Conversion of waste into organo-mineral fertilizers: current technological trends and prospects

Youness Bouhia · Mohamed Hafidi · Yedir Ouhdouch · Mohammed El Mehdi El Boukhari · Chango Mphatso · Youssef Zeroual · Karim Lyamlouli

Received: 28 February 2022 / Accepted: 22 April 2022 / Published online: 10 May 2022
© The Author(s) 2022

Abstract One of agriculture’s most important goals is finding the proper equilibrium between sustainability and intensification of production. The exponential growth of the world population, climate variability, and soil degradation are essential factors that require the development of novel agricultural practices to achieve food security. In this context, organo-mineral fertilization has been proposed as a promising approach. Such a concept is based on novel fertilizers formulations combining organic and mineral resources features, which could simultaneously address soil fertility and health issues. The manufacturing processes of organo-mineral fertilizers (OMF) are highly versatile and revolve around the co-processing of organic and mineral matrices. OMF’s peculiarity resides in using systemic methodologies for waste valorization to generate cost-effective and eco-friendly products in alignment with the bio-circular economy. Despite their advantages, OMF adoption by farmers is still not satisfactory, which could be attributed to the difficulty of accessibility and a stagnant market. This work critically reviews recent advances in the organo-mineral fertilization concept. Our review provides an in-depth understanding of the chemical, biological, and thermal methodologies used for OMF generation through mineral and organic matrices co-processing. We also discuss the positive effect of such products on the plant-soil system by focusing on the mechanism of action. Furthermore, this review scrutinizes the innovation profile of OMF based on trends of patent submission during the last 20 years. It also provides future research and development pathways based on current drawbacks and limitations of the industry.
Keywords  Organo-mineral fertilizers · Organic matter · Fertilization · Sustainable agriculture; soil health; crop yield · Waste management

Abbreviations

DAP  Diammonium phosphate
MAP  Monoammonium phosphate
PS  Potassium sulphate
RP  Roch phosphate
NPK  Nitrogen, phosphate, and potassium
MgO  Magnesium oxide
Fe  Iron
NPK SFe  Nitrogen, phosphate and potassium + sulfur and iron
K₂O  Potassium oxide

1 Introduction

Limited raw material and land resources with the rising global population are currently critical factors hampering agriculture in achieving food security goals (Alves et al. 2014; Reynolds et al. 2016). The last green revolution has brought pivotal technologies enabling the implementation of intensive and highly productive agrosystems. Those agri-models driven by productivity were mainly based on overfertilization and monocropping systems, which led to soil degradation issues, such as erosion, depletion of soil organic matter (SOM), salinization, and nutrient imbalance (Aguilera et al. 2013; Hartemink et al. 2014). SOM is one of the most critical soil health indicators due to its multifaceted effects on soil traits such as soil microbial activity, nutrient dynamic and cycling and physical characteristics (Hoffland et al. 2020). Many agro-practices have been proposed to improve the level of SOM to ensure sustainable fertility of degraded soil, including cover cropping, limited or no-till farming, integrated nutrients management, and amending soil with stable organic matter (Bationo et al. 2007; Lal 2009; Vanlauwe et al. 2010; Molina-Peñate et al. 2022). For example, organic farming has been widely viewed as an eco-efficient approach to improving SOM status. However, many still consider it a low production system as it is highly dependent on ecosystem services, which are variable by nature as they are strongly affected by environmental changes (Smith et al. 2018). According to Durham and Mizik (2021), organically managed farms produce
10–20% fewer yields than conventional farms. Still, in terms of profits, the trend is inversed, which is attributed to lower operating costs, better plant stress resistance, the premium price of the end products, and a less complex supply chain. Conversely, Kirchmann (2019) stated that the current meta-analysis had overestimated the agricultural production of organic farming as the assessment is more based on a nature-related philosophical thinking; rather than relevant biological science, and statements corroborating the complete substitution of mineral fertilizers are scientifically irrelevant. Moreover, according to Swedish statistical data, conversion to organic farming without losing the yield will plausibly require increasing arable land by 50% (Kirchmann 2019).

Both conventional and organic farming have their respective advantages and drawbacks. One promising approach that could be applied is combining organic and mineral inputs. Both resources are theoretically compatible, and according to several research investigations, this is possibly the best solution to maximize the agronomic efficiency and crop productivity without neglecting sustainable soil health and fertility (Laird et al. 2010; Ayalew and Dejene 2012; Ichami et al. 2019; Liu et al. 2020). Such a concept has recently gained more interest, leading to the development of a novel category of fertilizer products, namely the organo-mineral fertilizers (OMF). These latter are fertilizers resulting from combining through a chemical reaction, inorganic fertilizers with a high content of nutrients with an organic matrix or soil improver (Antille et al. 2013a; Kominko et al. 2019). A key advantage of OMF products is that their manufacturing process is fundamentally based on organic waste valorization, which aligns with the circular economy concept (Barje et al. 2012; Bouhia et al. 2020, 2022a; Costa et al. 2022). Furthermore, manufacturing methodologies are not limited to chemical processes. Depending on the nature of the feedstock, a diversity of techniques can be used, such as thermal conversion, anaerobic digestion, and solid-state fermentation. Implementing procedures for the co-processing of mineral and organic resources instead of single applications is justified by the gained additional value of the final products due to specific chemical interactions. This includes improved bioavailability of nutrients, higher chemical reactivity, and slow-release properties (Kominko et al. 2019). OMF are often reported for their multiple beneficial effects on agrosystems, including their ability to improve soil physico-chemical properties and biological functionalities and enhance plant physiological traits (Obalum et al. 2012; Carvalho et al. 2014; Pawlett et al. 2015; Boiffard et al. 2016; Zainab et al. 2016; Silva et al. 2017; Farrar et al. 2018).

Review reports on OMF are scarce. The only relevant example is the work of Kominko et al. (2019) which mainly focused on the chemical co-processing of sewage sludge and mineral fertilizers. In this context, this critical review aims to complement previous investigations by providing a more systemic analysis of the concept of organo-mineral fertilization. Conventional and novel technologies (not limited to chemical processes) used in products manufacturing are thoroughly described. The valorization of the mineral byproducts of the phosphate industry into OMF is also addressed for the first time. Furthermore, the effect of such products on soil physico-chemical and biological properties, plant agrophysiological traits, and agronomic productivity is depicted, focusing on the mechanism of action. Ultimately, we describe the current status of the market, highlight significant limitations and provide future perspectives on moving forward this vital segment of the fertilizer industry.

2 Manufacturing processes of organo-mineral fertilizers

The manufacturing processes used to convert organic and mineral wastes into organo-mineral fertilizers are highly diverse (Fig. 1). Several research investigations demonstrated that chemical, thermochemical and biological methodologies are equally efficient for obtaining products with satisfactory fertilizing properties. The choice of an adequate process depends mainly on the nature of the used feedstock and the targeted market. This section systematically reviews the most notable chemical and biological methodologies employed in OMF development through valorizing organic/mineral waste and low-grade phosphate.

2.1 Conventional manufacturing processes of organo-mineral fertilizers based on organic waste and chemical fertilizers

Implementing a process to produce OMF is mainly dependent on the raw material properties, which often include an organic waste and a mineral fraction. Diverse formulations have been assayed (Table 1). However, the granular and pelletized formulations are
the most dominant. Considering the great diversity of the generated organic waste, the possibilities are almost limitless.

The conversion of organic waste into OMF formulations requires achieving a double objective. First, generating a product with a high fertilization quality, and second, creating agronomic value from a given organic waste. For example, when processing sewage sludge, the most important aspect would be the elimination of microbial pathogens, which is usually carried out through the addition of alkali compounds such as lime, potassium hydroxide, and sodium hydroxide or acidic compounds such as phosphoric acid. Interestingly, these compounds have an additional benefit, increasing the final product’s nutritional value. Adding inorganic fertilizers or their precursors is necessary to balance bio-waste derived fertilizer products (Kominko et al. 2019). Technically speaking, the most straightforward procedure consists of mixing the moistened organic raw material with an alkaline co-product such as gypsum, cement, lime, and fly ash. Then the NPK ratio/content is optimized by adding potash, phosphates, and liquid ammonia (Kominko et al. 2019; Gómez-de la Cruz et al. 2020). Several technologies have been proposed to produce OMF, and most of them are based on simple two or three-step chemical processes, including pretreatment. Pathogen elimination could also be carried out

![Diagram of valorisation routes for the conversion of organic and mineral waste into high added value organo-mineral fertilizers](Image)
| Type of stable organic compounds | Manufacturing process | Product properties | References |
|---------------------------------|-----------------------|-------------------|------------|
| Vitamin C-substrate | Mixing vitamin C commercial product as a substrate with mineral fertilizer | Granulated with 21% vitamin and an NPK composition of 18.9:14:4.0 with 100% solubility | Chae et al. (2018) |
| Biochar based bamboo or manure | Mixing 25% of biochar with 15% of organic fertilizer, 10% clay materials, 5% of straw ash, and 2% of magnetite, moistened and homogenized, and then baked in trays in an oven at 80 °C for 3 h | Granulated organo-mineral fertilizer with the following content: 16–40% organic matter, NPK composition 1.72:2.30:3.01, 6.45% Ca, and 2.4% Sulphur | Farrar et al. (2018) |
| Compost | Adding sulfate, compost, and potassium humate with a ratio of [2:10:1 (w/w/w)] | Granulated organo-mineral fertilizer with the following properties: pH: 7.2, NPK composition 2.2:3.02:4.2, C/N ratio of 18.6, and 0.36 available Ca²⁺ and Mg²⁺ | Abd El-Mageed and Semida (2015) |
| Vermicompost | Mixing similar rate of vermicompost with NPK 15-15-15 applied at doses of 100 kg/ha | Organo-mineral fertilizer mixture with the following NPK composition of 16.4:7.6:7.6, the organic part presents 50% of formulated product | Otowoake et al. (2022) |
| Humic acid | A mixture of calcium sulfate, ground rice bran, and humic acid with a ratio of [2:10:1(w/w/w)] | Granulated organo-mineral fertilizer with an NPK composition of 2.81:0.71:3.02, 7.98% Ca²⁺ and 12.49% of humic acids | Rady (2012) |
| Tannic acid | Combining Montmorillonite, Hydroxyl-Al ions, and Tannic acid and mixing them under vigorous stirring with 0.1 M NaOH (10 ml/min) until achieving a pH of 4.5 | Suspension of organo-mineral fertilizer with 22% of carbon and a CEC of 111.2 (meq/100 g) | Buondonno et al. (1989) |
| Biosolid based digested sewage sludge cake | 25% of biosolid, which is dried at 80 °C and treated with enzyme hydrolysis to control pathogens, coated with melted urea (46% N) and ground potash (60% K₂O) | Granulated organo-mineral fertilizer (granule diameter 1.18–5.50 mm) has an NPK composition of 10:4:4 and 15:4:4. Total Cd, Cu and Zn are 0.98 ppm, 268.4 ppm, and 442.7 ppm dry solids, respectively | Antille et al. (2013a, b) |
| Compost and Humic acid | Mixing organic matrixes with NPK 15-15-15 at a basal dose of 66:30:30 kg ha⁻¹ | NPK average content is (1.96:0.62:3.06), while total Fe, Zn, and Mn concentrations are 70.36 and 69 g/kg dry matter | Bakashwain et al. (2013) |
| Biosolid based poultry manure, peat, and straw | Mixing the three organic fractions with diammonium phosphate (DAP) and KCl with a moisture less than 10% | Granulated organo-mineral fertilizer with 37.35% of carbon, an NPK ratio of (9:4:4), 1.78% Mg²⁺ and 0.59% Ca²⁺ | Mazeika et al. (2016) |
| Unstabilized sewage sludge and poultry litter | Sewage sludge is milled, and the ash is mixed with poultry litter and mineral fertilizer. The obtained product was dried at 70 °C for 3 h | Granulated organo-mineral fertilizer with an NPK ratio of (11.5:5.12:16.2) and a Zn content of 566 mg/kg | Kominko et al. (2019) |
by heat treatment, given that the issue of toxic vapor emission is resolved. For example (Jourdain 1996) suggested a methodology for manufacturing solid OMF through processing organic wastes such as sewage sludge and liquid manure. Briefly, OMF granules (2, 3 mm) are produced by combining a mineral mixture obtained from mineral fertilizer and organic mixture (manure and sewage sludge). The generated paste is then granulated, and oven treated at more than 200 °C for less than 80 to eliminate possible pathogens. The ammoniacal vapor is recovered, cooled down, and returned to the mixture. Depending on the used raw organic material, heat treatment may not require elevated temperature, as demonstrated by patent (Antonius and Terlouw 2007). Those authors proposed technology for producing OMF pellets using four different materials, namely an inorganic fertilizer (DAP, MAP, PS, Roch phosphate...), urea, manure (chicken, poultry, cattle) and a lignin compound (ammonium lignosulfonate). Prior to blending, the organic materials are heat-treated at only 75 °C; then the mixture is palletized at a pressure between 90 and 120 bars, leading to an NPK 14-5-8+2MgO+0.5 Fe formulation. The added value of such a product is its slow-release property, which is attributed to the formation of urea-lignin bonds. Alkaline Ammonia Pulse (AAP) is another interesting technology proposed by (Burnham 2015), which enabled the production of what he named an “inorganically-enhanced bio-organic fertilizer” with the following composition NPK SFe 10-10-10+1:20. Such technology is mostly based on varying the pH along the process to obtain a specific desired effect. Briefly, sewage sludge is supplemented with ammonia and lime to rise the pH mixture, which stresses pathogens and increases the N content. The mixture is then transferred to a second reactor where pH is decreased, and P content is enhanced by adding phosphoric acid waste. Ultimately, the granulation process is achieved by adding molasses and a binding agent. (Cabello-Fuentes 2010) developed a technology based on reverse AAP for treating sewage sludge. Compared to the AAP, the process includes a heat-based pretreatment for decontamination purposes. Afterward, sludge pH is reduced up to 2 by adding phosphoric acid, eliminating the remaining pathogens and enhancing P content. The mixture is then transferred to a second reactor where pH neutralization is performed by adding magnesium hydroxide containing lime, which induces tricalcium phosphate and dicalcium phosphate. Finally, the mixture is treated with sulfuric acid, granulated, and neutralized with phosphoric acid, ammonia, and potassium (Kominko et al. 2019). When it comes to formulation, advanced methodologies such as a polymer based-coating technique may be efficiently applied to OMF. For example, Antille et al. (2013b) succeeded in elaborating an OMF product using spray coating. Granules of NPK OMF were produced through granulating 80 °C heated digested sewage sludge and then coating the generated granules via spraying with a liquid mixture containing urea (46% N) and potassium (60% K₂O). More recently, Gonçalves et al. (2020) assayed an OMF formulation based on sugarcane wastes. Briefly, the sugarcane filter cake was composted and supplemented with mineral nutrients, namely, urea, potassium chloride, monoammonium phosphate, boron, and oxy-sulfate. Then OMF pellets (3.9 mm×9.1 mm) were produced after adding an organic polymer. Overall, the methodologies used in the chemical manufacturing of OMF based on organic waste showcase several similarities with the routinely used processes in the chemical fertilizer industry. Mandatory steps such as grinding, granulation, acid treatments, heating, and coating are often reported, which pose the question of economic viability. In other terms, at an equal scale are OMF economically justified compared to chemical fertilizer? This furthers the need for in-depth technical-economical evaluation taking into consideration machinery, labor, consumables, waste collection/transportation, and added value to farmers.

2.2 Production of organo-mineral fertilizers based on co-processing of mineral and organic byproducts

From a theoretical standpoint, OMF technologies are highly suitable for the valorization of mineral waste, especially those generated by the phosphate industry. Such matrices are widely abundant and rich in several fertilizing compounds. Tow mineral wastes are produced along the phosphate value chain (from ore beneficiation to fertilizer production), phosphate washing sludge (PWS), and phosphogypsum (PG) which is the result of the “wet process” used to produce phosphoric acid through the processing of RP by sulfuric acid. PG is the most significant by-product of the phosphate industry. Worldwide production of PG is estimated at between 200 and 250 million tons.
per year, among which only 15% is recycled. Moreover, by 2025 total discarded PG is estimated to reach 8 billion tons (Tayibi et al. 2009). PG is a very low water-soluble acidic powder constituted of oxides of sulfur, calcium, silicon, aluminum, iron, P, silicate, fluorine aluminate, and fluoride phosphate. Although scarce and mainly limited to compost and biochar production, research investigations dealing with PG processing into OMF have shown promising results. For example, Karim et al. (2019) evaluated the possibility of producing a nutrient richer and less toxic biochar (compared to PG) through the coplasma processing of banana peduncles and PG. The operations were carried out in an extended arc thermal plasma reactor using three different plasmagen gases (argon, ammonia, and oxygen). Using argon allowed to obtain biochar with higher potassium (12.7%) and sulfur (13.3–17.8%) contents compared to PG, while the use of ammonia resulted in a lower leachable fraction of fluoride and heavy metals in biochar. In another study, Yang et al. (2015) attempted to address the issue of the by-products of kitchen waste composting (greenhouse gas emission) using PG (10%) as an additive. Results showed that PG significantly reduced methane and ammonia emissions by 85.8% and 23.5%, respectively, without affecting compost maturity. The reduction of gas emission was attributed to a lower pH, higher $\text{NH}_4^+$ concentration, and a higher content of sulfate in the PG treatment, which may simultaneously suppress methanogens and improve the compost agronomic value. Likewise, works of Elfadil et al. (2020) demonstrated that co-composting cattle manure with PG and the waste of the phosphate flotation enhanced the composting process and improved the nutritional value of the final product. Agronomic assays showed that compost-based on PG and phosphate flotation wastes resulted in higher biomass production of chickpea compared to the sole application of compost-based manure. All those studies demonstrated that eco-friendly and simple technologies such as compost or biochar are efficient for developing OMF through processing intricate mineral matrices. Even more straightforward, recently Matveeva et al. (2021) proposed a methodology for the industrial process of PG into OMF via simple mixing of lignin waste sludge (75–80%), PG (20–25%) and mineral NPK. Agronomic trials under controlled conditions revealed that mixing the soil with the OMF in equivalent quantity induced optimal plant growth. It also reduced PG toxicity due to limited strontium assimilation by plant tissue, which was attributed to calcium/strontium competition.

PWS is another important environmental concern of the phosphate industry. It is estimated that 28 tons of PWS are produced in Morocco alone each year (Mobaligh et al. 2021). PWS is usually dumped in decantation basins without prior treatment. Although the importance of such mineral waste, little has been done concerning its valorization into Agri-inputs. The only example is the work of Mobaligh et al. (2021), who investigated the co-composting of PWS, olive mill waste sludge, green waste, and sugar lime sludge. Using PSW at a rate of 20% resulted in better compost quality in terms of hygienic properties, humification process, and nutrient content compared to the single-use of sugar lime sludge. Those results are valuable, but further studies need to be performed to ascertain the technical feasibility of producing OMF from PWS. This latter could plausibly showcase a significant physico-chemical inconsistency due to variation in RP properties and the environmental effect of the decantation basin.

2.3 Development of high added value organo-mineral fertilizers via direct valorization of valuable ore: the case of natural rock phosphate

Low-grade RP is currently gaining significant momentum in the organic farming market as a source of plant nutrients. While highly attractive, RP mainly displays an unavailable P form, and efficacy depends on the rock reactivity and soil pH. Using biological methods in OMF development could enhance RP agronomic efficiency and widen the targeted market as the generated products are highly suitable for producing organically labeled crops. The process used in the development of RP-based OMF is exclusively based on co-composting or organic wastes and RP under reactor systems or composting windrow and may require the addition of microbial inoculum to simultaneously enhance the degradation of recalcitrant organic compounds and rock solubilization. An example of this is the work of Pandey et al. (2009), who showed that the organic matrix based poultry manure with the addition of RP and P solubilizing microorganisms resulted in concentrations up to 2.32 mg g$^{-1}$ of available P in the OMF product. Using
various organic waste (urban waste and plant residues), Naher et al. (2018) reported that co-composting with RP addition increased the P solubilization dynamic. Similarly, the addition of phosphate solubilizing microbes, such as *Aspergillus niger*, *Aspergillus flavus*, and *Trichoderma harzianum* during waste treatment production increased the P availability to almost 8.19% without affecting the decomposition rate (Gaind 2016). Vermicomposting is also a promising technology that can improve P solubilization. Research investigation by Mupondi et al. (2018) demonstrated that using *Eisenia fetida* earthworms during co-composting of RP and a manure-paper mixture resulted in significantly higher resin extractable P, better humification and lower heavy metals contamination. In mechanistic terms, increased P solubilization is attributed to the direct intervention of microbial enzymes such as phosphatase and dehydrogenase (Kutu et al. 2019). In addition, the ligands of stable organic matter compete with P during cation adsorption, which makes P more available in the soil (Pawlett et al. 2015; Tang et al. 2019).

Biswas & Narayanasamy (2006) investigated the enrichment of OMF product using rice straw (C/N = 86.2), low-grade RP (8.62% total P), waste mica (10% total K), and a fungal inoculum (*Aspergillus awamori*), showing optimization of P availability in the OMF final products. Various mixtures were prepared with and without P/K and phosphate solubilizer, notably, 2 concentrations of P and K (2 and 4%) were added to 15 kg of straw rice, which was supplemented with urea to adjust the C/N ratio and cow dung (5 kg per 100 kg straw rice) as a natural inoculum. The obtained results showed that the addition of RP and the fungal inoculum significantly increased the Olsen P content (higher with 4% RP). (Naher et al. 2018) studied the biochemical features of an OMF produced from urban waste, plant residue, and RP. Sugarcane waste was added to enrich the compost with NPK and RP was used at 5 and 8%. Moreover, adding other organic matrices such as (rice straw, mustard waste, and sugarcane waste) into OMF significantly reduced the decomposition rate. More importantly, this product enhanced the overall microbial activity but was more selective toward phosphate solubilizing microbes when RP was added.

Bustamante et al. (2016) investigated the efficiency of developing an OMF by the co-composting process with RP (27% P$_2$O$_5$) and green waste with the addition of elemental sulfur (0.5%). In this study, two concentrations of RP (2.3 and 4.6%) were used, and several green wastes, including palm, prunings, grass (*Lolium perenne L.*) clippings, and a mixture (1:1) of olive tree (*Olea europaea L.*) and conifer. Results showed that the extractable water P increased in all the mixtures. However, such an increase was surprisingly higher in the RP-free treatments. These observations are in line with the works of Biswas and Narayanasamy (2006) and Lu et al. (2014), who reported a reduction of water-extractable P after RP addition due to the precipitation of P with calcium. At the end of the experiment (maturation phase), P release was more significant in the 2.3% RP supplemented treatment, which was attributed to the nitrification process and sulfate addition.

Choosing the correct dose of RP in the OMF-based compost is paramount. The current observations prove that RP concentration and the release of water-soluble P are negatively correlated. Additionally, to other factors such as the nature of the feedstock, the manufacturing process, and chemical features of RP. Theses aspects were well documented by Singh (1985), who studied the effect of RP addition (20.6% P$_2$O$_5$) at 5, 10, and 25% during OMF production using the composting process of farm wastes consisting of grasses, wheat straw, bean, and tree leaves. This author showed that RP addition significantly enhanced the biodegradation of organic matter, which was optimal in the treatment supplemented with 10% RP. Most importantly, a further increase of RP content (25%) reduced the loss of organic matter, which was attributed to the toxic effect induced by salt excess in RP. Moreover, both organic P and citric soluble P were higher at 10% RP supplemented treatment. Such organic P is critical as it represents mostly P entrapped in microbes. This organic P could operate as a slow-release fertilizer due to the slow rate of decomposition. Thus, providing available P to the plant for a more extended period. Overall, the formulated product demonstrated an agronomic efficiency equivalent to single super phosphate.
3 Beneficial effect of organo-mineral fertilizer on soil–plant systems

3.1 The effect of using stable organic matter in organo-mineral fertilizer products on soil physico-chemical properties

Research investigations addressing the influence of OMF on soil physico-chemical properties are scant; however, their predicted effect should be equivalent to the one obtained in trials involving the co-application of stable organic matter (SOM) and mineral fertilizers, which are the main constituent of OMF. For example, co-application of the SOM (vermicompost, compost, and biochar) and mineral fertilizer are reported to improve soil health indicators such as pH, soil organic carbon, total N and cation exchange capacity (CEC) (Tian et al. 2018; Sia et al. 2019; Silva et al. 2019). Soil response is highly dependent on the used raw material quality (Zhu et al. 2014; Hadroug et al. 2019; Hoover et al. 2019). The organic fraction of OMF may indirectly enhance the bioavailability of soil nutrients by adjusting soil pH. For example, in acidic soils, compost-based OMF can have an equivalent effect to lime with respect to reducing soil acidity (Duruigbo et al. 2007; Laird et al. 2010; Mensah and Frimpong 2018). Another frequently reported effect of OMF application is stabilizing the initial CEC values, which is attributed to their high buffering capacity (Yasmeen et al. 2018). Akhtar et al. (2015) and Wright et al. (2008) showed that amending a sandy, loamy soil with OMF based on municipal biosolids composted waste or wood biochar material corrected the soil salinity efficiently. Likewise a co-application of two OMF based on green waste/biosolid compost and biochar in saline-sodic soil decreased the EC value by 79% compared to unamended soil (Chaganti et al. 2015). Such organic matrices also positively affect bulk density parameters concomitantly with improving soil nutrient and SOM content (Qiao et al. 2020).

The high soil CEC depends mainly on soil physico-chemical properties and cations storing properties. The high retention capacity of soil can be significantly improved following the application of stable organic matter such as humic substances and biochar (Indraratna et al. 2007; Karimi et al. 2019). When these fractions interact with soil oxygen and water after an extended period, a higher level of oxidation occurs, thus resulting in an increment of soil negative charges and CEC. Soil organic matter aggregation becomes highly associated with those negative charges (Ouyang et al. 2013; Calvo et al. 2014). Reactive surfaces characterize biochar and humic substances due to reactive functional groups such as (–C–H, –C–O, C=O, –COOH, –NH). Using such fractions during OMF formulation is highly appreciated. The temperature and moisture conditions directly influence the humic acid (HA) polymerization and composition, which could vary drastically. At low temperature and under adequate humidity (Tundra landscape), only 20–45% of soil extractable humic acids can resist acid hydrolysis. However, this value is much higher (64–75%) in standard temperature and moisture conditions (Steppe landscape). Additionally, such environmental conditions affect HA composition. The same authors found that a lesser C: N induced a higher biodegradation resistance and long persistence. Similar results were reported by Veen and Paul (1981), who suggested that soil humic fractions are more resistant to degradation and turnover (up to thousands of years) because of their association with soil mineral colloids. More stability suggests more aromatic cores and more reaction with mineral surfaces, directly increasing soil CEC.

Due to their richness in organic carbon, OMF can be considered an efficient carbon sequestration solution. Such application tends to form a black color with a strong resistance to degradation, unlike the naturally occurring SOM in the environment (Wattel-Koekkoek et al. 2003). Additionally to aromatic structures, SOM also contains aliphatic carbon compounds, easily degraded and oxidized (Dergacheva et al. 2012; Jindo et al. 2014). Adding more SOM may lead to an increase in the soil’s ability to retain plant-available nutrients. The use of OMF based compost and biochar showed the ability to retain cations, and even some anions such as P. These properties make these two organic matrices recoverable in agricultural lands, able to improve crop yield while reducing the impact of environmental pollution induced by nutrient leaching (Schmidt et al. 2014). Overall, the functionalities of the organic matrix depend on the initial organic compounds composition. For example, a very rich substrate in functions such as lignin, phenols, or lipids can theoretically improve the final product’s chemical function, thereby increasing nutrient use efficiency upon soil application. Conversely, the
opposite result could be obtained in a silty-clayey or clayey soil, as the association with this stable organic matter could prevent the plant from accessing these nutrients. Hence, the choice of the organic matrix must be well studied and should depend not only on the soil’s nutritional needs but also on its nature.

3.2 Effect of organo-mineral fertilizers on soil biological traits

Soils are complex mediums that permanently change according to several aspects, including edaphic, pedoclimatic, fertilization, and land use factors, directly affecting indigenous microorganisms' diversity, distribution, and functionalities (Fig. 2). Supplementing the soil with SOM significantly affects its biota and its microbial component (Zhang et al. 2010).

Those variations result from the relative stability and the quality of available carbon in these formulations with the main products presented in (Table 2). The positive effect of OMF on soil microbial activity is attributed to a better soil porosity resulting in higher substrate availability and a more efficient enzymatic activity in the vicinity of organic particles (Głąb et al. 2016; Tang et al. 2019).

Many studies reported that OMF supplemented with phosphate solubilizing microorganisms (PSM) could significantly improve microbial P solubilization, which depends on soil and plant characteristics, feedstock, and the manufacturing process (Jones and Oburger 2011; Saxena et al. 2016; Qian et al. 2019). However, raw materials such as wood, industrial waste, and sewage sludge during OMF development could negatively affect microbial biomass and diversity (Bouhia et al. 2021). The SOM fraction of OMF formulations have a natural ability to absorb inorganic nutrients and some low-weight organic compounds. The low decomposition confers a progressive release of nutrients and carbon sources in the soil. Consequently, each microbial community (actinobacteria, bacteria, and fungi) behaves differently according to the physico-chemical properties of soils and SOM porosity (Quilliam et al. 2013; Jaafar et al. 2014). Li et al. (2020) revealed that OMF based on compost and mineral fertilizer (rice straw and pig manure) improved sugar content and yield attributes of sugarcane compared to the single-use of mineral fertilizers, which was mainly attributed to the higher

Fig. 2 The effect of organo-mineral fertilizers (OMF) on key components of agrosystems
| OMF origin | Application rate | Crop | Effect on plant assimilation | Effect on plant growth | References |
|------------|------------------|------|------------------------------|------------------------|------------|
| OMF based Rice straw compost and NPK fertilizer | Applications of différentes rates: 5 t ha\(^{-1}\), 10 t ha\(^{-1}\), 15 t ha\(^{-1}\) and 20 t ha\(^{-1}\) | Maize | Application Improved Leaf and Root nitrogen, phosphorus, and potassium from 20, 10, 10 mg/kg to 500, 400 and 1200 mg/kg respectively | Leaf and root biomass were improved up to 300% at 5 t ha\(^{-1}\) rate | Sia et al. (2019) |
| OMF based Straw corn biochar and NPK polymer coating | Mineral fertilizer with biochar applied at 5 t ha\(^{-1}\) each cotton season | Cotton | Significantly increased the potassium and phosphorus available to the plant in the 0.20 cm of the soil layer | Enhanced the cotton lint yield by 8.0–15.8%, 9.3–13.9%, and 9.2–21.9% in 2013, 2014, and 2015 respectively | Tian et al. (2018) |
| OMF based compost and humic acid | Compost and humic acid applications with a rate of 18 t ha\(^{-1}\) and 18 kg ha\(^{-1}\), respectively, NPK rating of 66:30:30 kg ha\(^{-1}\) | Pearl-millet | Leaves N, P, and K content enhanced from 13, 5, and 25 g kg\(^{-1}\) dry matter in 19, 6, and 30 g kg\(^{-1}\) dry matter, respectively, for compost and 18, 6, and 31 g kg\(^{-1}\) dry matter respectively for humic acid | The single-use of compost gave the best result compared with other treatments, with a yield production of up to 40% compared to control | Bakhashwain et al. (2013) |
| OMF based vitamin C-substrate and NPK fertilizer | Lettuce | Leaves phosphorus and potassium significantly increased to almost 6 and 7%, respectively | The final yield increased from 127 to 174% compared to the control | Chae et al. (2018) |
| OMF based compost and mineral fertilizer | Cucumber | – | Yield increased by 53.49% compared to the control | Abd El-Mageed and Semida (2015) |
| OMF based organic natural sources and fertilization and seaweed product | Organic, natural (manure and coffee husk) bioclastic granulates and seaweed | Olive tree | Leaves Nitrogen and Magnesium content increased significantly from 17 g kg\(^{-1}\) and 2.2 g kg\(^{-1}\) to 28 g kg\(^{-1}\) and 2.7 g kg\(^{-1}\), respectively | Carvalho et al. (2014) |
| OMF based waste and mineral fertilizer | Organic amendment-based waste and NPK 20:10:10 | Tomato | The use of OMF increased the uptake of micro and macronutrients in tomato leaf tissues | Tomato yield increased up to 200, 600, and 300% using 12.5 and 25 g kg\(^{-1}\) of OMF | Ayeni and Ezeh (2017) |
| OMF based vermicompost and mineral fertilizer | Vermicompost (cow manure) and mineral fertilizer at a rate of 900 kg, 560, and 900 kg, respectively for N, P and K | Tomato | – | Tomato yield increased by 74% compared to the control | Zhao et al. (2020) |
microbial diversity and functions of added SOM fractions. These authors showed that energy metabolism and the abundance of some species, such as *acidobacteria*, *proteobacteria*, *chloroflexi*, and *gemmatimonadetes*, were higher in OMF treatment, which was strongly correlated with the dynamic of soil nutrients. Similarly, using vermicompost extract bacteria species such as *Azotobacter vinelandii*, *Bacillus megaterium*, and *Frateuria aurantia* improved tomatoes yield and quality (Ruiz and Salas Sanjuan 2022). Other works based on predictive metagenomic showed that applying organic inputs (liquid and palletized digestate), OMF-based digestate, and slow-release mineral fertilizers, with equivalent N quantities resulted in significant differences in tomato root-associated microorganisms with respect to diversity and functionality (Caradonia et al. 2019). Such effect was peculiarly striking in the OMF treatments with palletized digested. The number of rhizosphere operational taxonomic units was significantly higher than other treatments, which was attributed to the level of plant-available N that might reduce specific microbial abundance and activity in case of significant availability (mineral fertilizers). Other works showed that co-application of OMF-based compost or biochar and mineral fertilizer improved microbial biomass and reduced N leaching compared to single-use of mineral fertilizer (Trupiano et al. 2017). The application of OMF improved soil organic matter, which increased carbon availability for microorganisms, resulting in a stimulation of microbial activity and its requirement for high nitrogen demand, especially in nitrate. OMF does not only increase plant nutrient concentration and total soil carbon content, but has also been reported to promote biological nitrogen fixation through better nodulation (Coyotl et al. 2018).

Arbuscular mycorrhizal fungi (AMF) are another critical microbial component of agro-systems that may be influenced by OMF application, which may positively or negatively affect nutrient cycling. According to many authors (Warnock et al. 2007; Hale et al. 2013; Mukherjee and Zimmerman 2013; Conversa et al. 2015), root colonization by AMF is affected by SOM depending on the applied doses and properties. AMF is regulated by phytoavailable P in the soil. The higher the P content, the lesser the symbiosis efficiency. As stated previously, the SOM fraction of OMF bestows a slow-release property to the final product. Hence, we could theoretically predict

| Table 2 (continued) |
|---------------------|
| Crop                | Effect on plant assimilation | Application rate | OMF origin | Application | Effect on plant growth |
| Cucumber            | The OMF application improved the cucumber quality by increasing the vitamin C and sugar water contents 14.5% and 25.6%, respectively | 15:15:15         | OMF-based vermicompost and NPK fertilizer | OMF was applied by using 5 g per pot | OMF compared with single poultry manure and NPK fertilizer |
| Moringa             | The use of OMF increased available phosphorus and potassium content in moringa by 26% and 50%, respectively | (3:1), (1:1) of NPK and Husk | OMF compared with an NPK and kola pod husk | The mixture based on (3:1), (1:1) of NPK and Husk | Yield was enhanced by 260 and 400% |

Wang et al. (2021)

Dania et al. (2014)

Makinade et al. (2011)

Dania et al. (2014)

Makinde et al. (2011)

Wang et al. (2021)

Dania et al. (2014)

Makinde et al. (2011)

Wang et al. (2021)
that the use of OMF should result in better AMF functionality and diversity. In a comparative study, Van Geel et al. (2016) investigated the effect of the P sources on AMF features, OMF-based compost and mineral P, and slow-release P fertilizers. The application of organic-based slow-release fertilizer induced higher AMF diversity than its fast release inorganic counterpart in the rhizosphere (dominated by inferior AMF mutualists), which was mainly attributed to soil P content.

3.3 Effect of organo-mineral fertilizers on crop yields and agrophysiological properties

OMF application is often associated with improved crop yield, which is mainly attributed to better nutrient availability in the soil (Fig. 2). According to several research investigations, compared to chemical fertilization, the OMF effect can be directly related to their organic constituents (Table 2). For example, an application of an OMF based on straw, rice composts (5 t ha⁻¹), and mineral NPK significantly enhanced shoot/root nutrient content and the overall biomass of maize compared to the sole application of mineral fertilizer (Sia et al. 2019).

Similarly, Abd El-Mageed and Semida (2015) reported a higher yield (53%) of cucumber treated with an OMF mixture based on sulfate, compost, and potassium humate. As demonstrated by Tian et al. (2018), OMF showcases a long-lasting effect on soil fertility. These authors showed that applying an OMF based on polymer-coated biochar/NPK granules improved cotton yield significantly over three successive harvesting periods (2013, 2014, and 2015), which was attributed to better nutrient retention in the 0–20 cm soil layer. Pawlett et al. (2015) revealed that the application of an OMF formulation based on bio-solids, urea, and potassium with low NPK ratios (10:4:4 and 15:4:4) increased soil fertility through enhancing nutrients availability and retention by 13 and 15% for N and P respectively, compared to a single application of mineral NPK.

The nature of the used organic matter in OMF formulation is essential with respect to the agronomic efficiency of the final product. For example, using non-stabilized organic matter during OMF formulation can result in fast biodegradation due to favorable microbial development conditions, which may alter the slow-release properties of the final product. Additionally, some minerals resulting from biodegradation may contribute actively to the precipitation of these elements. Several works reported that the use of untreated organic matter such as poultry manure, organic waste, or other natural products during OMF formulation could induce a similar beneficial effect (compared to treated SOM) on plant nutrients. According to Ayeni and Ezeh (2017), an OMF based on untreated manure and mineral fertilizer increased tomato yield by 600% compared to unfertilized treatment. Moreover, OMF treatment positively affected soil macro/micronutrients and the nutrient content of tomato shoots. Moreover, Makinde et al. (2011) investigated the effect of a single application of pacesetter’s Grade B and untreated kola pod husk (UKPH), as well as their combination with mineral NPK fertilizer on nutrient uptake of Amaranthus Cruentus (L); these authors assayed several OMF formations based Organic/mineral at different ratios and found that the best P, N, K, Ca²⁺ and Mg²⁺ plant uptake was obtained following the application of UKPH/NPK (75:25) formulation. These results can be related to the high nutrient content in waste, directly related to its N-NH₄⁺ richness. However, a high NH₄⁺/NO₃⁻ ratio could be toxic to soil and plants (Barje et al. 2012; El Fels et al. 2014). Inversely, it was reported that using untreated organic waste could negatively affect plants’ agro-physiological parameters at the early stages of plant development (Kapellakis et al. 2015; Tajini et al. 2020; Bouhia et al. 2022b). Dania et al. (2014) showed that using a mineral NPK and rich P/N poultry manure-based OMF (5 g/pot) decreased stem girth up to 8% compared to the control despite enhancing the nutrient content moringa shoots. The use of unstable organic matter affects the plant growth parameters and can also induce asphyxiation of the soil due to its instability and oxygen consumption. Moreover, the use of such organic compounds could bring a variety of pathogens such as Actinobacillus, Bordetella, Clostridium, Corynebacterium, Escherichia coli, Listeria, Salmonella, Mycobacterium, Streptococcus and Staphylococcus which present a potential danger to consumer health (Lovett et al. 1969; Lu et al. 2003; Stern and Robach 2003; Ngodigha and Owen 2009; Bolan et al. 2010).
| OMF manufacturer/country       | Product commercial name/nutrients ratio | Formulation                          | Product use                                                                 | References (Web ID)                                                                 |
|--------------------------------|----------------------------------------|--------------------------------------|------------------------------------------------------------------------------|-------------------------------------------------------------------------------------|
| Bactogen innovative farming Istanbul/ Turkey | BACTOLIFE HIGH ORGANO (NPK 5-5-5) | Liquid organo-mineral fertilizer     | Used as bottom fertilizer, slow release of nutrients to minimize washing and enhance fertilizer use efficiency | http://www.bactogen.com/eng/world.htm                                                 |
| Humintech Grevenbroich/Germany | POWHUMUS/HUMAGRA 0-0-11/10-0-3          | Granular/Liquid organo-mineral fertilizer by 60%/20% of Humic acid (w/w) | Dealing with physical soil degradation issues such as soil compaction, increased aeration, permeability and water holding capacity and increasing soil CEC | https://www.humintech.com/agriculture/products/overview                             |
| Plantin Specialist in fertilization Courthezon/France | FUBOPLANT (NPK(+MgO) 6-14-5 (+2)) | Granular organo-mineral fertilizer with 55% of organic matter and a C/N ratio of 4.6 | Increase soil organic matter, content, enhance soil structure, increase the CEC and provide a balanced supply of nutrients | https://www.plantin.fr/an/range/organo-mineral-fertilizers.html                        |
| MeMon Netherlands             | NPK 4-6-12+ 3 MgO                      | Granular organo-mineral fertilizer produced from vegetable raw materials and minerals and has 40% of organic matter | There is a high percentage of stable organic matter, up to 90% of organic matter content | http://www.memon.nl/en-gb/Products/Advantages                                            |
| Anorel Hove/Belgium           | NPK: 4-4-4 100% organic                | Granulated organo-mineral fertilizer, mainly based on chicken manure, containing nitrogen, phosphorus, and potassium | NO INDICATION                                                               | https://www.anorel.net/en/products/biomagic                                             |
| Vivekon Nashik/India          | ULTRA-PK® The ratio is not indicated   | Powdered fungicide rich in Phosphorus and Potassium | Controls a broad spectrum of fungi and improves plant immunity. Enhances growth and crop yield and quality | https://www.vivekonexport.com/Home/ProductDetails?pId=23                              |
| Scam Strada Bellaria/Italy    | AZOTOP 30 (NPK 6-0-0)                  | A mixture of peat and humic and fulvic acids with Total nitrogen, 30%, SO₃ (15%), Organic carbon (11%), and 36% moisture |                                                                                   | http://www.scam.it/en/french-catalogue/100                                             |
4 Market, innovation profile, and legislation

Despite a significant diversity of already commercialized products (Table 3), available data on the OMF market size is low. Bridge Market (2020) estimates that the OMF market will reach USD 616 million by 2027, which corresponds to a compound annual growth rate (CAGR) of 4.7% in the forecasting period from 2020 to 2027. Those numbers are trivial compared to the massive market of inorganic fertilizer, estimated at USD 95.27 billion in 2020 (The Brainy Insights 2020), and even pale in comparison to the USD 2.3 billion worth biofertilizer based microbes’ market (Research Market 2017). According to Bridge Market (2020), several factors are hindering the growth of the OMF market, notably the limited analytical value of the organic sources, the absence of data with respect to OMF physico-chemical properties, and the higher production costs. This latter is highly debatable as the cost may vary mainly depending on the source and availability of organic raw materials (produced in-farm or imported), the required machinery, and soil fertility status (Loncaric et al. 2013).

Evaluating the innovation profile of a given technology is helpful to determine key technological trends over a period, as well as gaps and market opportunities. We have thoroughly analyzed patents related to OMF based on wastes from 2000 till 2020 using several patent databases, namely, google patents, World Intellectual Property Organization, Espacenet, Patenscope, Lens, and United States Patent and Trademark Office. The analysis involved the number of patents per year, top countries issuing

---

**Fig. 3** Innovation profile of organo-mineral fertilizer technologies based on a number of patent applications and issued patents from 2000 to 2020, and b Top 10 of the most cited patent
representations of these patents, and the most cited patents (Fig. 3). For example, the grant rate is helpful to understand the date from which the technology protection is established and the rate of successful applications over a period. Figure 3 shows that in the last 20 years, the number of patent applications had remained constant (10–13/year), except for 2002 and 2011, when patent applications reached 24. Similarly, between half and two-thirds of applications are constantly granted.

A ranking of the top countries in which the earliest application was filed reveals that China is the country from which most patents originated with 46 patents between 2000 and 2020, followed by Korea (30), Russia (27), United States (22) and Germany (19). Overall, these data demonstrate that the OMF market is stagnating, which is further corroborated by a low CAGR compared to other segments of the fertilizer market.

In terms of legislation and quality requirements, both the Brazilian commission and the European consortium of the organic-based fertilizer industry (ECOFI) have extensively addressed those aspects. Following their 2014 meeting, the ECOFI proposed a new definition for OMF, which state that “OMF means a complex fertilizer obtained by industrial co-formulation of one or more inorganic fertilizers with one or more organic fertilizers and organic soil improvers into solid forms (except for dry mixtures) or liquids. The organic C and the mineral nutrients must be present in each unit”. From this definition, we can conclude that a clear distinction has been made between OMF and essential blends where all raw materials can still be distinguished. Interestingly, the fertilizer regulation (EC) No 765/2008 categorized the OMF products within the microbial plant biostimulant segment, which can be delivered in two forms: (1) solid form characterized by structural rigidity and resistance to change of shape or volume, and in which atoms are closely related to each other, either in a regular or irregular geometric form. Regarding the contaminant threshold, the OMF content of toxic trace elements should not exceed 1.5; 2; 1; 50; 120, and 40 mg kg−1 dry matter for cadmium (Cd), chromium VI (Cr VI), Mercury (Hg), Nickel (Ni), lead (Pb) and Arsenic (As) respectively. (2) Liquid form refers to a suspension or a solution. A suspension is a two-phase dispersion in which solid particles are maintained in suspension in the liquid phase, and a solution is a liquid free of solid particles. Moreover, the Copper (Cu) and Zinc (Zn) concentration must be lesser than 300 and 800 mg kg−1 dry matter, respectively. Similarly, in the OMF product, the bacterial pathogen charge should be reduced to a minimum of 1000 CFU/g of Salmonella spp. Within the final product. In the case of non-stable OMF, the nitrification degrees must be controlled and should demonstrate a 20% reduction in ammoniacal nitrogen (NH3-N) oxidation 14 days after application at the 95% confidence level. In the case of the Brazilian legislation, quality criteria remain broad, and they mainly suggest that a quality product should have a minimum of 8% organic carbon; 80 mmol kg−1; 10% isolated primary macronutrients (N, P, K), or a mixture (NK, NP, PK, NPK); 5% of secondary macronutrients; 1% micronutrients and 30% maximum moisture (European Parliament and Council 2019).

Regarding safety aspects, ECOFI addressed mainly the heavy metals issue. ECOFI proposition suggested that the contamination limit in OMF should be as follow: Cd concentration should not exceed 3 mg kg−1 dry weight for OMF with P2O5 concentration lower than 5%, similarly to inorganic fertilizer when P2O5 is higher than 5%. The maximum limit of Cr, Hg, Ni, Pb, Cu and Zn is 2, 2, 50, 120, and 600 mg kg−1 dry weight, respectively.

5 Conclusion and future perspectives

The current literature review demonstrates that the concept of OMF is highly promising. Such a novel segment of the fertilizer industry will assuredly gain further attraction as it simultaneously addresses pivotal challenges of the agribusiness, namely food production, and waste management, which aligns with the highly desirable “circular economy.” Nevertheless, further studies are required to address key technical and business challenges. For example, the influence of the composition of the used raw materials in OMF production may play a role as precursor when the humification/polymerization process is dominant. The primary function in this substrate needs to be studied to select the right combination with inorganic fertilizers to improve interactions and provide the possibility of a lengthy association.

During the OMF production process, several interactions occur. Those interactions may be highly
complex and unpredictable, which can hinder the quality consistency of the final product. Therefore, simulation of interaction and modeling of complex valorization routes for the conversion of waste to OMF are required to achieve better optimization of the process.

OMF development through the co-processing of organic waste and phosphate mineral by-products is still scarcely addressed. It should be further investigated as the implication on the phosphate value chain could be substantial.

At the agronomic level, long-term trials are needed to investigate the persistence and evolution of OMF constituents after successive crop cycles and culture rotation and their effect on plants’ agro-physiological traits and soil properties (aggregation, pH, enzymes, microbial activity). Studies focusing on the bio-stimulants properties of OMF are required, namely the effect of OMF on root architecture and development and their effect on plant physiological features. Moreover, the effect of such product on plant tolerance to biotic and abiotic stresses needs to be clarified through conducting targeted studies. OMF positively affects soil biology, biochemistry, and nutrient cycling; hence plant resistance to drought, salinity and pathogen should be affected under OMF fertilization. This will provide further claims that will improve product attractivity.

Regulation should be further clarified. The recommendation should not be limited to contamination level. It should also cover important aspects such as the nature of the used feedstock (treated or untreated), the minimum nutrient content, and the organic/mineral fraction ratio.

Finally, business-wise, the OMF market needs to be better segmented concerning product composition and manufacturers’ claims. There is a wide variety of products for which the agronomic target (crop, soil type, and application method) is unclear. Hence, selecting an appropriate product to meet a specific need is often complex for the consumer. Furthermore, marketing strategies based on farmer intimacy should be adopted to increase end-consumers awareness. This could be done through field demonstration and targeted communication campaign.

Acknowledgements Authors are very grateful for the support of the Agribiosciences program team at the Mohammed6 Polytechnic University.

Authors’ contributions Conceptualization, the design of the review and reviewing: Y.B., M.H., Y.O. and K.L; Y.B and K.L. writes—original draft preparation; C.M. writing participation chapter (2); Y.B and M.E.M.E.B. illustration and reviewing. All authors have read and agreed to the published version of the manuscript.

Funding This project is funded by the OCP innovation Unit, Casablanca.

Conflicts of interest Authors declares no competing interests.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article’s Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article’s Creative Commons licence, unless indicated otherwise in a credit line to the material, this article is intended to be used, shared, adapted, distributed and reproduced in any medium or format, as long as appropriate credit to the original author(s) and the source are given, provide a link to the Creative Commons licence, if you do not modify the content and indicate if changes were made. The images or other third party material in this article are included in the article’s Creative Commons licence, unless indicated otherwise in a credit line to the material. The permitted use, sharing, adaptation, distribution and reproduction in any medium or format, as long as appropriate credit to the original author(s) and the source are given, provide a link to the Creative Commons licence, if you do not modify the content and indicate if changes were made. The images or other third party material in this article are included in the article’s Creative Commons licence, unless indicated otherwise in a credit line to the material. This licence does not permit any use for commercial purposes. For any other use, please obtain permission from the right holders.

References

Abd El-Mageed TA, Semida WM (2015) Organo mineral fertilizer can mitigate water stress for cucumber production (Cucumis sativus L.). Agric Water Manag 159:1–10. https://doi.org/10.1016/j.agwat.2015.05.020

Aguilera E, Lassaletta L, Gattinger A, Gimeno BS (2013) Antifungal activity of phenolic compounds identified in flowers from North Eastern Portugal against Candida species. Future Microbiol 9:139–146. https://doi.org/10.2217/fmb.13.147

Alves CT, Ferreira ICFR, Barros L et al (2014) Antifungal activity of phenolic compounds identified in flowers from North Eastern Portugal against Candida species. Future Microbiol 9:139–146. https://doi.org/10.2217/fmb.13.147

Antille DL, Sakrabani R, Tyrel SF et al (2013a) Development of organomineral fertilisers derived from nutrient-enriched biosolids granules: product specification. In: Am Soc Agric Biol Eng Annu Int Meet 2013a, ASABE 2013a, vol 5, pp 4152–4170. https://doi.org/10.13031/aim.20131620153

Antille DL, Sakrabani R, Tyrel SF et al (2013b) Characterisation of organomineral fertilisers derived from
nutrient-enriched biosolids granules. Appl Environ Soil Sci. https://doi.org/10.1155/2013/694597

Antonius E, Terlouw A (2007) (12) Patent Application Publication (10) Pub. No.: US 2007/0095118A1. 1

Ayalew A, Dejene T (2012) Combined application of organic and inorganic fertilizers to increase yield of barley and improve soil properties at Fereze, in Southern Ethiopia. Innov Syst Des Eng 3(1):10

Ayeni L., Ezeh OS (2017) Comparative effect of NPK 20:10:10, organic and organo-mineral fertilizers on soil chemical properties, nutrient uptake and yield of tomato (Lycopersicon esculentum). Appl Trop Agric 22:111–116. https://doi.org/10.13140/RG.2.2.18726.63049

Bakhashwain AA, Daur I, Abohassan RAA, El-Nakhlawy MA (2014) Properties of organo-mineral complexes formed by different addition sequences of hydroxy-Al, montmorillonite, and tannic acid. Clays Clay Miner 37:235–242. https://doi.org/10.1346/CCMN.1989.0370306

Burnham JC (2015) Organic containing sludge to fertilizer alkaline conversion process. US patent 2015/0020560 A1

Bouhia Y, Hafidi M, Ouhdouch Y et al (2016) Phosphorus availability from rock phosphate: combined effect of green waste composting and sulfur addition. J Environ Manag 182:557–563. https://doi.org/10.1016/j.jenvman.2016.08.016

Cabello-Fuentes J (2010) United States Patent US Patent. United States Pat U S 2:0–10. US007713416B2

Calvo P, Nelson L, Kloooper JW (2014) Agricultural uses of plant biostimulants. Plant Soil 383:3–41. https://doi.org/10.1007/s11104-014-2131-8

Caradonia F, Ronga D, Catellani M et al (2019) Nitrogen fertilizers shape the composition and predicted functions of the microbiota of field-grown tomato plants. Phyto-biomes J 3:315–325. https://doi.org/10.1094/PBIOM-ES-06-19-0028-R

Carvalho RP, Moreira RA, Cruz MCM, Fernandes DROA (2014) Organomineral fertilization on the chemical characteristics of Quartzarenic Neosol cultivated with olive tree. Sci Hortic (amsterdam) 176:120–126. https://doi.org/10.1016/j.scienta.2014.07.006

Chae HS, Noh HJ, Song WS, Cho HH (2018) Efficiency and effectiveness of vitamin C-substrate organo-mineral straight fertilizer in lettuce (Lactuca sativa L.). Chem Biol Technol Agric 5:1–8. https://doi.org/10.1186/s40538-017-0115-7

Chaganti VN, Crohn DM, Šimůnek J (2015) Leaching and reclamation of a biochar and compost amended saline-sodic soil with moderate SAR reclaimed water. Agric Water Manag 158:255–265. https://doi.org/10.1016/j.agwat.2015.05.016

Conversa G, Bonasia A, Lazzizera C, Elia A (2015) Influence of biochar, mycorrhizal inoculation, and fertilizer rate on growth and flowering of Pelargonium (Pelargonium zonale L.) plants. Front Plant Sci. https://doi.org/10.3389/fpls.2015.00429

Costa CFFA, Amorim CL, Duque AF et al (2022) Valorization of wastewater from food industry: moving to a circular bioeconomy. Rev Environ Sci Biotechnol 21:269–295. https://doi.org/10.1007/s11157-021-09600-1

Coyotl M de los AV, Tecpoyotl ZGL, Castro, Engelberto Sandoval Mario ATC, Peralta MAC (2018) The organo-mineral fertilization on the yield of faba bean in soil and hydroponics in protected agriculture. 9:1603–1614

Dania SO, Akpansubi P, Eghagara OO (2014) Comparative effects of different fertilizer sources on the growth and nutrient content of Moringa (Moringa oleifera) seedling in a greenhouse trial. Adv Agric 2014:1–6. https://doi.org/10.1155/2014/726313

Dergacheva MI, Nekrasova OA, Okoneshnikova MV et al (2012) Ratio of elements in humic acids as a source of information on the environment of soil formation. Contemp Probl Ecol 5:497–504. https://doi.org/10.1134/S1995425512050022
Durham TC, Mizik T (2021) Comparative economics of conventional, organic, and alternative agricultural production systems. Economies 9:1–22. https://doi.org/10.3390/economies9010004

El Fels L, Zamama M, El Asli A, Hafidi M (2014) Assessment of biotransformation of organic matter during co-composting of sewage sludge-lignocellulosic waste by chemical, FTIR analyses, and phytotoxicity tests. Int Biodeterior Biodegrad 87:128–137. https://doi.org/10.1016/j.ibiod.2013.09.024

Elfadil S, Hamamouch N, Jaouad A et al (2020) The effect of phosphate flotation wastes and phosphogypsum on cattle manure compost quality and plant growth. J Mater Cycles Waste Manag 22:996–1005. https://doi.org/10.1007/s10163-020-0097-5

Farrar MB, Wallace HM, Xu CY et al (2018) Short-term effects of organo-mineral enriched biochar fertiliser on ginger yield and nutrient cycling. J Soils Sediments 19:668–682. https://doi.org/10.1007/s11368-018-2061-9

Gaid S (2016) Phosphate dissolving fungi: mechanism and application in alleviation of salt stress in wheat. Microbiol Res 193:94–102. https://doi.org/10.1016/j.micres.2016.09.005

Głąb T, Palomska J, Zaleski T, Gondek K (2016) Effect of biochar application on soil hydrological properties and physical quality of sandy soil. Geoderma 281:11–20. https://doi.org/10.1016/j.geoderma.2016.06.028

Gómez-de la Cruz FJ, Palomar-Carnicero JM, Hernández-Escobedo Q, Cruz-Peragón F (2020) Determination of the drying rate and effective diffusivity coefficients during convective drying of two-phase olive mill waste at rotary dryers drying conditions for their application. Renew Energy 153:900–910. https://doi.org/10.1016/j.renene.2020.02.062

Gonçalves CA, de Camargo R, de Sousa, Robson TXS, Roberto CST, Mayara CS, Regina MQL (2020) Chemical and technological characteristics of sugarcane as a function of pelleted organomineral fertilizer with filter cake or sewage sludge sources. bioRxiv. https://doi.org/10.1101/2020.07.16.206136

Hadroug S, Jellali SL, Kwapiszka M, Jeguirim M, Hamdi HKW (2019) Pyrolysis process as a sustainable management option of poultry manure: characterization of the derived biochars and assessment of their nutrient release capacities. Water (switzerland) 11:1–18. https://doi.org/10.3390/w11112271

Hale SE, Alling V, Martinson V, Mulder J, Breedveld GDCG (2013) Chemospore yr the sorption and desorption of phosphate-P, ammonium-N and nitrate-N in cacao shell and corn cob biochars. Chemosphere 91:1612–1619. https://doi.org/10.1016/j.chemosphere.2012.12.057

Hartemink AE, Gerzabek MH, Lal R, McSweeney K (2014) Soil carbon research priorities

Hofland E, Kuyper TW, Comans RNJ, Creamer RE (2020) Eco-functionality of organic matter in soils. Plant Soil 455:1–22. https://doi.org/10.1007/s11104-020-04651-9

Hooover NL, Law JY, Long LA, Kanwar RS, Soupir ML (2019) Long-term impact of poultry manure on crop yield, soil and water quality, and crop revenue. J Environ Manag 252:109582. https://doi.org/10.1016/j.jenvman.2019.109582

Ichami SM, Shepherd KD, Silva AM et al (2019) Fertilizer response and nitrogen use efficiency in African smallholder maize farms. Nutr Cycl Agroecosystems 113:1–19. https://doi.org/10.1007/s10705-018-9958-y

Indraratne SP, Koh TB, Shindo H (2007) Sorption of organic compounds by hydroxy-interlayered clays through chelation and humification processes. Geoderma 139:314–320. https://doi.org/10.1016/j.geoderma.2007.02.009

Jaafar NM, Clode PL, Abbott LK (2014) Microscopy observations of habitable space in biochar for colonization by fungal hyphae from soil. J Integr Agric 13:483–490. https://doi.org/10.1016/S2095-3119(13)60703-0

Jindo K, Mizumoto H, Sawaya Y, Sanchez-Monedero MAST (2014) Physical and chemical characterization of biochars derived from different agricultural residues. Biogeosciences 11:6613–6621. https://doi.org/10.5194/bg-11-6613-2014

Jones DL, Oburger E (2011) Solubilization of Phosphorus by Soil Microorganisms. In: Bünemann E, Oberson A, Frossard E (eds) Phosphorus in Action. Soil Biology, vol 26. Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-642-15271-9_7

Jourdain D (1996) Preparation of organo-mineral fertilisers. Patent FR2757504A1

Kapelakiss I, Tzanakakis VA, Angelakis AN (2015) Land application-based olive mill wastewater management. Water 7:362–376. https://doi.org/10.3390/w7020362

Karim AA, Kumar M, Mohapatra S et al (2019) Co-plasma processing of banana peduncle with phosphogypsum waste for production of lesser toxic potassium–sulfur rich biochar. J Mater Cycles Waste Manag 21:107–115. https://doi.org/10.1007/s10163-018-0769-7

Karimi A, Moezzi A, Chorom M, Enayatizamir N (2019) Application of biochar changed the status of nutrients and biological activity in a calcareous soil. J Soil Sci Plant Nutr. https://doi.org/10.1007/s42729-019-00129-5

Kirchmann H (2019) Why organic farming is not the way forward. Outlook Agric 48:22–27. https://doi.org/10.1177/0030727019831702

Kominko H, Gorazda K, Wzorek Z (2019) Potentiality of sewage sludge-based organo-mineral fertilizer production in Poland considering nutrient value, heavy metal content and phytotoxicity for rapsseed crops. J Environ Manag 248:109283. https://doi.org/10.1016/j.jenvman.2019.109283

Kutu FR, Mokase TJ, Dada OA, Rhode OJH (2019) Assessing microbial population dynamics, enzyme activities and phosphorus availability indices during phospho-compost production. Int J Recycl Org Waste Agric 8:87–97. https://doi.org/10.1007/s40093-018-0231-9

Laird DA, Fleming P, Davis DD et al (2010) Impact of biochar amendments on the quality of a typical Midwestern agricultural soil. Geoderma 158:443–449. https://doi.org/10.1016/j.geoderma.2010.05.013

Lal R (2009) Soils and food sufficiency. A review. Agron Sustain Dev 29:113–133. https://doi.org/10.1051/agro:2008044

Li R, Pang Z, Zhou Y et al (2020) Metagenomic analysis exploring taxonomic and functional diversity of soil microbial communities in sugarcane fields applied with
organic fertilizer. Biomed Res Int. https://doi.org/10.1155/2020/9381506

Liu L, Li C, Zhu S et al (2020) Combined application of organic and inorganic nitrogen fertilizers affects soil prokaryotic communities compositions. Agronomy. https://doi.org/10.3390/agronomy10010132

Loncaric R, Jozo K, Loncaric Z (2013) Mineral or organic fertil-ization: financial aspects. Eur Sci J 1:133–138

Lovett J, Messer JW, Read RB (1969) The microflora of southern Ohio poultry litter. Public Heal Prot Consum Serv Environ Heal 746–751

Lu J, Sanchez S, Hofacre C et al (2003) Evaluation of broiler litter with reference to the microbial composition as assessed by using 16S rRNA and functional gene markers. Appl Environ Microbiol 69:901–908. https://doi.org/10.1128/AEM.69.2.901

Lu WC, Ma YX, Holger B (2014) Technological options to ameliorate waste treatment of intensive pig production in China: an analysis based on bio-economic model. J Integr Agric 13:443–454. https://doi.org/10.1016/S2095-3119(13)60582-1

Mupondi LT, Makenci PNS, Muchaonwerwa P, Mupambwa HA (2018) Vermicomposting manurepaper mixture with igneous rock phosphate enhances biodegradation, phosphorus bioavailability and reduces heavy metal concentrations. Heliyon. https://doi.org/10.1016/j.heliyon.2018.e00749

Makinde EA, Ayeni LS, Ojenyi SO (2011) Effects of organic, organomernal and NPK fertilizer treatments on the nutrient uptake of Amaranthus cruentus (L) on two soil types in Lagos, Nigeria. J Cent Eur Agric 12:114–123. https://doi.org/10.5513/JCEA01/12.1.887

Matveeva VA, Smirnov YD, Suchkov DV (2021) Industrial processing of phosphogypsum into organomineral fertilizer. Environ Geochem Health. https://doi.org/10.1007/s10653-021-00988-x

Mazeika R, Staugaitis G, Baltrusaitis J (2016) Engineered pel-letized organo-mineral fertilizers (OMF) from poultry manure, diammomnium phosphate and potassium chloride. ACS Sustain Chem Eng 4:2279–2285. https://doi.org/10.1021/acssuschemeng.S01748

Mensah AK, Frimpomm KA (2018) Biochar and/or compost applications improve soil properties, growth, and yield of maize grown in acidic rainforest and coastal Savannah soils in Ghana. Int J Agron. https://doi.org/10.1155/2018/6837404

Mobaligh M, Meddich A, Imziln B, Fares K (2021) The use of phosphate washing sludge to recover by composting the leachate from the controlled landfill. Processes. https://doi.org/10.3390/pr9101735

Molina-Peñate E, Artola A, Sánchez A (2022) Organic municipal waste as feedstock for biorefineries: bioconversion technologies integration and challenges. Rev Environ Sci Biotechnol 21:247–267. https://doi.org/10.1007/s11157-021-09605-w

Mukherjee A, Zimmerman AR (2013) Geoderma Organic carbon and nutrient release from a range of laboratory-produced biochars and biochar—soil mixtures. Geoderma 193–194:122–130. https://doi.org/10.1016/j.geoderma.2012.10.002

Naher UA, Sarkar MIU, Jahan A, Biswas JC (2018) Co-composting urban waste, plant residues, and rock phosphate: biochemical characterization and evaluation of compost maturity. Commun Soil Sci Plant Anal 49:751–762. https://doi.org/10.1080/00103624.2018.1435799

Ngodigha EM, Owen OJ (2009) Evaluation of the bacteriologi-cal characteristics of poultry litter as feedstock for cattle. Sci Res Essays 4:188–190

Obalum SE, Buri MM, Nwite JC et al (2012) Soil degradation-induced decline in productivity of sub-saharan african soils: the prospects of looking downwards the lowlands with the sawah ecotechnology. Appl Environ Soil Sci. https://doi.org/10.1155/2012/673926

Olowoake AA, Wahab AA, Lawal OO, Subair SK (2022) Assessing the potential of organic wastes through vermicomposting: a case study with cucumber (Cucumis sativus). Proc Natl Acad Sci India Sect B Biol Sci 92:131–140. https://doi.org/10.1007/s40011-021-01321-3

Ouyang L, Wang F, Tang J et al (2013) Effects of biochar amendment on soil aggregates and hydraulic properties. J Soil Sci Plant Nutr 13:991–1002. https://doi.org/10.4067/S0718-95162013000500078

Pandey AK, Gaidn S, Ali A, Nain L (2009) Effect of bioaug-mentation and nitrogen supplementation on composting of paddy straw. Biodegradation 20:293–306. https://doi.org/10.1007/s10532-008-9221-3

Pawlett M, Deeks LK, Sakrabani R (2015) Nutrient potential of biosolids and urea derived organo-mineral fertilisers in a field scale experiment using ryegrass (Lolium perenne L.). F Crop Res 175:56–63. https://doi.org/10.1016/j.fcr.2015.02.006

Qian T, Yang Q, Jun DCF et al (2019) Transformation of phosphorus in sewage sludge biochar mediated by a phosphate-solubilizing microorganism. Chem Eng J 359:1573–1580. https://doi.org/10.1016/j.cej.2018.11.015

Qiao Y, Miao S, Zhong X et al (2020) The greatest potential benefit of biochar return on bacterial community structure among three maize-straw products after eight-year field experiment in Mollisols. Appl Soil Ecol 147:103432. https://doi.org/10.1016/j.apsoil.2019.103432

Quilliam RS, Glanville HC, Wade SC, Jones DL (2013) Soil biology & biochemistry life in the ‘charosphere’—does biochar in agricultural soil provide a significant habitat for microorganisms. Soil Biol Biochem 65:287–293. https://doi.org/10.1016/j.soilbio.2013.06.004

Rady MM (2012) A novel organo-mineral fertilizer can miti-gate salinity stress effects for tomato production on reclaimed saline soil. S Afr J Bot 81:8–14. https://doi.org/10.1016/j.sajb.2012.03.013

Research Market report (2017) Organic fertilizers market by source (plant, animal, and mineral), form (dry and liquid), crop type (cereals & grains, oilseeds & pulses, and fruits & vegetables), and region (North America, Europe, Asia-Pacific, and RoW)—global forecast to 2022

Reynolds MP, Quilligan E, Aggarwal PK et al (2016) An inte-grated approach to maintaining cereal productivity under climate change. Glob Food Secur 8:9–18. https://doi.org/10.1016/j.gfs.2016.02.002
Zhao F, Zhang Y, Li Z et al (2020) Vermicompost improves microbial functions of soil with continuous tomato cropping in a greenhouse. J Soils Sediments 20:380–391. https://doi.org/10.1007/s11368-019-02362-y

Zhu L, Hu N, Yang M et al (2014) Effects of different tillage and straw return on soil organic carbon in a rice-wheat rotation system. PLoS ONE. https://doi.org/10.1371/journal.pone.0088900

Publisher’s Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.