Waste Biomass Valor (2017) 8:1781–1791
DOI 10.1007/s12649-016-9805-9

ORIGINAL PAPER

The Possibility of Organo-Mineral Fertilizer Production from Sewage Sludge

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Received: 16 June 2016 / Accepted: 19 December 2016 / Published online: 3 January 2017

Abstract A lot of attention has been paid in current literature to sewage sludge due to its increasing amount and problem with its disposal. In the age of expensive energy sources and depletion of natural feedstocks it is necessary to find ways of reusing and recycling waste. Sewage sludge has a high valuable fertilizing potential. It is known as a rich source of nutrients. In addition, it includes a large amount of organic matter, which could facilitate the bioavailability of macro- and micronutrients and improves the soil structure. However, a direct application of sewage sludge to the soil is restricted by heavy metals content. Sewage sludge commonly includes pathogenic microorganisms and toxic compounds. The aim of the study was to determine the state of the art and availability of technology for fertilizers production based on waste, especially on sewage sludge. As sewage sludge from different wastewater treatment plants varies in its chemical composition and physical properties, it is important to find a local solution to the problem of sewage sludge disposal. It has been found that organo-mineral fertilizers (OMFs) derived from sewage sludge and modified by the addition of mineral fertilizers seem to be suitable for application to the soil. Adding acids or alkali agents provide sterilization and binding of the components. Novel OMFs gave a comparable crop yield response as conventional fertilizers. They show a slow release of nutrients, which is the main advantage in relation to mineral fertilizers.

Keywords Organo-mineral fertilizer · Sewage sludge · Phosphorus · Nitrogen uptake

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Introduction

The global population growth will increase a demand for agricultural and food production. It leads to a rising dependence on fertilizer inputs. The world demand for N, P and K is estimated to increase annually by 1.4, 2.2, and 2.6% respectively, in 2014–2018 [1]. P is known as a non-renewable resource which may be exhausted in next 50–130 years [2], according to Dawson and Hilton [3] phosphate reserves will be available for 300–400 years. It is necessary to minimize the loss of P and convert it into a closed cycle.

On the other hand, urbanization and industrialization increase the generation of sewage sludge. Due to the risk which sewage sludge poses to human health and the environment, it should be properly disposed of. More than 11 m tonnes of sewage sludge expected as dried solids were generated in the EU27 in 2010 and it is estimated that in 2020 the quantity will amount to almost 13 m tonnes [4]. There are three main methods for sewage sludge disposal: soil application, landfilling, and incineration. The use of sewage sludge as fertilizer seems to be the best practicable option in most circumstances. Sewage sludge provides a valuable source of major nutrients required for plant growth. Approximately 50% of the solid fraction of sewage sludge is organic matter, which has a significant effect on physical, chemical, and biological properties of the soil in the result of its application. Organic matter improves the soil porosity, increases water retention and movement. Some components of organic matter play an important role in soil aggregation [5]. Addition of organic matter to the soil promotes the decomposition of substances and establishes microbial equilibrium. On the other hand, recycling biosolids to the land presents some challenges, among which are a high content of heavy metals that could accumulate in plants [6], organic pollutants and pathogenic microorganisms. The direct application of sewage sludge makes risk for humans and environment [7].

Despite a relatively high nutrients content in sewage sludge, the concentration of macronutrients is not sufficient to meet crop requirements. In addition, the low N:P ratio, which usually occurred in biosolids, leads to a P build-up in the soil resulting in phosphorus losses and water eutrophication. A lot of experiments on new fertilizers based on waste [8–12] have been reported. This type of fertilizers is a key to improve soil fertility and partly overcome the problem with an increasing amount of waste and by-products. Organo-mineral fertilizers (OMFs) derived from biosolids can significantly reduce costs of sewage sludge disposal. Different technologies are developed for disinfection, sterilization and nutrient-enrichment of sewage sludge in order to use it for balanced granulated fertilizers. Methods for biosolids-derived fertilizers production are usually based on chemical reactions between nutrients in sewage sludge and acid or alkali agents, which are added during the production process; on coating granulated biosolids with urea or just mixing biosolids with dry additives (inorganic fertilizers). It allows to obtain OMFs, which are characterized by gradual nutrients release. OMFs-treated soils showed an increase in organic matter content and nitrogen use efficiency. Studies found the increase of dry matter yield of crops, treated by OMFs [13]. All these account for the fact that biosolids-derived OMFs have a great potential to improve crop and minimize the nutrients losses in the environment.

Current Fertilizer Trends

It is expected that in the next 40 years the demand for food will increase by over 60% as the global population will rise to 9.3 billion in 2050 [14]. Agricultural and food production are among major causes of natural resources depletion. The age of cheap feedstock is over. The prices of natural resources increased by more than 300% between the years 1998 and 2011 [15]. Resource scarcity leads to increasing input and production costs and tightening the market, as demand rises faster than production capacities. The efficient and sustainable use of natural resources could ensure food security.

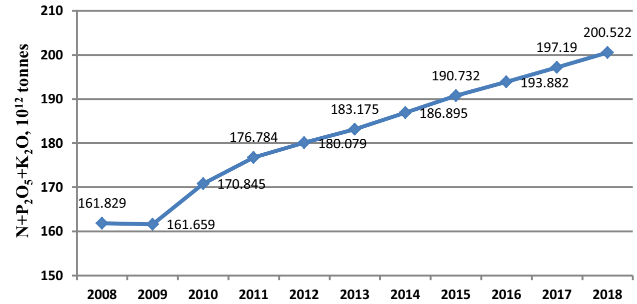

Fig. 1 Global nutrients consumption ($N+P_2O_5+K_2O$) [1]

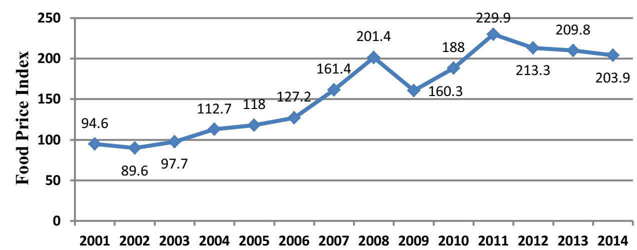

Fig. 2 Annual food price index (2002–2004 = 100) [1]

Fertile soil is the key to balanced commercial-scale production of crops. Very few agricultural soils have a sufficient content of nutrients to mitigate the requirements of crop yields. Most of them become more dependent on a regular application of fertilizers. The total fertilizer consumption ($N+P_2O_5+K_2O$) in 2013 was estimated at 183,200,000 tonnes, with a growth of 1.8% per year, it is forecast to achieve 200,500,000 tonnes by the end of 2018 [1]. Figure 1 presents a predicted world demand for total fertilizer nutrients from 2014 to 2018.

According to FAOSTAT [16] in the year 2009 China was the leader in fertilizer production, accounting for 33% of global production. Other counties with significant participation in the world fertilizer production were United States (10%), India (9%) and the Russian Federation (9%).

Fertilizer prices are expected to be high [17]. The production of commercial fertilizers requires a lot of energy. Near 74% of energy used in fertilizer production comes from natural gas [18]. Natural gas is also the main input in nitrogen fertilizer production. Increasing natural gas prices will lead to rising costs of ammonia [19]. On the other hand, the transportation costs significantly influence fertilizer prices. In 2014 the fertilizer prices index will increase by 15% in comparison with the year 2010 (Fig. 2) [1].

In pre-industrial agriculture nitrogen was the most yield-limiting nutrient. In 1909 Haber–Bosch synthesis of ammonia from its elements was developed and this barrier was broken [20]. The global output of ammonia synthesis rising from 3.7 Mt N in 1950 to about 133 Mt N in 2010.

About 75% of total N is used for fertilizer production [21]. Almost all nitrogen fertilizers are produced initially from ammonia. About 70% of methane is used for ammonia synthesis, which leads to the dependence of nitrogen fertilizer prices on natural gas prices [3].

The world demand for nitrogen fertilizer increased to 113,100,000 tonnes in 2014 in comparison with the year 2013 (111,400,000 tonnes). The increase in nitrogen fertilizers consumption is expected to come from Asia, mainly from China, India, Indonesia and Pakistan, Latin America (Brazil, Argentina, Colombia and Mexico), Europe (Ukraine and the Russian Federation) and from North Africa (Egypt and Morocco) [1].

Recently, almost all phosphate fertilizers have been produced from phosphate rocks, which are known as a limited resource [22]. Mining phosphate rocks used in fertilizer production started from the nineteenth century. Before that time agriculture was based on the application of animal phosphorus-based fertilizers such as guano, manure, bones. Phosphate rocks are ordinarily extracted with the surface mining techniques and its world production capacity is estimated near 165–195 million tonnes per year [23]. 80% of total P_2O_5 is used for fertilizer production, share of detergents is near 5%, animal feeds −7%, food additives −2% and special applications, for example lightning and metal treatment, −3% [24].

Phosphate reserves are far from being uniformly distributed across the world. Top 12 countries produce 95% of total phosphate rock production. The USA, China, and Morocco currently produce two-third of the total phosphate ore [25]. Of these major producers, the Moroccan reserves of phosphate rocks constitute near 50% of the world total. The USA and China hold around 20% of global resources [1].

Potassium is found in various mined and manufactured salts. Potash recovery requires expensive mining techniques, as potassium deposits lay deep under the earth's surface. Global reserves of potassium are expected to be high with respect to the current demand [26]. The major producer of potash fertilizers is Canada, followed by Belarus, the Russian Federation, and China. Potassium fertilizer consumption increased to 31,040,000 tonnes in 2014 and its further annual grow is estimated at 2.6% [1].

Since the year 2000 the pressure on prices of the major P and N fertilizer has increased, which is connected with higher production costs of ammonia and Sulphur. As food production is increasing, the agriculture will become more dependent on mineral fertilizers. There is a rising concern about the availability of nutrients and future feedstock scarcity. The depletion of natural resources is accompanied by inappropriate application of conventional fertilizers polluting the environment. From food security perspectives, the global cycle of nutrients should be taken into account. It is necessary to correct the quantity and quality of fertilizers for soil application, to find alternatives for mineral fertilizers by using waste and by-products [27]. This could help to make balance between agriculture and industry.

Sewage Sludge Characterization

Due to the population growth, urbanization and industrialization, wastewater production as well as the amount of sewage sludge have increased significantly. The problem with treatment and disposal of sewage sludge remains open due to its quantity. A few decades ago municipal sewage sludge was disposed of in seawater or used as fertilizer, the alternative ways of its utilization, like incineration or landfilling, were also used. After the year 1998 the disposal of sewage sludge at sea was prohibited in order to protect the environment, excluding: Japan, the Philippines and the Republic of Korea. The Sewage Sludge Directive 86/278/EEC introduced restrictions on the sewage sludge application to the land because of high concentration of heavy metals. Next Directive – 99/31/EC – restricted the storage of sewage sludge. Alternative methods to landfill and land-spreading are incineration and aerobic or anaerobic digestion [28]. New trends in sludge management, like gasification, pyrolysis, co-combustion and wet oxidation, were generated [29].

Sewage sludge is insoluble residue produced in the wastewater treatment processes and following stabilization process, such as aerobic and anaerobic digestion. Usually aerobic digestion is more profitable in small wastewater treatment plants, while anaerobic one is used in big treatment plants. The characteristic of sewage sludge depends on the nature of the treated sewage and treatment technology. Digested sludge after the process in anaerobic conditions shows a high content of nutrients (primarily nitrogen and phosphorus), which can be used

Table 1 Typical chemical composition of untreated/digested sewage sludge [28]

Item/sludge	Untreated primary		Digested primary	
	Range	Typical	Range	Typical
Total dry solids (TS), %	2.0–8.0	5.0	6.0–12.0	10.0
Protein, (% of TS)	20–30	25	15–20	18
Nitrogen, (N, % of TS)	1.5–4	2.5	1.6–6.0	3.0
Phosphorus, (P_2O_5, % of TS)	0.8–2.8	1.6	1.5–4.0	2.5
Potash, (K_2O, % of TS)	0–1	0.4	0.0–3.0	1.0
pH	5.0–8.0	6.0	6.5–7.5	7.0

as a potential fertilizer source and soil conditioner [30]. Table 1 presents the chemical composition and properties of untreated and digested sewage sludge.

Many researchers reported positive effects of using sewage sludge in agriculture [31–33]. The application of sewage sludge to soil improves its physicochemical and biological properties, which causes better growth of plants. Organic matter content in municipal sewage sludge is usually higher than 50% of dry matter. The application of organic matter in the form of sewage sludge increases soil aggregate formation and stability, improves water infiltration, and increases soil total porosity [34]. The addition of sewage sludge can increase microbial activities, their population, and biomass production.

Sewage sludge is a valuable source of nitrogen and phosphorus. Nitrogen is a component of all proteins and nucleic acids, it is an essential element for plants. The content of total nitrogen in sewage sludge is near 40–50 kg/t, but only a small part of nitrogen is immediately available for plants [35]. Because of mineralization of sewage sludge, nitrogen is transformed into an available form. Phosphorus is an essential element, which is required for many metabolic reactions in plants and animals. The addition of sewage sludge to an agricultural soil increases the content of phosphorus from 2–4 mg/kg to 114 mg/kg and the accumulation of phosphorus is still significant in deeper layers of amendment soil [36].

However, the application of sewage sludge to soil is strictly limited by the presence of heavy metals, toxic compounds, and microbial pathogens [37]. Heavy metals get into sewerage systems generally from industry, mainly from electroplating, chemical industry (manufacturing of organic and inorganic compounds, pharmaceutical industries, dyes and pigment manufacturing), metal processing industries, as well as from runoff and corrosion from sewerage systems [38]. Three approaches to decreasing heavy metals content in sewage sludge have been known. The first one is to control individual sources of heavy metals discharges, the second one is connected with controlling diffuse sources (using lead-free gasoline, copper-free tap water transport systems) and the third one is the removal of heavy metals from sewage sludge. The process of heavy metals removal from sewage sludge consists of four steps: solubilization of heavy metals by changing the pH and oxidation–reduction potential, separating the liquid including mobilized metals, chemical precipitation of heavy metals, and removal from leachate [39].

The accumulation of heavy metals in the soil may have phytotoxic effects on cereals, vegetables, fruits, and fodder crops. Consumption of these commodities by animals and humans can cause health hazards. The concentration of heavy metals in sewage sludge depends on the sewage origin, sewage treatment process and sewage sludge treatment process [40]. The most important factor controlling the mobility of metal compounds in the soil is the pH. The soil pH influences the precipitation and dissolution of mineral-organic complexes and insoluble hydroxides. Zn uptake is greater in the acidic soil than in the alkaline one. The bioavailability of Cu is higher in alkaline soil [41]. Organic matter of sewage sludge is a good adsorptive medium for trace metals in the soil. Soluble organic matter from sewage sludge has two groups of exchange sites: the first one, binding Ca, Mg, Zn, Ni, Co, Mn, Cd, and Fe, and the second one, binding Cu, Pb, and H [34].

Metal content in the soil treated with sewage sludge increases. The ratio of Cd content increase is higher than those for Pb, Cu and Zn [41–43]. Wang and co-worker indicated that the addition of 40 t of sewage sludge per ha in rice production resulted in the build-up of about 4, 5, 2, and 11 times more of Cd, Cr, Ni and Pb, respectively, in comparison with non-treated soil. Pb might be the most absorbed element. Most heavy metals have a good mobility in the soil and are accumulated in roots of plants [44].

According to Rulkens [45], sewage sludge can be used as a resource for energy production by chemical/thermal and biological processes. A complex oxidation of organic and toxic compounds will be achieved as a result of chemical/thermal processes. Heavy metals are immobilized in the ash and can be used for the production of building materials.

Waste-based Organo-mineral Fertilizers

The production of commercial fertilizers requires a large amount of phosphorus, which is a limited resource, or a lot of energy in case of nitric fertilizers, whereas nitrogen is an available resource. The literature abounds with research about organic and organo-mineral fertilizers added to a crop for improving agronomic performance. According to scientists [46–48], the application of organic matter to the soil improves its physical, chemical, and biological properties by reducing mineral sorption of phosphorus, decreasing P transformation in bioavailable forms, decreasing bulk density, and increasing total porosity.

Organo-mineral fertilizer can be defined as "a fertilizer obtained by blending, chemical reaction, granulation or dissolution in water of inorganic fertilizers having a declarable content of one or more primary nutrients with organic fertilizers or soil improver" [49]. Therefore, fertilizers can be produced from different organic and inorganic sources. Akanni [50] reported that the organo-mineral fertilizer composed of municipal waste, poultry and cow manure combined with urea and superphosphate increased the soil organic matter, N, P, K, Ca, and Mg content in the soil under maize, pepper and amaranthus. The crops treated by organo-mineral fertilizer gave the highest values of leaf area, cob weight and grain yield. The same results were received by Audu [51], who investigated organo-mineral fertilizer formulated with an N:P:K (ratio 9:3:3) using urea, rock phosphate, wood ash, neem seed, blood meal, cotton seed cake, manure, and poultry droppings. Using such a fertilizer for rice cultivation had a significant effect on all the growth parameters. Studies carried out by Ayeni [52] confirmed that organo-mineral fertilizer improves the soil fertility. According to his experiment the addition of a small amount of NPK (15:15:15) fertilizer to organo-mineral fertilizer can enhance earlier mineralization of nutrients.

Bello [53] found that composting rock phosphates with agricultural waste increases solubility of phosphates dependent on the kind of organic matter and the rate of decomposition. The organic ligands, which are present in organic matter, compete with phosphorus at the same adsorption sites in soil. It increases the phosphorus release rate from the soil. In this work diammonium phosphate and Sokoto rock phosphate were combined together with different organic sources (palm kernel deoiled cake, sheanut deoiled cake and refuse of palm ground bunch) and applied into the soil; as a result the best performance in all the growth parameters and nutritional content of oil palm were achieved.

The treatment of soil with mineral fertilizers to increase yield might be effective as a short-term solution. One of the most important features of using organo-mineral fertilizers is the "slow release" effect. Paul [54] reported that compost nitrogen was evenly available in each of the three following years during fertilizer treatment. In addition, the release rate of nutrients can be controlled by the diameter of pellets [55, 56]. Tejada [57] compared results of soil treatment with inorganic fertilizers and organic matter as two separate products and organo-mineral fertilizers. He found out that for inorganic fertilizers there were 16.1% more nitrogen losses than for inorganic and organic together. This corresponds to the losses of other macro- and micronutrients.

In Brazil organo-mineral biofertilizer (BIOFOM) was produced using waste from sugar and alcohol industry [12, 58]. The production process of solid granulated organo-mineral fertilizer included mixing the filter cake, boiler ashes and soot, modified vinasse with a mineral source of N, P, and K. The standard method for comparing fertilizers were used to evaluate agronomic potential of biofertilizer. The study was conducted in greenhouse in randomized blocks, using sugarcane, as plant test. Experiment consisted of 25 trials with different fertilizers including control (without fertilizer) and four replications. After 50 days plant samples were taken and analyzed in respect to foliar area, shoot and root dry mass and content of macro- and micronutrients in plant shoot. The study showed the efficiency and economic attractiveness of BIOFOM. It was founded that the fertilization by BIOFOM resulted in increasing the dry matter yield four times. The N, P, and K content in an aerial part of the tested plants increased more than 6, 9, and 12 times, respectively, in comparison with the control sample [12]. Organo-mineral fertilizers promoted increasing crop yields, improved physicochemical properties of the soil, cation exchange capacity and porosity. The BIOFOM treatment caused a greater accumulation of phosphorus in plant shoot than in the control sample. In addition, a part of phosphorus in BIOFOM was not available for 45 days after use. It confirms that organo-mineral fertilizers have a slow release of nutrients.

There is a lack of information about physical properties of organo-mineral fertilizers. However, understanding the dependence between physical properties of organo-mineral fertilizers and N, P, and K content, organic matter type and manufacturing process allows to predict its behavior while transporting, storage, and handling. Physical properties can also be used to control the timing and rate of granule dissolution and, consequently, nutrient diffusion.

Organic matter content has the most significant effect on physical parameters of organo-mineral fertilizers [59–61]. With an increasing content of organic matter total porosity and tensile strength are also increasing, whereas such parameters as bulk density, granule density and the angle of repose decrease with an increasing organic matter content in fertilizers. The tensile strength depends on granule density and free water content.

Organo-mineral Fertilizers with Sewage Sludge

Numerous technologies of fertilizer production from sewage sludge have been developed. An important feature in fertilizer production from such waste is disinfection of sewage sludge, which usually occurs by adding alkali compounds (lime, kiln dust, potassium hydroxide, sodium hydroxide) or acids (sulphuric acid, phosphoric acid or its mixture). Furthermore, the addition of these agents increases the nutrient content in a fertilizer product. Often the need for adding inorganic fertilizers or their precursors exists when balanced biosolids-derived fertilizers are produced.

Simpler technologies are based on mixing sewage sludge, usually characterized by water content not less than 70%, with some by-products like gypsum, which is widely-used as corrective substance [62], cement kiln dust, lime kiln dust, hydrated lime [63], fly ash from coal-fired boilers [64], coal waste [65]. When sewage sludge is converted to fertilizers, it usually has to lower the nutrient content. To optimize the N:P:K ratio potash, phosphates and liquid ammonia could be added [66].

Patent EP 2,653,455 [67] describes the technology of organo-mineral fertilizer production from post-fermentation waste in a suspension form. Waste from biogas plants, containing 5–40% of dry weight, was mixed with lime in a water jacket pressure reactor (2.0 MPa). Such conditions allowed for rapid hydrolysis and denaturation of proteins and cellular structures. Then grinded magnesium carbonate and concentrated phosphoric acid were added. The mixing was conducted within 30 min, the temperature exceeded 150 °C.

The usage of sewage sludge is connected with a high content of heavy metals which restrict its application to the soil without treatment. In patent PL 169,896 [68] basaltic detritus has been used for heavy metals transformation in slightly soluble compounds. Basaltic detritus acts like a natural sorbent and ionic exchanger with strong affinity for metal ions and its hydroxides. Post-fermentation waste (18% dry weight content) was mixed with cement dust from electrostatic precipitator which consisted of 34% of CaO, partially calcined dolomite and basaltic detritus. Partially calcined dolomite comprised $CaCO_3$ and MgO; the former acts as a soil pH stabilizer after applying such fertilizer to cropland.

Generally fertilizers are produced in granular or pelleted forms. It makes them easy to spread, transport and store. In fertilizer production from biosolids it is important to maintain nutrients in organic matrix. A method of preparing homogeneous biosolids-derived fertilizers is described in patent US 2014/0223979 [69]. The production process consisted of a few steps: premixing wet sewage sludge cake with macro- and micronutrients in mixer I, which could be a pug mill or plow mixer, mixing homogeneous mixture with recycled dried granules or pellets of a fertilizer product in mixer II, granulating or pelleting and drying in a rotary drum or heated screw drying system. The water content in sewage sludge cake is sufficient to incorporate nutrients into the homogeneous mixture. Macronutrients could be chosen from a group of urea, ammonium nitrate, ammonium sulphate, diammonium phosphate, monoammonium phosphate, potassium chloride, potassium sulphate, potassium nitrate, etc.

In the United States of America the method of treating waste and converting it into valuable fertilizers—Alkaline Ammonia Pulse (AAP) process—was developed [70]. The AAP process is based on mixing sewage sludge to form thixotropic material, deodorizing, addition of alkali agents, ammonification, acidification, and granulation of the obtained product.

The first step can be conducted in plow blender dual-shafted pug mill or another vigorous mixer. In order to deodorize the mixture, chlorine dioxide, potassium or calcium ferrate could be used. Ferrate is a very strong oxidant, which not only oxidizes organic odors and amins, but also decomposes proteins and other organic molecules. Lime kiln dust, as an alkali agent, was added to the reactor, which resulted in the pH rising to 12 and higher. The next step was adding 9% aqueous ammonia to the mixture for disinfection and increasing nitrogen concentration. Such a pH value and ammonia presence cause chemical stress for microorganisms, which makes them more sensitive to subsequent acidification. Acidification took place in the second mixer, wherein waste phosphoric acid (65% P_2O_5) was added to the mixture. This process reduced the pH value below 7 and caused the formation of ammonium phosphates. Optionally, in this step different inorganic fertilizers (urea, potash, ammonium nitrate, ammonium sulphate, etc.) could be added in order to increase the nutrient value of a final product. Further, granulating agents like industrial molasses and proprietary binding agents were added to facilitate converting the mixture into spherical granules (2.0–3.5 mm). The final step in the AAP process was fertilizer drying and sieving. It is possible to obtain organo-mineral fertilizer with composition 10:10:10:0:1:20 (N:P:K:S:Fe:Organic matter).

A similar technology is described in patent US 7,713,416 [71], which is characterized by converting liquid sludge to granular fertilizer with high nutrient content. Disinfection of sludge was conducted by heating at a temperature 70 °C. Next, the sludge was fed to a static mixer and phosphoric acid was added. As a result, the pH value decreased to less than 2.0, which caused the destruction of pathogens. The mixture was transferred to the agitated tank and mixed within 30 min. For neutralization lime slurry consisting of magnesium hydroxide was fed to the second agitated tank. Due to the reaction between phosphoric acid and lime slurry, tricalcium phosphates (85%) and dicalcium phosphates (15%) were obtained. The technique includes a filtration step, which allows to reduce 50% of the water content. After crumbling, the sludge cake was fed to pug mill, where a reaction with sulphuric acid took place. Water content of the mixture was reduced to 90% as a result of an exothermic reaction. The product was granulated with recycled fines, pre-neutralized phosphoric acid, anhydrous ammonia and potassium salts. The obtained fertilizer was dried and classified.

A pipe-cross reactor, which was widely used in the past for NPK fertilizer production, could be used for treating waste and converting it to granular fertilizer [72]. First, sewage sludge should be mixed with water to form slurry suitable for pumping. Next, the slurry was transferred to the pipe-cross reactor, wherein ammonia, sulphuric and phosphoric acids were added. Due to the neutralization process, the temperature reached 149 °C, which caused sterilization and deodorization of the mixture. Granulating system was provided with an ammonia sparger allowing a complete reaction between the acid and the base. Melt was sprayed onto fine recycled particles in the granulator, the obtained granules were fed into the rotary dryer and then they were screened into fines, product, and oversize material. The fines and oversize material were recycled in the process. Potash could be added to the granulator during the melting process. The composition of fertilizer, obtained by the presented method, had an NPK composition 12:3:6.

In the United Kingdom new biosolids-derived organo-mineral fertilizers for an application in grassland and arable crops were developed. Such a product can overcome a problem of nutrients cycling between urban and agricultural ecosystems. OMFs were produced in two formulations of an N:P:K ratio: 15:4:4 (OMF_{15}) and 10:4:4 (OMF_{10}). Biosolids were used as a core of the OMF, as a slow-release nutrients source. The addition of urea and potash was applied to raise the concentration of N and K, as the content of nutrients in biosolids is not sufficient to meet the requirements of crops. Urea was chosen as a less expensive source of N compared with ammonium nitrate, and due to a lower explosive risk during mixing with dried sewage sludge. P was not added to new OMFs, which allowed to decrease the N:P ratio in biosolids and the general imbalance of nutrients, which in turn could lead to the build-up of P in the soil.

At first, granules were dried to achieve 95% of dry solids content and then sieved. Biosolids of between 3 and 6 mm in diameter were sprayed with urea (46% N) in the presence of steam (95–100 °C) to form the coating. The spraying process was carried out in a rotary drum mixer, where ground potash (60% K_2O) was added at the same time. Air drying followed the spraying of urea in order to dry the coatings [73]. The chemical analysis of OMFs and biosolids is shown in Table 2.

Heavy metals contents of biosolids-derived OMFs were lower than the recommended values. The OMFs had a low concentration of soluble P, which corresponds with phosphorus forms present in biosolids and OMFs not available for plant uptake. Field studies by Antille [74] confirmed that the majority of P in OMFs is not readily available. This follows from phosphorus removal techniques used in the wastewater treatment process. Salts of Fe are usually used for the precipitation of P, as a result Fe-phosphates unavailable for plant are formed. This was also confirmed in the research of O'Connor [75].

Sewage sludge, which underwent the biological P removal, showed a lower P phytoavailability than biosolids after a conventional treatment process. The P uptake was about 25% lower in relation to the triple superphosphate. However, Hogan [76] highlighted that Fe-phosphates can react with soil preferentially forming Fe-hydroxides, which results in P release in plant available forms.

Crop yields depend on the nitrogen uptake, which is influenced by readily available N. During field studies it was found that the largest increase of soil mineral nitrogen was reached after the first 30 days of the OMFs treatment. It was probably connected with a rapid release of NH_4^+-N present in the coated granules. The fact that soil mineral nitrogen in OMF-treated plots achieved approximately the same value as in urea-treated plots after 90 days after application confirms a slow nitrogen release from biosolids. A soil analysis conducted 120 days after the OMFs treatment showed the decrease of soil organic nitrogen; this can be attributed to the N-immobilization and gaseous losses, which are the result of denitrification process. The losses of nitrogen resulting from the volatilization of ammonia can occur within a surface application of fertilizers [77]. A correlation between nitrogen uptake and nitrogen rate was observed. Meteorological factors and a type of soil also have a significant influence on nitrogen uptake. A high content of organic matter in the soil promotes a larger amount of soil mineral nitrogen [78]. It is important to understand the availability of nutrients in the soil treated with organic materials, which is necessary in terms of return applied nutrients and environmental protection.

The application of biosolids and OMFs increases soil organic matter, which leads to an increase of microbial biomass. The large C content in biosolids and OMFs improves the provision of substrates needed for proliferation of microorganisms. It could promote a greater immobilization degree of nutrients in the soil microbial community [79].

Soil treatment with OMFs derived from sewage sludge gives a crop yield response comparable to that of

Table 2 Characterization of OMFs and biosolids [49]

Fertilizer material determination	Biosolids granules	OMF_{15}	OMF_{10}
Total N (% DS)	4.5 ± 0.73	13.0 ± 2.75	9.0 ± 1.55
Total P_2O_5 (% DS)	5.5 ± 0.97	3.8 ± 0.23	4.3 ± 0.52
Total K_2O (% DS)	0.2 ± 0.07	3.2 ± 0.92	3.0 ± 0.61
Total Cd (mg kg^{-1} DS)	1.20 ± 0.03	0.98 ± 0.07	0.98 ± 0.15
Total Cu (mg kg^{-1} DS)	329.3 ± 11.6	268.4 ± 10.7	264.2 ± 11.0
Total Zn (mg kg^{-1} DS)	493.0 ± 5.1	422.7 ± 3.8	422.2 ± 5.6
Soluble P (% DS)	0.20 ± 0.05	< 0.10 ± 0.02	< 0.10 ± 0.02
$N:P_2O_5$ ratio	0.80 ± 0.29	3.4 ± 0.75	2.1 ± 0.41

Table 3 The comparison of known technologies for organo-mineral fertilizers from sewage sludge

	Type of sewage sludge	Technological operations	Product
EP 2,653,455 [67]	Post-fermentation sewage sludge	Adding CaO, $MgCO_3$ and H_3PO_4 Mixing in acid-proof hermetic reactor with water jacket	Suspension of organo-mineral fertilizers with the following content: 2–9% MgO, 2–16% CaO, 5–50% P_2O_5, 5–25% organic matter
US 2014/0223979 [68]	Primary and/or secondary sludge sourced from aerobic digestion/combination of aerobic and anaerobic digestion	Mixing sewage sludge cake with nutrients selected from nitrogen, phosphorus and potassium compounds Granulation or pelleting dried mixture Recycling the portion of granules/pellets to mixer	Granulated/pelleted biosolids fertilizers product with NPK composition 4–15:1–10:4–15
US 2015/0020560 [70]	Untreated dewatered biological sludge/ dewatered (25% of solids) biosolids	Converting sludge into thixotropic material Adding alkaline agents Ammonification step in pugmill Acidification step in second mixer Adding straight mineral fertilizers and granulating agents Granulation and screening Recycling fines to mixer	Granulated inorganically-enriched bioorganic fertilizer with composition: 6–16% N, 4–14% P_2O_5, 6–10% K_2O, 1% Fe, >20% organic matter
US 7,713,416 [71]	Liquid sludge (78% of moisture)	Drying sludge Mixing with mineral acids in static mixer Neutralizing sludge with lime slurry in agitated tank Filtering under high pressure Crumbing obtained cake and adding H_2SO_4 Mixing with ground recycled fines in ribbon mixer Granulation with anhydrous ammonia, potassium salts and pre-neutralized H_3PO_4	Granulated fertilizer with 30–50% NPK content
US 2010/0018823 [72]	Sewage sludge	Mixing sewage sludge in agitation tank to form slurry Mixing with acid (H_2SO_4/H_3PO_4) and ammonia in pipe-cross reactor Spraying melt from pipe-cross reactor on recycled fines in rotating drum granulator with addition of KCl	Granulated fertilizer with NPK composition 12:3:6
Antille et al. [49]	Drying digested sewage sludge cake	Sewage sludge cake drying in tumble dryer Coating sludge granules with melted urea and ground potash	Granulated organo-mineral fertilizer with NPK composition 10:4:4 and 15:4:4
Deeks et al. [10]	Drying digested sewage sludge cake	Sewage sludge cake drying Spraying with melted urea on biosolids granules	Granulated organo-mineral fertilizer with composition: 14.08% N, 3.74% P_2O_5, 0.05% K_2O

conventional fertilizers like urea and ammonia nitrate [10, 80]. Deeks [10] used OMFs derived from sewage sludge for improving performances of cereal, oilseed rape and bean within 3 years. The technology of OMFs production was similar to the technology in Antille's [49] studies. Digested dried sewage sludge granules (3–6 mm in diameter) were sprayed by melted urea in a rotary drum mixer. Muriate of potash as a source of potassium was added separately directly to the soil together with OMFs.

As a result of field studies, the nutrients release characteristics and fertilizer formulation indicate a potential for further application of OMF products to the soil. An advantage of OMF is that mineral components are protected by binding and adsorption of organic components. The coating of OMF granules with urea provides a quick release of NH_4^+-N to the soil. Nutrients release from the biosolids core occurs later, as the organic-N fraction is very stable and needs more time to become available. This ensures longer efficiency of organic-based fertilizer in relation to mineral fertilizers which work only for a short time.

The comparison of main technologies for fertilizer production from sewage sludge is presented in Table 3.

It should be highlighted that both treated post-fermentation sewage sludge and untreated sludge can be used for organo-mineral fertilizers. Sterilization and disinfection of untreated sewage sludge occurred after the addition of ammonia or other alkali agents (CaO, $Ca(OH)_2$, KOH, NaOH, cement kiln dust) and/or acids [70–72]. A sudden increase or decrease in the pH causes stress in microorganisms and results in their reduction. Nevertheless, such technologies include more steps, which leads to an increase of operating costs, and are complicated from a technical point of view. During technological processes chemical reactions taking place result in the formation of mono- and dihydrogen phosphates of calcium [66] or dicalcium phosphates [71]. Mineral fertilizers, which were added to sewage sludge cake and resulted in homogeneous fertilizers, will provide ready-available nutrients for plants during application in the first period and nutrients from sewage sludge will be available during the next periods after decomposition of organic matter. Such slow-release fertilizers are more efficient than conventional straight fertilizers and can reduce nutrient losses to the environment. An interesting solution for slow-release fertilizers is coating biosolids with urea [16, 49] but during a technological process the losses of nitrogen occurred. In most technologies [16, 49, 68–72] organo-mineral fertilizers are produced in a granulated or pelleted form, which is beneficial for spreading. An overview of existing technologies showed that sewage sludge should be treated as secondary raw materials and can be successfully used for organo-mineral fertilizer production. It is an optimal solution for sewage sludge disposal especially for small wastewater treatment plants. However, each wastewater treatment plant should be approached individually, as sewage sludge from different WWTPs will be characterized by different properties. The heavy metals content is an important issue in applying sewage sludge for fertilizer production and a proper proportion of sewage sludge and other components should be selected to achieve balanced fertilizers fulfilling appropriate requirements.

Conclusions

Due to a large amount of still increasing sewage sludge there is a problem with its disposal. As sewage sludge is rich in nutrients and organic matter, it can be effectively used for the production of organo-mineral fertilizers. On the other hand, untreated sewage sludge contains a high concentration of heavy metals and pathogenic microorganisms. Different alkali compounds (lime, kiln dust, potassium hydroxide, sodium hydroxide) or acids (sulphuric acid, phosphoric acid or its mixture) are usually used in fertilizer production process in order to disinfect and deodorize sewage sludge. The technology of organo-mineral fertilizer production from sewage sludge often includes an addition of mineral fertilizers or other wastes (gypsum, cement kiln dust, lime kiln dust, waste phosphoric acid) as sources of N, P, K, Ca, Mg, etc. It allows to obtain balanced fertilizers with an optimal N:P:K ratio. Basaltic detritus and coal waste can be added to sewage sludge in order to adsorb heavy metals and transform them into hardly soluble compounds. After the sterilization and modification of product composition usually granulation and drying occur. Granulated or pelleted fertilizers are easy for spread, transportation and storage.

Organo-mineral fertilizers can be produced by mixing sewage sludge with additives in pug mill, plow mixer or other vigorous mixers and also by coating the granulated sewage sludge with melted urea. As a result gradual-release NPK organo-mineral fertilizers are obtained. Physical characteristics of a product allow for using standard equipment for application to the soil.

OMFs give similar crop yield responses to conventional fertilizers. OMFs application to the soil increases soil organic matter and soil mineral nitrogen, yet it does not influence significantly heavy metals contents in the soil.

Biosolids used for fertilizer production can reduce the costs of sewage sludge disposal and reliance on mineral fertilizers. It is a step towards a Circular Economy policy focused on environmentally-friendly and resource-efficient society by re-using and recycling materials and making a closed-loop system.

References

1. Food and Agriculture Organization of United Nations: Worlds Fertilizer Trends and Outlook to 2018. Food and Agriculture Organization of United Nations, Rome (2015)
2. Cordell, D., Drangert, J., White, S.: The story of phosphorus: global food security and food for thought. Glob. Environ. Change **19**, 292–305 (2009)
3. Dawson, C.J., Hilton, J.: Fertilizer availability in a resource-limited world: production and recycling of nitrogen and phosphorus. Food Pol. **36**, S14–S22 (2011)
4. Milieu Ltd., WRc, RPA: Environmental, economic and social impacts of the use of sewage sludge on land, Final report, Part II: Report on Options and Impacts (2010).
5. Guidi, C.: Relation between organic matter of sewage sludge and physicochemical properties of soil. In: L'Hermite P. et al. (eds.), Characterization, Treatment and Use of Sewage Sludge, pp. 530–544. Springer Netherlands (1981).
6. McBride, M.B.: Toxic metals in sewage sludge-amended soil: has promotion of beneficial use discounted the risks? Adv. Environ. Res. **8**(1), 5–19 (2003)
7. Goss, M.J., Tubulleh, A., Gorahoo, D.: A review of the use of organic amendments and the risk to human health. Adv. Agron. **120**, 275–379 (2013)
8. Mazeika, R., Staugaitis, G., Baltrusaitis, J.: Engineered pelletized organo-mineral fertilizers (OMF) from poultry manure, diammonium phosphate and potassium chloride. ACS Sustain. Chem. Eng. **4**, 2279–2285 (2016)
9. Rao, J.R., Watabe, M., Stewart, T.A., Millar, B.C., Moore, J.E.: Pelleted organo-mineral fertilisers from composted pig slurry solids, animal wastes and spent mushroom compost for amenity grasslands. Waste Manage. **27**, 1117–1128 (2007)
10. Deeks, L.K., Chaney, K., Murray, C., Sakrabani, R., Gedara, S., Le, M.S., Tyrrel, S., Pawlett, M., Read, R., Smith, G.H.: A new sludge-derived organo-mineral fertilizer gives similar crop yields as conventional fertilizers. Am. J. Plant Sci. **3**, 1708–1721 (2012)
11. Wiater, J., Żebranowicz, E.J.: Fertilization value of the granulate made from sewage sludge. Pol. J. Chem. Technol. **7**(2), 80–84 (2005)
12. Oliverio, J.L., Boscariol, F.C., Mantelatto, P.U.: Integrated production of ogranomineral biofertilizer (BIOFOM) using by-products from the sugar and ethanol agro-industry, associated with the cogeneration of energy. Sugar Tech. **13** (1), 17–22 (2011).
13. Antille, D.L., Sakrabani, R., Godwin, R.J.: Field-scale evaluation of biosolids-derived organomineral fertilisers applied to ryegrass (Lolium perene L.) in England. Appl. Environ. Soil Sci. (2013). doi:10.1155/2013/960629
14. Lee, R.: The outlook for population growth. Science. **333**, 569–573 (2011)
15. Ecorys: Mapping resource prices: the past and the future. Summary Report–Final Report, Rotterdam (2012)
16. Food and Agriculture Organization of United Nations, Statistic Division (2011).
17. European Commission, JRC Scientific and Policy Reports. Fertilizer markets and their interplay with commodity and food prices. European Commission, Luxembourg (2012)
18. Blanco, M.: Supply of and Access to Key Nutrients NPK for Fertilizers for Feeding the World in 2050. UPM, Madrit (2011).
19. Bartels, J.R.: A Feasibility Study of Implementing an Ammonia Economy, Iowa State University, Iowa (2008)
20. Smil, V.: Nitrogen and food production: proteins for human diets. AMBIO **31**(2), 126–131 (2002)
21. Smil, V.: Nitrogen cycle and world food production. World Agr. **9–13** (2011).
22. Heckenmuller, M., Narita, D., Klepper, G.: Global Availability of Phosphorus and its Implications for Global Food Supply: An Economic Overview. Kiel Institute for the World Economy, Kiel (2014)
23. Steen, P.: Phosphorus availability in 21 century. Management of non-renewable resource. Phosphorus and Potassium **217**, 25–31 (1998).
24. Scholz, R.W., Ulrich, A.E., Eilitta, M., Roy, A.: Sustainable use of phosphorus: a finite resource. Sci. Total Environ. **461–462**, 799–803 (2013)
25. Cocker, M.D., Orris, G.J.: World Potash Developments, in, Conway, F.M., ed., Proceedings of the 48th Annual Forum on the Geology of Industrial Minerals, Phoenix, Arizona, April 30–May 4, 2012. Arizona Geological Survey Special Paper #9, Chap. 1, 1–16 (2013).
26. Cooper, J., Lombardi, R., Boardman, D., Carliell-Marquet C.: The future distribution and production of global phosphate rock reserves. Resour. Conserv. Recy. **57**, 78–86 (2011).
27. Buckwell, A., Nadeu, E.: Nutrient Recovery and Reuse (NRR) in European agriculture. A review of the issues, opportunities and actions. Commission of European Communities, Brussels (2016)
28. Fytili, D., Zabaniotou, A.: Utilization of sewage sludge in EU application of old and new methods—a review. Renew. Sust. Energ. Rev. **12**, 116–140 (2008)
29. Cieślik, M.B., Namieśnik, J., Konieczka, P.: Review of sewage sludge management: standards, regulations and analytical methods. J. Clean. Prod. **90**, 1–15 (2015).
30. Arthurson, V.: Proper sanitization of sewage sludge: a critical issue for a sustainable society. Appl. Environ. Microbiol. **74**(14), 5267–5675 (2008)
31. Seleiman, M., Santanen, A., Manninen-Egilmez, P. et al.: Sewage sludge as nutrient source for bioenergy crops. Maataloustieteen Päivät, Jokioinen, p.5 (2010)
32. Mtshali, J.S., Tirunech, A.T., Fadiran, A.O.: Characterization of sewage sludge generated from waste water treatment plants in Swaziland in relation to agricultural uses. Resour. Environ. 4 (4),190–199 (2014).
33. Sohaili, J., Zaidi, N.S., Loon, S.C.: Nutrients content of sewage sludge and its utilization towards horticulture plants. JETEAS **3** (1), 81–85 (2012).
34. Usman, K., Khan, S., Ghulam, S., Khan, M.U., Khan, N., Khan, M.A., Khalil, S.K.: Sewage sludge: an important biological resource for sustainable agriculture and its environmental implications .Am. J. Plant Sci. **3**, 1708–1721 (2012)
35. Pakhnenko, E.P., Ermakov, A.V., Ubugunov, L.L.: Influence of sewage sludge from sludge beds of Ulan-Ude on the soil properties and the yield and quality of potatoes. Mosc. Univ. Soil Sci. Bull. **64** (4), 175–181 (2009).
36. Nyamangara, J., Mzezewa, J.: Effect of long-term application of sewage sludge to a grazed grass pasture on organic carbon and nutrients of a clay soil in Zimbabwe. Nutr. Cycl. Agroecosys. **59**, 13–18 (2001)
37. Lu, Q., He, Z.L., Stoffella, P.J.: Land application of biosolids in USA: a review. Appl. Environ. Soil Sci. **2012**, 11 p. (2012).
38. Andreoli, C.V., Sperling, M., Fernandes, F.: Sludge Treatment and Disposal. IWA Publishing, London, UK (2007)

39. Marchioretto, M.M.: Heavy Metals Removal from Anaerobically Digested Sewage Sludge Wageningen University, Wageningen (2003)
40. Singh, R.P., Adrawal, M.: Potential benefits and risks of land application of sewage sludge. Waste Manage. **28**(2), 347–358 (2008)
41. Morera, M.T., Echeverria, J., Garrido, J.: Bioavailability of heavy metals in soils amended with sewage sludge. Can. J. Soil Sci. **82**(4), 433–438 (2002)
42. Moreira, R.S., Mincato, R.L., Santos, B.R.: Heavy metals availability and soil fertility after land application of sewage sludge on dystroferric red latosol. Ciênc. agrotec. **37** (6), 512–520 (2013).
43. Wang, X., Chen, T., Ge, Y., Jia, Y.: Studies on land application of sewage sludge and its limiting factors. J. Hazard. Mater. **160**(2–3), 554–558 (2008)
44. Chen, Y., Li, X., Shen, Z.: Leaching and uptake of heavy metals by ten different species of plants during an EDTA-assisted phytoextraction process. Chemosphere. **57**(3), 187–196 (2004)
45. Rulkens, W.: Sewage sludge as a biomass resource for the production of energy: overview and assessment of the various options. Energ. Fuel. **22**, 9–15 (2008)
46. Eifediyi, E.K., Mohammed, K.O., Remison, S.U.: Influence of organomineral fertilizer (OMF) on the performance of jute mallow (*Corchorius olitorius*) in North Central Nigeria. NJAFE 9 (3), 54–58 (2013).
47. Edet, M.A., Tijani-Eniola, H., Okechukwu, R.U.: Comparative evaluation of organomineral fertilizer and NPK 15:15:15 on growth and yield of cassava varieties in Ibadan, south-western Nigeria. Afr. J. Root Tuber Crops. **10**(1), 9–14 (2013)
48. Olaniyi, J.O., Akanbi, W.B., Olaniran, W.B., Ilupeju, O.T.: The effect of organo-mineral and inorganic fertilizers on the growth, fruit yields, quality and chemical composition of okra. J. Anim. Plant Sci. **9**(1), 1135–1140 (2010)
49. Antille, D.L., Sakrabani, R., Tyrell, S.N., Le, M.S., Godwin, R.J.: Characterization of organomineral fertilizers derived from nutrient-enriched biosolids granules. Appl. Environ. Soil Sci. (2013). doi:10.1155/2013/694597
50. Akanni, D.I., Ojeniyi, S.O., Awodun, M.A.: Soil properties, growth yields and nutrient content of maize, pepper and amaranthus as influenced by organic and organomineral fertilizer. JAST **1** (7 A), 1074–1078 (2011).
51. Audu, M., Samuel, I.: Influence of organomineral fertilizer on some chemical properties of soil and growth performance of rice (*Oryza sativa* I.) in Sokoto, Sudan savanna zone of Nigeria. J. Nat. Sci. Res. 5 (14), 64–68 (2015).
52. Ayeni, L.S., Adeleye, E.O., Adejumo, J.O.: Comparative effect of organic, organomineral and mineral fertilizers on soil properties, nutrient uptake, growth and yield of maize (Zea Mays). IRJAS **2** (11), 493–499 (2012).
53. Bello, W.B., Ogunjinmi, S.O., Ajani, A.O.: Comparative evaluation of different levels and types of organo-mineral fertilizers on growth and performance of nursery palm. ABJNA **5** (4), 175–182 (2014)
54. Paul, J.W., Beauchamp, E.G.: Nitrogen availability for corn in soils amended urea, cuttly slurry, and solid and composted manures. Can. J. Soil Sci. **73**, 253–266 (1993)
55. Richards, J.E., Daigle, J.Y., LeBlanc, P., Paulin, R., Ghanem, I.: Nitrogen availability and nitrate leaching from organo-mineral fertilizers. Can. J. Soil Sci. **73**, 197–208 (1993)
56. Hountin, J.A., Paul, J.W.: Phosphorus availability for corn and rye grass in organic-based fertilizer-amended soils. AAFC (2006). doi:10.1111/j.1750-3841
57. Tejada, M., Benitez, C., Gonzalez, J.L.: Effects of application of two organomineral fertilizers on nutrient leaching loses and wheat crop. Agron. J. **97**(3), 960–967 (2005)
58. Gurgel, M.N., Correa, S.T., Neto, D.D.: Technology for sugarcane agroindustry waste reuse as granulated organomineral fertilizer. Eng. Agríc. **35** (1), 63–75 (2015).
59. Allaire, S.E., Parent, L.E.: Physical properties of granular organic-based fertilizers, part 1: static properties. Biosyst. Eng. **87** (1), 79–87 (2004).
60. Allaire, S.E., Parent, L.E.: Physical properties of granular organic-based fertilizers, part 2: dynamic properties related to water. Biosyst. Eng. **87** (2) 225–236 (2004).
61. Pare, M.C., Allaire, S.E., Khiara, L., Nduwamungu, C.: Physical properties of organo-mineral fertilizers – Shot Communication. Can. Biosyst. Eng. **5** (3), 22–27 (2009).
62. Toft, S.R., Williams, L.L., Miller, C.O., Blanchet, M.K.: Fertilizer production. US Patent 8,968,440 B1 (2015).
63. Nicholson, J.P., Burnham, J.C.: Method of treating wastewater sludge. US Patent EP0,283,153 B1 (1992).
64. Kubica, K., Kubica, S., Robak, J., Ściążko, M., Topa, F., Tramer, A.: The method of organo-mineral fertilizers production. PL 194103 (2002) (in Polish).
65. Kalembasa, S.: The method of sewage sludge utilization. PL 178719 (1997) (in Polish).
66. Joyce, J.V.: Sewage-sludge-derived fertilizer and method of making. WO 2008/067524 A2 (2008).
67. Kędzia, W.J., Merta, R.: Fertilizer and method of obtaining a suspension of mineral-organic fertilizer from waste post-fermentation. EP 2653455 (2013).
68. Lipowski, M.Ł., Słomkiewicz, P.M., Zdenkowski, J.A.: The method of post-fermentation sewage sludge hygienization. PL 169896 (1994) (in Polish).
69. Wiseman, T.L., Lambalot, R.E., Haris, K.J., Cochran, K.D., Holt, T.G., Peeden, G.S.: Homogeneous enriched biosolids product and process of bio-nutrient granulation for making same. US patent 2014/0223979 A1 (2014).
70. Burnham, J.C.: Organic containing sludge to fertilizer alkaline conversion process. US patent 2015/0020560 A1 (2015).
71. Cabello-Fuentes, J.: Process for transforming sludge into NPK type granulated fertilizer. US patent 7,713,416 (2010).
72. Dahms, J.L., Greer, G.D.: Organic recycling with pipe-cross or tubular reactor. US patent 2010/0018823 (2010).
73. Antille, D.L.: Formulation, utilization and evaluation of organomineral fertilizers. Cranfield University, Bedford, UK. (2011)
74. Antille, D.L., Sakrabani, R., Godwin, R.J.: Phosphorus release characteristics from biosolids-derived organomineral fertilizers. Commun. Soil Sci. Plan. **45**, 2565–2576 (2014).
75. O'Connor, G.A., Sarkar, D., Brinton, S.R., Elliott, H.A., Martin, F.G.: Phytoavailability of biosolids phosphorus. J. Environ. Qual. **33**(2), 703–712 (2004)
76. Hogan, F., McHugh, M., Morton, S.: Phosphorus availability for beneficial use in biosolids products. Environ. Technol. **22** (11), 1347–1353 (2001).
77. Antille, D.L., Sakrabani, R., Godwin, R.J.: Effects of biosolids-derived organomineral fertilizers, urea and biosolids granules on crop and soil established with ryegrass (*Lolium perenne* L.). Commun. Soil Sci. Plan. **45**, 1605–1621 (2014).
78. Antille, D.L., Sakrabani, R., Godwin, R.J.: Nitrogen release characteristics from biosolids-derived organomineral fertilizers. Commun. Soil Sci. Plan. **45**, 1687–1698 (2014).
79. Pawlett, M., Deeks, L.K., Sakrabani, R.: Nutrient potential of biosolids and urea derived organo-mineral fertilizers in field scale experiment using ryegrass (*Lolium perenne* L.). Field Crop. Res. **75**, 56–63 (2015).
80. Smith, G.H., Chaney, K., Murray, C., Le, M.S.: The effect of organo-mineral fertilizer applications on the yield of winter wheat, spring barley, forage maize and grass cut for silage. J. Environ. Prot. **6**, 103–109 (2015).