agreed to be a critical factor that directly influences the optimization of the vermi-degradation process as it directly influences substrate microbial activity, enzyme activity, and other processes (Mupambwa and Mnkeni 2016). Similar to the C/N/P ratio, earthworm stocking density also influences the feeding rate which drives the gut-associated processes during vermicomposting (Ndegwa et al. 2000) as illustrated in Fig. 1. As noted earlier, the amount of organic material that earthworms consume depends to a large extent on the biodegradable fraction of the substrate, thus making optimization of stocking density for vermicomposting more complex (Ndegwa et al. 2000). Though many researchers have investigated the issue of stocking density, much of the work has focused on the growth and development of the earthworms under different stocking densities and not on the biochemical properties of the compost (Mupambwa and Mnkeni 2016; Garg et al. 2008).

It is widely agreed in literature that optimum stocking density of different earthworm species on different organic materials varies widely (Malinska et al. 2017). It is also important to note that several researchers have also reported positive vermi-degradation without compromising vermicompost quality under various stocking densities. Sahariah et al. (2014) and Goswami et al. (2013), using *E. fetida* on different industrial wastes, employed 10 worms per kg of substrate based on laboratory experience, reporting positive macro-nutrient mineralization and reduction in toxic heavy metals within the final vermicomposts. Similarly, Das et al. (2016a, b), utilizing another earthworm species, *Metaphire posthuma* at 10 worms per kg, during vermi-degradation of toxic jute mill waste, reported increased bioavailability of N, P, and K, humification parameters and microbial biomass compared to where there were no earthworms. In another recent study, Usmani et al. (2017) employed two epigeic earthworm species, *E. fetida* and *E. eugeniae*, and one epi–endogeic species, *Lumbricus rubellus*, during vermicomposting of fly ash–cow dung mixtures inoculated with 12 worms per kg, reporting positive but different results between the three species on nutrient mineralization and heavy metal remediation. Though all these studies report positive results on vermicomposting and nutrient mineralization under varying stocking densities, research on optimized stocking density for different organic materials and different earthworm species is still scarce. Some of the work that has been done on the effects of earthworm stocking density on vermicomposting is summarized in Table 1.

As highlighted in Table 1, much of the research work has focused on optimizing the stocking density of mostly *E. fetida* with only very few reports on other epigeic or endogeic earthworm species. Evidently, stocking density recommendations cannot be generalized for all materials as recommended by Ndegwa et al. (2000). More research needs to focus on substrate quality (biodegradation fraction) as this affects earthworm feeding and growth, while evaluating the differences between earthworm species to allow for more conclusive results and optimized vermicomposting. This could create a window of opportunity for making higher quality vermicomposts faster, potentially making vermicomposting more profitable.

Compost quality

Though vermicomposts can be optimized in terms of degradation efficiency and nutrient content, there has been very limited information on product standards and indicators or compost quality parameters to govern their marketing and field application (Fan et al. 2016; Brinton 2000). This is unlike inorganic fertilizers that have to carry a mandatory label declaring their nutritional composition. Specification of compost quality is important as it enables compost users to more effectively manage their "plant growing systems" (Cerda et al. 2018, Fan et al. 2016; Brinton 2000). Brinton (2000) provided an in-depth analysis of the status of compost standards in North America and Europe but other countries including India have also developed such guidelines. Table 2 shows compost parameters used in the USA and India for guiding the agronomic use and management of composts. Generally, the development of compost standards has placed greater emphasis on environmental than on agronomic considerations. Accordingly, compost quality is commonly categorized based on heavy metals, non-organic content, maturity, and stability (Cerda et al. 2018). Table 3 shows typical maximum permissible values of selected heavy metals in composts adopted in the indicated countries. The wide country-to-country variation on acceptable permissible levels of heavy metals indicates the need for ongoing international engagement to establish permissible metal levels for critical compost quality parameters which have greater universal acceptance. It is noteworthy that only India has attempted to develop standards for vermicomposts. Therefore, the optimization of vermicomposting needs to be coupled with the development of standards for this amendment whose importance is steadily growing.

Potential of nutrient amendments in enhancing vermicompost nutrient value

Though vermicomposts are being promoted as organic fertilizers, their adoption as commercial fertilizers in agriculture is limited by their low macro-nutrient concentrations relative to inorganic fertilizers. For example, commercial inorganic fertilizers can have as much as 46% N and 48% P, while vermicomposts have been reported to have around 0.96% N and 0.21% P when made from cow dung and banana wastes (Padmavathiamma et al. 2008). In another study, Singh et al. (2008) reported macro-nutrient levels of N (0.92%), P (1.21%), and K (1.45%) for a vermicompost prepared from vegetable waste and cow dung. This means that, to achieve the same nutrient level as inorganic fertilizers, organic sources of nutrients need to be applied at higher volumes per land area or amended with inorganic fertilizer sources as suggested by Singh et al. (2008) and Arancon et al. (2006). However, organic fertilizers have other extra benefits such as improving soil physical, chemical, and biological properties, slow release of nutrients, reducing physiological disorders in vegetables, and being environmentally friendly if properly managed, compared to inorganic fertilizers (Singh et al. 2008; Bhattacharya et al. 2012; Das et al. 2016a, b). As a solution to the low nutrient content of organic fertilizers, several researchers have looked at the potential of amending vermicomposts with other nutrient-rich inorganic materials (Kumar and Singh 2001). One important macro-nutrient whose concentration can be enhanced through amending vermicomposts with inorganic materials is phosphorus (P), and this has been the subject of several studies (Bhattacharya and Chattopadhyay 2002; Edwards et al. 2010; Adhami et al. 2014; Unuofin et al. 2016).

Apart from nitrogen, phosphorus is the most important plant nutrient that plays critical roles in almost all major biochemical processes within plants such as photosynthesis,

Table 1 Influence of earthworm stocking density and species on vermi-degradation, nutrient mineralization, and earthworm development

Substrates used	Earthworm species, stocking density and duration	Observations and research gaps	Reference
• Cow dung mixed with waste paper and incorporated with 2% phosphorus as rock phosphate	• *Eisenia fetida* inoculated at 0, 7.5, 12.5, 17.5, and 22.5 g worm per kg dry substrate and vermicomposted for 42 days.	• A stocking density of 12.5 g worms per kg of substrate resulted in highest earthworm development, decrease in C/N ratio, and highest humification parameters. • However, for P mineralization, a higher stocking density of 22.5 g worms gave the highest results. • This study demonstrated a definite relationship between biodegradation, nutrient mineralization, and earthworm stocking density. • The duration of the experiment was, however, short as P release showed a continuing trend at 42 days when the experiment was terminated. • Additional insights could have been obtained if the influence of the C/P ratio on biodegradation and its interaction with the stocking density were examined as well. • Special consideration could also be given to the C/P ratio.	Unuofin and Mnkeni (2014)
• Cow dung (CD) and textile mill wastewater sludge (STMS) mixed to achieve three substrates with different quality, i.e., 100% CD; 80% C + 20% STMS, and 70% CD + 30% STMS.	• *E. fetida* inoculated at 1, 2, 4, 8, and 12 worms per 150 g, which translated to 6.7, 13.3, 26.7, 53.3, and 80 worms per kg of substrate. • The study was done over 12 weeks.	• This study reported that earthworm growth rate was faster at higher stocking densities, with biomass gain being faster, however, at lower stocking densities. • Sexual maturity was attained earlier at higher stocking densities. • In this study, no biochemical parameters of the vermicompost were measured, which are critical in reporting compost quality. • C/N ratio was very high and not optimized for vermi-degradation (C/N ratio ranging from 64 to 192). • It would have been interesting if the substrate mixtures would have been based on the biodegradation fraction of the materials.	Garg et al. (2008)
• Cow dung–waste paper mixtures (CP) with fly ash (FA) incorporation at CP:FA ratio of 2:1 (*w/w*).	• *E. fetida* inoculated at 0, 12.5, 25, and 37.5 g worms per kg of substrate. • The study was undertaken over a 10-week period.	• The study showed that vermicompost maturity, indicated by a decrease of the C/N ratio from 30 to below 15, was realized even with the lowest stocking density. • However, unlike maturity, nutrient mineralization seemed to be significantly higher at higher stocking density of 25–37.5 g worm per kg. • The observed trend suggested that greater mineralization rates could have been realized at higher stocking densities beyond 37.5 g worm per kg. • This study did not look at the biodegradable fraction of the material as it involved use of paper which has high lignin content. • Future studies may need to investigate the influence of substrate quality on optimum	Mupambwa and Mnkeni (2016)

Table 1 (continued)

Substrates used	Earthworm species, stocking density and duration	Observations and research gaps	Reference
		earthworm stocking density during vermicomposting.	
• Sandy loam soil amended with Alder leaves (*Alnus glutinosa*)	• *Lumbricus rubellus* was inoculated to the soil–leaf litter mixture at a stocking density of 2–9 worms per container. The study was undertaken for a period of 6 months.	• This study showed that as the stocking density increased from 2 to 9, the life history parameters of the earthworms were affected. • The results showed that the individual growth, maturation, and cocoon production significantly decreased at higher stocking density though feed was optimum.	Klok (2007)
• Cow dung mixed with bakery industry sludge at different ratios from 100% cow dung to 70% cow dung.	• *E. fetida* inoculated at 1, 2, 4, 8, and 16 worms per waste mixture. Study was undertaken for 14 weeks.	• Across all the substrate mixtures, the lower the stocking density, the higher the net biomass gained and mean growth rate. • However, reproduction was higher under the higher stocking densities and lower in the lower stocking densities. • On maturity, the C/N ratio was lowest under the highest stocking density of 16, while stocking densities of 1 and 2 did not result in mature composts recording C/N ratio above 20. • This study looked at substrates that probably had different biodegradable fractions, which was however not reported as the original C/N ratio or lignin content of the mixtures was not described. • In this study, more chemical parameters rather than earthworm growth parameters could have been measured to link stocking density to nutrient dynamics.	Yadav and Garg (2016)

energy transfer, and molecular biosynthesis (Roy 2017; Sharma et al. 2013). Although P is abundant in soils, it is mostly insoluble and precipitated in different forms which are not easily available for plant uptake (Scervino et al. 2010; Sharma et al. 2013). Due to this, available P levels in soils have to be supplemented in most agricultural soils by adding chemical P fertilizers to improve crop productivity, which represents a major cost in agriculture and poses great environmental risks (Alamgir et al. 2012). The economic and environmental challenges associated with the use of chemical P fertilizers such as eutrophication and diminishing P reserves have resulted in a renewed interest in alternative sources of P-like phospho-composts (Alamgir et al. 2012). Recent research has focused on two inorganic materials that have been shown to have potential in improving the phosphorus nutrition of organic vermicompost namely, rock phosphate (Kumar and Singh 2002; Aria et al. 2010; Busato et al. 2012; Unuofin and Mnkeni 2014) and fly ash (Bhattacharya and Chattopadhyay 2002; Malik and Thapliyal 2009; Bhattacharyaa et al. 2012; Mupambwa et al. 2015). What has created this interest is the high total P content within fly ash and rock phosphate, which can be converted into bioavailable forms through processes like vermicomposting.

Mineral chemistry of rock phosphate and fly ash and its agronomic significance

Phosphate rock or rock phosphate is a term that describes any naturally occurring geological material that contains high concentrations of phosphate-bearing minerals with a phosphate content of 15 to 20% (Edwards et al., 2010). There are various types of these rock phosphates with varying chemical, mineralogical, and physical properties depending on origin (Van Kauwenbergh 2010). Fly ash, on the other hand, is a product of coal combustion, which is captured through electrostatic precipitators at thermal power stations, and there are different types depending on the origin of the coal materials (Mupambwa et al. 2015; Ukwattage et al. 2013; Pandey and Singh 2010). Though there are more than 200 known phosphorus minerals, the main mineral group of agronomic importance in rock phosphate and fly ash are the apatites (Valentim et al. 2016; Van Kauwenbergh 2010). Apatite is a group of minerals containing phosphorus, and there are three main groups, i.e., hydroxylapatite ($Ca_5(PO_4)_3(OH)$), fluorapatite ($Ca_5(PO_4)_3F$), and chlorapatite ($Ca_5(PO_4)_3Cl$) (van Straaten 2002). Based on origin, the rock phosphates can either be of sedimentary or igneous type and these two types have different solubility in soil. In the sedimentary rock phosphate, significant amount of the Ca in the structure has been replaced by Mg and Na, while almost 25% of the P has been replaced by carbonates (CO_3^{2-}); however, the igneous fluorapatite is almost pure, with no substitution (van Straaten 2002). The substitution of Ca and P with other elements with different valency but similar size in the apatite structure results in a more charged molecule with a higher reactivity; hence, the sedimentary rock phosphate is more soluble in soil compared to igneous rock phosphate. Similar to the igneous rock phosphate, the main type of apatite in fly ash is the non-substituted fluorapatite (MIF 2003; Valentim et al. 2016).

Due to the limited P solubility of the fluorapatite dominant in igneous rock phosphate and fly ash, their contribution when applied directly to soil is very limited. For a finite material like rock phosphate, it is imperative to improve the phosphorus solubility prior to its utilization in agriculture. This is even more important in developing countries like South Africa, Zimbabwe, and Brazil where 15–20% of the world rock phosphate stocks are found, and are predominantly igneous type, while fly ash generation in these countries is also increasing annually creating disposal challenges (Mupambwa et al. 2015; Edwards et al. 2010). Under natural conditions, when a material which contain apatite, like rock phosphate and fly ash, is applied to the soil, the orthophosphate ($H_2PO_4^-$ or HPO_4^{2-}) is released as shown in Eq. 2 (Edwards et al. 2010).

$$Ca_{10}(PO_4)6F_2 + 12H^+ \leftrightarrow 10Ca^{2+} + 6H_2PO_4^- + 2F^- \qquad (2)$$

The dissolution of the apatite in fly ash and rock phosphate when applied directly to the soil which is shown in Eq. 2 above is influenced by factors such as pH and cation exchange capacity (CEC). Therefore, the release of orthophosphate from apatite is generally greater in acidic soils due to the abundance of the protons (H^+). However, it has also been shown that other proton-generating processes like composting and vermicomposting can improve apatite mineralization (van Straaten 2002; Adhami et al. 2014). Though several researchers have linked the enhanced release of P in rock phosphate or fly ash-amended composts to organic acids, there is a dearth of information on the quantification of these and the micro-organisms involved in their release. Identifying the micro-organisms that produce the highest quantities of these effective apatite-mineralizing organic acids can result in the development of more efficient microbial cocktails which can be used as microbial inoculants during vermicomposting. Microbial inoculants are gaining momentum as another avenue that can be used to further optimize the vermi-degradation process (Mupambwa et al. 2016).

Rock phosphate enrichment of vermicomposts

Increasing the practical options available for enhancing the phosphorus nutrition in soils is considered very critical, particularly within an organic fertility management context (Edwards et al. 2010). Rock phosphate (RP) has been pivotal in this regard as it is among the few inorganic compost amendments that are allowed in organic agriculture (Edwards et al. 2010). Though rock phosphate can be directly applied to soils, this is not a common practice due to the very low solubility of phosphorus in rock phosphate (Aria et al. 2010). However, the possibility of selected soil microbes to solubilize P in rock phosphate has motivated researchers into inducing microbial mineralization of phosphates through vermicomposting (Pramanik et al. 2009). It is understood that during the vermicomposting of organic materials amended with nutrient insoluble materials like rock phosphate, decomposition of organic matter results in production of several organic acids and humic molecules that are responsible for driving the nutrient solubilization (Adhami et al. 2014). The ability of these low molecular weight organic acids and humic acids to release anions like phosphate and sulfate in soils has been well established (Bolan et al. 1994). These organic acids have also been observed to be higher in materials rich in organic matter. Bolan et al. (1994), for example, reported a soil sample having a total of 42.8 μg/g while poultry manure had in access of 22,000 μg/g of total organic acids. It is interesting to note that different microbe species, which are the drivers of biodegradation leading to organic acid production, have different abilities to produce different organic acids (Scervino et al. 2010).

Studies on how organic acids are produced and how they influence rock phosphate solubilization have been reported mainly during normal composting, with few studies focusing on vermicomposting. In a study using leaf compost and sheep dung, Adhami et al. (2014) observed that incorporation of 6% raw RP or 2% modified RP into sheep dung on average increased sodium bicarbonate extractable inorganic P by 54 and 7.9% with or without earthworm presence, respectively, compared to the control with no RP. Such a trend was also observed within the HCl and NaOH extractable P fraction in the same study, demonstrating the P mineralization potential of vermicomposting compared to normal composting without earthworms. Mupondi (2010) also incorporated RP on an elemental P basis to provide 0, 2, 4, 6, and 8% P as RP into cow

Table 2 Typical physio-chemical characteristics of selected composts and vermicompost in the USA and India

Compost parameter	USA[a]	India[b]	
	Municipal compost	City compost	Vermicompost
pH	6.0–7.5	6.5–7.5	–
Soluble salts (dS/m)	5.0 or below	4.0 or below	–
C:N ratio	–	< 20	–
Nutrients			
N (%)	1.0 or above	0.8 or above	1.0 or above
P (%)	1.0 or above	0.17 or above	0.35 or more
K (%)	–	0.33 or above	0.66
Organic matter content (%)	50–60	21	31
Water holding capacity (dry basis) (%)	100 or more	–	–
Moisture content (%)	40–50	15–25	15–25
Particle size			
Bulk density	0.47–0.59 g/cm^3	< 1.0 g/cm^3	0.7–0.9 g/cm^3
Particle size	Pass through 1-mm screen or smaller	90% must pass through a 4-mm IS screen	
Growth screening	Must pass seed germination test and plant growth assay	–	–
Stability	Stable to highly stable	–	–
Pathogens	–	Nil	–

[a] Brinton (2000)

[b] http://ncof.dacnet.nic.in/Training_manuals/Training_manuals_in_English/BF_and_OF_in_FCO.pdf [downloaded on December 19, 2017]

dung–waste paper vermicompost, with the control having no RP and earthworms (*E. fetida*). The results of this study also indicated positive increase in various inorganic P fractions following the vermicomposting process, with the 8% P amendment showing the highest P release. In a similar study, Unuofin et al. (2016) incorporated RP on an elemental P basis of 0, 0.5, 1, 1.5, 2, and 4% as RP into cow dung–waste paper and earthworm inoculation at an optimized stocking density of 12.5 g worm per kg substrate. The results of this study focused on the vermi-degradation efficiency and reported highest biodegradation and compost maturation at 1% P as RP incorporation. All these studies focused on determining P transformations during vermicomposting with only speculation that the presence of earthworms contributed to this increase. More scientific studies that focus further on the mechanisms involved in P mineralization and how earthworm GAPs and CAPs contribute to this could be critical in further optimizing P nutrition in vermicomposts. As indicated by Scervino et al. (2010) that different microbes produce different quantities of organic acids, it will also be interesting to evaluate how different earthworm species, under different vermicomposting environments, influence organic acid production and P solubilization.

Though several researchers have looked at the possibilities of RP vermicomposting, much of the work has focused on using only *E. fetida* earthworm species. Also, though vermicomposting is reported to enhance the inorganic P release in these studies, the concentration of the inorganic P within the composts was still very low compared to that of inorganic P sources. Several researchers have reported rock phosphate incorporation during composting or vermicomposting at different levels, which obviously affects the ultimate P level within the final composts. It would be interesting to see if higher levels of P incorporation can be considered and how this will influence the total P concentration of the vermicompost and the vermi-degradation process. Though permissible in organic agriculture, RP being terrestrial in origin also contains some heavy metals, and there is paucity of research information on the solubility of these potentially toxic metals during optimized vermicomposting. For example, Mupondi (2010) reported that when incorporated to supply 8% P with RP during vermicomposting, the RP contributed to more than 150% more heavy metals compared to where there were earthworms but with no RP. The influence of different earthworm species and rock phosphate levels on the heavy metal levels and heavy metal bioaccumulation is an important area where research needs to be advanced.

Fly ash enrichment of vermicomposts

Fly ash is a by-product of coal combustion during thermal electricity generation which also contains significant total P concentrations but with very low bioavailable P. The high total

Table 3 Typical permissible heavy metal concentrations (mg/kg) in organic fertilizers in different countries

Element (mg/kg)	USA[b]	EU range[a]	EU standard[b]	Canada[b]	India[c]		Malaysia[d]
	Municipal compost and biosolids	Municipal compost	Municipal compost	Municipal compost	City compost	Vermicompost	Municipal compost
Pb	300	70–1000	150	150	100	100	300
Cu	1500	70–600	100	100	300	–	
Zn	2800	210–4000	400	500	1000	–	
Cr	1200	70–200	100	210	50	50	200
Ni	420	20–200	50	62	50	50	150
Cd	39	0.70–10.0	2.0	3	5	5	2
Hg	17	0.70–10.0	0.5	0.8	0.15	–	–
As	41	–	–	13	–	–	–
Se	36	–	25	2	–	–	–
B	–	–	300	–	–	–	–
Mo	–	–	10	–	–	–	–

[a] Brinton (2000)

[b] Wood's End Research Laboratory (2005)

[c] http://ncof.dacnet.nic.in/Training_manuals/Training_manuals_in_English/BF_and_OF_in_FCO.pdf

[d] Fan et al. (2016)

P has generated interest of using vermicomposting to improve its bioavailable P fraction (Mupambwa and Mnkeni 2015; Bhattacharya and Chattopadhyay 2002). Mupambwa et al. (2015), for example, indicated that the total P concentrations in fly ash can be up to 300% more than the plant available fraction. However, unlike RP which is accepted in organic agriculture, fly ash (FA) is not, mainly due to the possible heavy metal loads that can result from the direct application of FA into soil (Mupambwa et al. 2015). Though fly ash has a potential to pollute the environment with heavy metals, technologies like vermicomposting of fly ash incorporated into organic materials have been observed to significantly reduce the bioavailability of most heavy metals while increasing those of essential plant nutrients (Bhattacharya and Chattopadhyay 2006). What is interesting in these studies is that the bioavailability of trace metals such as Fe, Cu, Zn, and Mn increased while those of heavy metals such as Pb, Cd, and Cr decreased during vermicomposting, a situation attributed to the formation of organo-metallic complexes (Bhattacharya and Chattopadhyay 2006). On the contrary, Gupta et al. (2005) during vermicomposting of fly ash reported decrease in Cu and Zn after 180 days of vermicomposting, indicating the need for further research to fully understand the transformations of heavy metals during vermicomposting of organic composts amended with fly ash. Due to the absence of carbon and nitrogen in fly ash, possibilities of incorporating it into organic materials like cow dung to enhance the mineralization of the apatite to orthophosphate have been explored (Mupambwa et al. 2015). What is important to note during fly ash vermicomposting is that there is a possible reduction in the microbial activity due to the alkaline conditions created by fly ash. These alkaline conditions can reduce the vermidegradation process efficiency and nutrient mineralization, relative to the treatments with no fly ash addition. Bhattacharya and Chattopadhyay (2002), for example, reported that incorporating fly ash into cow dung at a ratio of 1:3 resulted in a 37% less Olsen extractable P compared to the cow dung alone. This observation could be due to the reduction in levels of phosphate-solubilizing microbes within the vermicompost from 33×10^8/g in cow dung alone to 4.6×10^8/g with incorporation of fly ash into the cow dung at 25% levels during vermicomposting. Mupambwa and Mnkeni (2015) also reported similar results, with the fly ash-incorporated treatments yielding less extractable P relative to the treatment with the organic matter (cow dung) alone. These observations support the idea that addition of fly ash, a mostly alkaline material, to organic materials has influence on the microbial activity, which possibly affects nutrient mineralization. During vermicomposting, earthworms and microbes tend to feed on the easily degradable organic materials rather than on the inorganic materials, thus, using organic matter decomposition only to evaluate maturity of such composts could be misleading (Sarojini et al. 2009, Mupambwa and Mnkeni 2015). In composts with fly ash addition, much of the nutrient mineralization is driven by cast-associated processes using metabolites from the earthworm–microbe activity, with very limited research having focused on these processes. It will be interesting to identify more active microbes like phosphate-

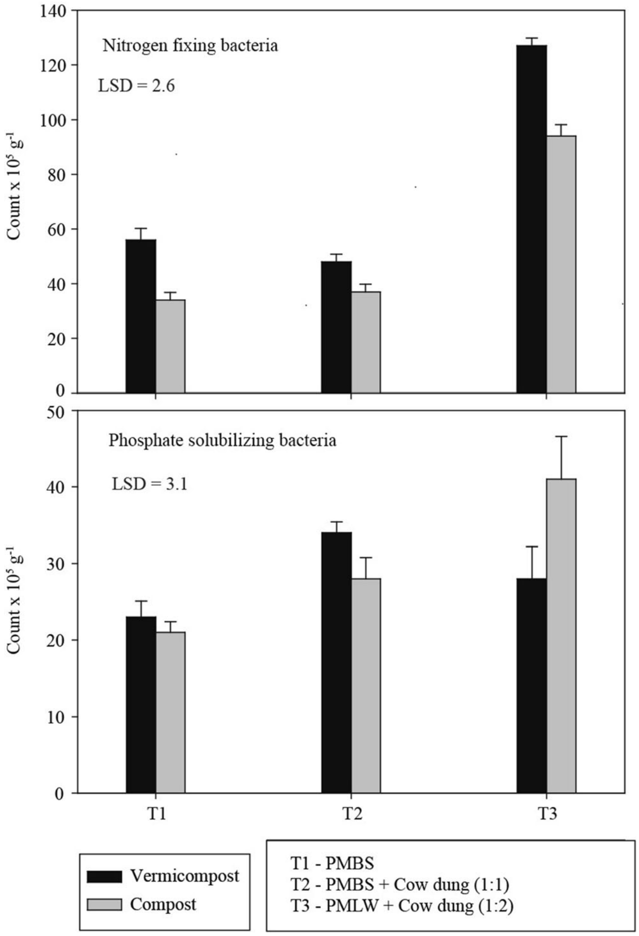

Fig. 3 Impact of neutral paper mill bamboo sludge (PMBS; pH 6–7.3) and alkaline paper mill lime waste (PMLW; pH 10.6–11.1) on the population of phosphate-solubilizing bacteria. Sahariah et al. (2014)

solubilizing microbes that are capable of releasing more organic acids to improve mineral solubility during vermicomposting of organic materials amended with materials like fly ash. Such microbes could be cultured and used to formulate microbial inoculants that can be further used to optimize the vermicomposting process of fly ash-amended composts.

Though fly ash is not considered as a safe amendment in organic farming like RP, there is very limited research evidence to show that fly ash-amended vermicomposts can contribute significantly to soil heavy metal loads. In a study where FA was incorporated at different ratios into cow dung, Bhattacharya and Chattopadhyay (2006) actually reported that the solubility of the heavy metals Cr, Cd, and Pb during vermicomposting was reduced and attributed this to possible formation of organo-metallic complexes. Studies that can identify these metal complexes can be important in understanding the implications of using fly ash-amended vermicomposts in agriculture (Bhattacharyaa et al. 2012). Though reported by several researchers that earthworms have the capacity to bioaccumulate heavy metals (Pattnaik and Reddy 2011; Li et al. 2010), such studies on fly ash-amended vermicomposts are very limited, though critical in evaluating the actual implications of fly ash-amended vermicomposts within organic soil fertility management systems. Recent research by Goswami et al. (2016) have only looked at fly ash generated from biological materials, and not that derived from terrestrial materials like coal, where the heavy metal contents are much higher. Studies that would not only look at heavy metal bioaccumulation in the popular *E. fetida*, but also in other species under comparative studies could generate important information, which could further optimize the vermicomposting of fly ash-amended vermicomposts. Such studies could be further supported by long-term studies on the possible heavy metal loads that are associated with optimized fly ash-based vermicomposts when they are used in soils as nutrient sources, as hitherto much of the research has focused on direct application of fly ash alone.

Opportunities for enhancing microbial activity during vermicomposting

There is limited information available on the changes in compost microbial activity and properties during vermicomposting of organic materials incorporated with either rock phosphate or fly ash. Bhattacharya and Chattopadhyay (2002) enumerated the occurrence of phosphate-solubilizing bacteria (PSB) in different composts in which fly ash had been incorporated at 0, 25, 50, 75, and 100%. They found that fly ash incorporation at 50% supported the highest population of PSB, while the 0, 25, and 75% showed 1.4, 16.1 and 9.5 times lower PSB counts, respectively, compared to the 50% treatment. Bhattacharya and Chattopadhyay (2004) in a similar study also enumerated nitrogen-fixing bacteria (NFB) after 50 days of vermicomposting a fly ash—cow dung mixture reporting significantly lower NFB where fly ash was incorporated at 1:3 and 3:1 levels but higher at 1:1 level. It is possible that the alkaline conditions induced into the compost due to the presence of the fly ash might have resulted in reduced microbial counts. Sahariah et al. (2014), in another study, observed reduced PSB counts during vermicomposting of highly alkaline paper mill lime waste compared to neutral paper mill bamboo sludge, as shown in Fig. 3. However, when neutral bottom ash from paper and tea industries was incorporated into cow dung during vermicomposting, significantly higher PSB and NFB were recorded in treatments with earthworms (Goswami et al. 2013). The studies reported above have, however, focused only on nutrient-mineralizing microbes, with no studies going further to monitor other microbes that are involved in the biodegradation process during vermicomposting. Though not being a part of this review, there is also a need to identify shifts that may occur in microbial diversity due to amendments of organic wastes with inorganic materials such as those reported by Mupambwa et al.

Table 4 Typical experiments involving inoculation of composts with the intention of enhancing elease of mineral P from rock phosphate or fly ash

Organic base	Apatite bearing material	Experimental procedure	Observations	Research gaps	Reference
• Cow dung and sunflower cake after oil pressing mixed at 3:1 (*w*/*w*). • Average combined C/N ratio of 14.7:1	• Igneous apatite rock phosphate from Brazil	• The organic materials initially pre-composted thermophilically for 60 days. • After pre-composting, the material was adjusted to 80% moisture. • 50 worms (*Eisenia fetida*) added for the 10 kg material. • The mixture was also amended with rock phosphate at 0.1% (wet weight). Inoculated with *Burkholderia* spp. at 25 mL (10^8 viable cells) per kg. • Two treatments based on either presence of inoculant and rock phosphate (inoculated VC) or without inoculant and rock phosphate (uninoculated VC).	• The C/N ratio after 120 days dropped from 14 to around 12. • 15% more humic acids (HA) and 10% high HA/Fulvic acid ratio under the inoculated vermicompost. • Water soluble P was 2.4 times less than the inoculated treatment after 120 days. • Addition of rock phosphate and microbial inoculants showed highest alkaline phosphatase activity during the first 90 days only. • Inoculated vermicompost showed higher number of diazotrophic bacteria throughout.	• Incorporate rock phosphate at more optimized rates to identify the P release response. • Optimize the C/N ratio and earthworm stocking density for effective vermicomposting and identifying its influence on mineralization under inoculation. • Quantifying the organic acids produced during vermicomposting under inoculation. • Use of more aggressive phosphate-solubilizing bacteria contrary to the diazotrophs used in this study. • Establishment of optimized inoculating rates for different microbes.	Busato et al. 2012
• Cow dung and paper waste mixed to achieve a C/N of 30:1	• Fly ash from Matla power station in South Africa	• Fly ash incorporated into the cow dung–waste paper at a ratio of 1:2 (*w*/*w*). • Material was pre-composted for 7 days. • Earthworms (*E. fetida*) inoculated at 25 g worm/kg after pre-composting. • Special cocktail of microbes (effective micro-organisms–EM) were also inoculated at 8 L/m^3. • Four treatment combinations based on: with worms or not, and with EM or not. • Material was composted for 10 weeks.	• C/N ratio decreased for all treatments but significantly different after 10 weeks with the earthworms only and earthworms + EM having a C/N ratio of 12.25 relative to 22.03 for the no earthworms + no EM control. • Throughout the 10 weeks of composting, the earthworms + EM treatment showed the highest increase in Olsen P (43.8% more than the control). • Alkaline phosphatase activity was significantly higher in the earthworm + EM treatment throughout the 10 weeks. • The presence of earthworms rather than EM resulted in an increase in phosphate-solubilizing bacteria.	• Evaluation of higher optimized rates of EM is required under earthworm presence. • Quantification of organic acids can identify which acids are mainly responsible for P mineralization. • A design with a treatment without fly ash can allow to isolate the contribution of the inorganic material to released P. • Mixing EM with other more aggressive phosphate solubilizing microbes can be interesting.	Mupambwa et al. 2016
• Mature vermicompost made from partially decomposed plant	• Rock phosphate from	• This experiment used a mature vermicompost inoculated with *E. fetida* at	• Addition of rock phosphate together with inoculation showed 29.6% more P after 75 days of incubation	• Increase in P was speculated to be due to organic acids which could be determined	Kumar and Singh 2001

Table 4 (continued)

Organic base	Apatite bearing material	Experimental procedure	Observations	Research gaps	Reference
residues and cow dung mixed at a ratio of 3:1.	Mussoorie, India.	10 worms per kg of material and composted for 80 days.	compared to where inoculation was done with no rock phosphate.	and quantified to prove this hypothesis. • Optimization of rock phosphate incorporation and earthworm stocking density could improve results.	
		• Four different N-fixing bacteria were used and one phosphate-solubilizing bacterium (*Pseudomonas striata*) inoculated at 2 g containing 10^8 cells/g/kg compost with or without rock phosphate. • Rock phosphate was inoculated at 1%. • Incubation was done over 75 days.	• Survival of the *P. striata* with rock phosphate amendment or without, however, showed a similar trend across the entire 75-day period.	• Inoculation rate could be optimized for better results under combined vermicomposting and PSB inoculation.	
• Municipal solid waste compost (MSWC) mixed with or without 10% of composted poultry litter	• Indian rock phosphate	• The MSWC was mixed with 10% composted poultry litter. • A microbial consortium containing *Azotobacter spp.*, *Pseudomonas fluorescence*, and phosphate-solubilizing bacteria was used at 0.5% of the 5-kg material used. • Rock phosphate was also added at a rate of 5% of the 5-kg material. • Other interesting treatments were MSWC alone and MSWC with poultry liter alone.	• Phosphorus-solubilizing bacteria only increased in the treatment with rock phosphate amendment with a surprising zero count for the other two treatments.	• Using microbial inoculants together with the composting process as opposed to initially composting the materials then inoculating could generate more positive results.	Kavitha and Subramanian 2007
		• The materials were incubated without earthworms for 20 days.	• Total phosphorus in the treatment with rock phosphate and microbial inoculation showed a 36.7% increase, while the MSWC and MSWC + poultry litter showed a respective 17.3 and 11.3% increase.	• Measuring the plant available phosphorus could indicate the portion that becomes available to the plant when the compost is used, instead of measuring total P. • Inclusion of earthworms at optimized rates could generate more positive rates. • Use of specific phosphate-solubilizing bacteria alone could avoid interactions with other additional microbes.	
• Mature vermicompost prepared from cow manure	• Hard rock phosphate from Iran and powdered	• A factorial experiment with four factors, i.e., sulfur rate, mature vermicompost presence (C/N 9.1: 1),	• Interestingly, the treatment with the mature vermicompost only showed no changes on water soluble	• Mature vermicompost used in this study removed the influence of the vermicomposting on P	Aria et al. 2010

Table 4 (continued)

Organic base	Apatite bearing material	Experimental procedure	Observations	Research gaps	Reference
	elemental sulfur	inoculation, and incubation time. • Treatments of interest are those with sulfur, vermicompost, and inoculation with *Thiobacillus thiooxidans* (a sulfur-oxidizing microbe) • The idea was to biologically oxidize sulfur using the inoculant and convert it to sulfuric acid in the compost mixture. • A 1 kg of rock phosphate was amended to all treatments. • Incubation time was 60 days.	P (WSP) across the 60 days of incubation. • Also, interestingly, the treatments with sulfur and inoculation with *Thiobacillus thiooxidans* showed similar changes in WSP with or without the presence of the vermicompost. • The inoculation showed more influence on the release of WSP compared to the presence of the vermicompost.	solubilization in this experiment. • It was assumed that the biological oxidation of the sulfur by the inoculant would be responsible for the solubilization of P in rock phosphate; however, this acid produced could be easily quantified. • The growth of the inoculated microbes could have been monitored and correlated to P release.	

(2016). The possible reduction in microbial activity as measured by the levels of PSB and NFB in the preceding studies has driven researchers into establishing the possibility of deliberately inoculating vermicomposts with beneficial microbes, creating an opportunity to further optimize the vermicomposting process (Mupambwa et al. 2016; Aria et al. 2010).

Microbial inoculants and phosphorus mineralization during vermicomposting

The growing realization that microbes are critical during the vermicomposting process, with earthworms playing a crucial role in influencing microbial diversity and dynamics, has created an opportunity to further optimize the vermicomposting process (Dominguez et al. 2010). It is also clear that research on optimizing the organic materials and the amendment rate of RP or FA is very critical if optimum earthworm activity is to be achieved during vermicomposting. Unlike the vermicomposting of purely organic materials which rely mainly on enzymatic activity for mineralization, the release of nutrients from RP- or FA-enriched organic vermicomposts mainly depends on the combined action of organic acids and enzymes (Sharma et al. 2013). Against this background, several researchers have evaluated the possibility of deliberately including specific microbes with the capacity to mineralize apatite with one such group of microbes being the phosphate-solubilizing microbes (PSMs). Some of the research that has been undertaken involving microbial inoculation of fly ash or rock phosphate-based vermicomposts is summarized in Table 4.

The literature reviewed indicates the potential benefits of inoculating composts with beneficial phosphate-solubilizing bacteria but there seems to be very limited research done to identify and quantify the organic acids speculated to be responsible for the breakdown of the apatite in rock phosphate- or fly ash-amended composts. Research to this end would enable the identification and development of effective and specific microbial cocktails that can enhance production of larger quantities of these organic acids, thus, achieving greater P mineralization from incorporated RP or fly ash.

Microbial cocktails that can be developed from these identified specific phosphate-solubilizing microbes can further be

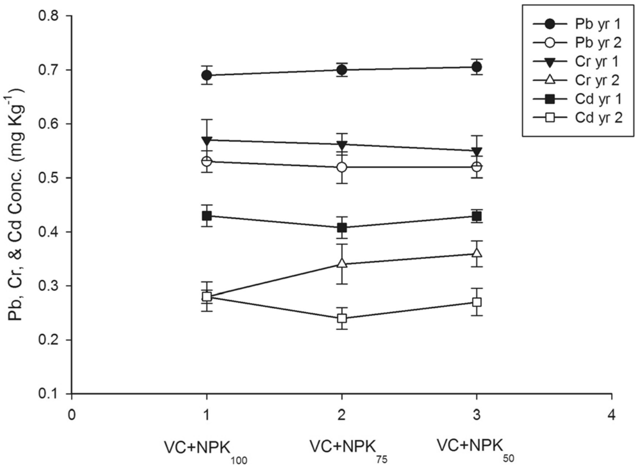

Fig. 4 Changes in Pb, Cr, and Cd over a 2-year period in soils amended with vermicomposted fly ash (VC) and NPK fertilizer at 100, 75, and 50% of the recommended rate. Bhattacharyaa et al. (2012)

optimized for application rates for effective vermicomposting. However, research that has looked at the possibilities of inoculating vermicomposts with microbial inoculants has rarely tried to optimize the inoculation rate. Rock phosphate-amended and microbe-inoculated vermicomposts can create a commercial opportunity for such optimized, microbe-inoculated phospho-composts in agriculture. By contrast, direct utilization of fly ash vermicomposts in agriculture is limited due to the potential heavy metal load associated with fly ash. Optimized FA-based phospho-composts could, however, be an important source of nutrients in the non-edible horticulture industry and in mine waste land reclamation (Mupambwa et al. 2017).

Potential of RP- or FA-based vermicomposts as planting media

There is a growing realization that soil is a critical component of the biosphere responsible not only for food production, but equally important in the maintenance of environmental quality (Ferreras et al. 2006). Thus, technologies that only focus on the agricultural potential of the soil rather than overall soil health are being realized to be unsustainable. Unlike inorganic fertilizers that only supply the soil with targeted nutrients, organic nutrient sources supply a wide range of essential macro- and micronutrients together with organic matter which is essential for improving soil quality and health. With the potential balanced nutrient supply from vermicomposts compared to inorganic fertilizers, several researchers have looked into the possibilities of using vermicomposts as artificial planting media. Positive results have been reported on both media quality and crop development, where vermicomposts were used as a combination of artificial media (Atiyeh et al. 2001; Arancon et al. 2003, 2005, 2006). With RP- and FA-based phospho-composts presenting a cheaper and sustainable nutrient source, research on their impact on crop productivity in different soils is important. However, there is also limited field-based research that has been done on evaluating the soil-improving properties of these potentially beneficial soil conditioners. With both rock phosphate and fly ash being terrestrial in origin, the potential long-term heavy metal loads associated with the application of vermicomposts amended with such materials has rarely received attention. Many researchers have only evaluated these vermicomposts in short-term greenhouse studies, with limited information being available of the long-term field environmental and ecotoxicological risks associated with these vermicomposts (Businelli et al. 2009).

Kumari and Ushakumari (2002) used a rock phosphate-enriched vermicompost to amend a soil planted with cow peas (*Vigna unguiculata*) and evaluated yield and nutrient uptake. Though the rock phosphate was applied after the vermicomposting process, it was interesting to observe that the combination of the vermicompost, and the rock phosphate showed the best results on grain yield, plant N, and P. Compared to the following treatments, no manure, vermicompost alone, and inorganic P fertilizer, the rock phosphate-enriched vermicompost resulted in a grain yield 49.5% greater, and plant P 93.5% greater compared to the average of all the other treatments (Kumari and Ushakumari 2002). It would have been interesting to observe the P mineralization had the RP been incorporated during the vermicomposting process rather than after, as it was done in this study. Also, the influence of the vermicompost on the soil properties like heavy metal accumulation was not evaluated in this study.

Mihreteab et al. (2016) used a compost prepared from grass clippings, palm, olive, and ornamental tree prunings with or without rock phosphate enrichment. It was noteworthy in this study that the rock phosphate-amended compost applied to supply 0.59 g P/kg-compost produced seedlings that were comparable to the substrates substituted with 1.18 P as rock phosphate per kilogram compost. These results clearly demonstrated the apatite mineralization potential of the composting, which could have even been more if vermicomposting had been done. What is interesting in all vermicomposting research is that though several researchers have indicated positive nutrient results following rock phosphate or fly ash vermicomposting, research that could compliment these studies, in terms of actual soil studies, are still rare. Such a study was performed by Bhattacharya et al. (2012) using a fly ash-based vermicompost on a red lateritic soil over a period of 2 years. Unlike the normal belief that fly ash-based vermicompost will contribute higher levels of heavy metals, this study reported slightly changed or even reduced heavy metal levels in soils in the second year as shown in Fig. 4. Such information is encouraging, as it points to the possibility of using materials like fly ash in organic soil fertility management systems, though thorough studies that support this possibility are still essential. Using fly ash as a P source, Mupambwa et al. (2017) used a cow dung–waste paper vermicompost amended with 33% fly ash as a substitute for pine bark-planting media and evaluated its ornamental horticulture potential. Compared to the pine bark alone, substitution of the fly ash based-vermicompost between 25 and 50% resulted in the best marigold germination and flower growth. However, this greenhouse study did not also determine the heavy metal uptake in the ornamental marigold.

Conclusions

Vermicomposts can be an important source of nutrients in organic fertility management systems, but their low macro-nutrient content still hampers their wide adoption as sources of nutrients in commercial agriculture. Ongoing research efforts are seeking to enhance the macro-nutrient content of essential elements like phosphorus through amending vermicomposts with inorganic P sources like fly ash and rock phosphate. These inorganic materials, however, have very limited bioavailable P contents, thus technologies that enhance the mineralization of phosphorus from these minerals are necessary. This review has shown that optimization of the vermicomposting process could improve nutrient mineralization in organic wastes amended with inorganic materials like fly ash or rock phosphate. This will entail optimizing the critical parameters that drive this earthworm–microbe-driven process such as C/N and C/P ratios—substrate biodegradation fraction, earthworm species, and stocking density. Incorporation of organic materials with inorganic P sources has been shown to cause a general reduction in microbial activity which could compromise the efficiency of the vermi-degradation process. Research is needed to optimize microbial inoculants for enhancing the vermicomposting of fly ash- or rock phosphate-amended composts. Microbial inoculation of vermicomposts is reported to enhance nutrient mineralization through the release of organic acids. However, there are no studies that have quantified these organic acids, which could then allow for the identification of more aggressive phosphate-solubilizing microbes during vermicomposting. Finally, field scale experiments that look at the long-term effects of optimized fly ash- or rock phosphate-based vermicomposts are essential to unravel their influence on different soil chemical, biological, and physical properties.

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