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Review

Biosolids: What are the different types of reuse?

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ABSTRACT

In recent years, rapid population growth and industrialization have increased the use of natural resources and the production of waste. To develop a circular economy, it is necessary to study and promote alternative long-term solutions for waste disposal, such as reuse and recovery. Wastewater treatment plants (WWTPs) can be an important part of circular sustainability if re-oriented to function as a water resource recovery facilities (WRRFs). In this context, biological sewage sludge (SS) can be treated in order to produce more stabilized residues: biosolids (BS). This paper aims to review the possible alternatives to reuse the BS in order to increase matter recovery.

Around 250 papers, reviews, books and conference proceedings have been examined. Authors explored the application of BS on land, such as soil amendment/fertilizer both in agriculture and for interventions on abandoned mine sites, and on engineering fields, in partial or total substitution of virgin materials. The reuse of BS as adsorbent materials and as a source of phosphorus is also discussed.

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1. Introduction

In recent years, high industrialization and urban development have led to a significant use of natural resources and the consequent production of a large quantity of solid waste (Sharma et al., 2017).

The simultaneous requirement to manage resources and wastes in a more rational way has meant that many communities worldwide have begun to search for long-term alternative solutions instead methods employed to dispose of their waste and to produce energy. Therefore, people and research, in many fields, are involved in an epochal paradigm shift: wastes are no longer a problem but an opportunity (Pradel et al., 2016; Smol et al., 2015).

The rapid growth of population, 7.3 billion in the 2015s' and it is expected to reach 8.5 billion by 2030 (UN DESA, 2015), increased the generation of biological sewage sludge (SS) that should be disposed of properly. It is estimated that more than 13 million of tonnes of sewage sludge expected as dry solids will be generate in the EU27 in 2020 (Kominko et al., 2017). Furthermore, the economic aspect has become important in recent years. Researchers showed that the cost of biological SS management is approximately 50% of the total running costs of the wastewater treatment plants (WWTPs) (Bertanza et al., 2015; Collivignarelli et al., 2015b).

Firstly, in the last years, researches are mainly focused on the development of technologies/management strategies aimed at preventing the biological SS production. For instance, Collivignarelli et al. (2015b, 2017a, 2018) studied the minimization of municipal biological SS by means of a thermophilic membrane bioreactor (TMBR), focusing the attention also on factors affecting foam formation (Collivignarelli et al., 2017b). Details on other sludge minimization techniques can be found for instance in Collivignarelli et al. (2019c) and Paul and Liu (2012).

The European Union, with the Directive 98/2008/CE (EP/CEU, 2008), has established a precise hierarchy in waste management: (i) minimization, (ii) recovery of matter, (iii) recovery of energy, and (iv) final disposal. Minimize the biological SS production in the WWTPs could not be simple and the residual, in order to respect the Directive 98/2008/CE (EP/CEU, 2008), should be subjected to processes of matter recovery.

In order to promote the reuse, recycling and recovery of wastes, the European Commission adopted an ambitious *Circular Economy Package* (EC, 2018). The aim of circular economy is closing the loop of product lifecycles keeping their added value for as long as possible and eliminate waste with obvious benefits for the environment and the economy. The urban WWTPs can be an important part of circular sustainability thanks to integration with the concept of reuse of biosolids (BS), namely treated biological SS (Neczaj and Grosser, 2018). In this context, WWTPs can be reoriented to function as water resource recovery facilities (WRRFs) (Cornejo et al., 2019; Zhao et al., 2019). In fact, traditional WWTPs are focused on the goals of human health and environmental protection; in the WRRFs the goal of resource recovery, through subsequently BS reuse, is added (Cornejo et al., 2019). BS, once considered a waste product by the industry, are now becoming increasingly recognised as a multifunctional resource with growing opportunities for marketable use (Short et al., 2018).

In order to demonstrate that the transition towards a more circular economy is feasible, a research project is financed within the *EU Research and Innovation programme - Horizon 2020*. In this context, the management of the residues produced by the wastewater treatment process is further complicated by the Urban Waste Water Treatment Directive 91/271/EC (UWWTD) (CEU, 1991) because, at the same time, the WWTPs have to: (1) collect and treat more polluted water; (2) satisfy the more stringent effluent quality standards foreseen by the UWWTD; (3) satisfy the waste hierarchy introduced by the Directive 98/2008/CE. However, as known, a better water treatment efficiency involves greater production of sludge with higher level of contamination (Mininni et al., 2015).

This paper provides a detailed review of existing reuse options for BS. Authors explored the application of BS on land, such as soil amendment/fertilizer both in agriculture and for recovery of abandoned mine sites, and on engineering fields, in partial or total substitution of virgin materials. The reuse of BS as adsorbent materials and as a source of phosphorus is also discussed.

2. Methodology and structure

In order to carry out the review according to the objectives described in section 1, a multi-step methodology has been used as reported by other authors in other systematic reviews (Kable et al., 2012; Martínez Fernández et al., 2019).

- *STEP 1:* SCOPUS database has been used to search relevant literature research papers, reviews, books and conference proceedings. As suggested by Kable et al. (2012) and Martínez Fernández et al. (2019), in order to find all relevant publications, the keywords used derived from the purpose statement and identify the concepts of interest: “biosolids reuse” and “biosolids recovery”. The analysis has been conducted searching the keywords on fields “Article title, Abstract, Keywords".
- *STEP 2:* These papers have been checked in order to eliminate duplicates. Only peer-review paper published in English on international journal have been considered. The other publications have been excluded and have not been mentioned in the present review. Regarding the distribution of publications in the world, in the case of co-authors from institutions in different countries, the classification has been made considering the origin of the first author.

- *STEP 3:* These data are also used in order to provide the following bibliometric analysis.

In recent years, the interest in the different type of reuse of BS is grown. This aspect is demonstrated by the increase in literature publications since 1989. Introducing the words "biosolids reuse" and "biosolids recovery" in *SCOPUS* the number of research papers, reviews, books and conference proceedings has enhanced from 4 (1989–1993) to 227 (2014–2018) (Fig. 1a). This aspect symbolizes the significant sensibility on this matter. Research on this field is not equally distributed in the world (Fig. 1b). Considering publications from 2009 to 2018, U.S.A., Australia and Canada represent the country where the interest on this matter is higher (respectively 155, 44 and 33 works published) followed by Spain and China.

Although the term recovery means not only matter recovery but also energy recovery, aim of this work is exploring only the potential reuse of BS as substitute of natural materials. Considering that matter reuse represents the main solution in Europe for BS (as described subsequently in section 3.2), clarify and explained the different types of matter reuse for BS has become very significant. Therefore, a comprehensive review of different methods reported in peer-reviewed journals, conference proceedings, published reports and other documents presenting, sustainable sludge management through recovery, recycling and reuse, has been done to prepare this document. Around 250 publications have been examined.

The review consists of five sections; the first one (Section 3) reports the main chemical-physical characteristics of biological SS and its difference with BS. Instead, in Section 4 the following application are explored: BS on land, such as amendment/fertilizer both in agriculture and for interventions on abandoned mine site. In Section 5 the reuse of BS in the engineering fields are discussed, *id est* where sludge is utilized in partial or total substitution of raw materials (e.g. bricks and cement production, road construction, etc.). In Section 6, the applications of BS as adsorbent material and as a source of phosphorus are reported. Finally, in Section 7 a brief discussion on the main advantages and drawbacks on BS reuse is presented.

This review does not only highlight the environmental aspects related to the possible reuse of BS, but also focuses on the technical-engineering and health aspects deriving from it.

3. What are biosolids (BS)?

Biological SS resulting from wastewater treatment operations and processes is usually in the form of a liquid or semisolid liquid that typically contains from 0.25 to 20% solids by weight, depending on the operations and processes used (Tchobanoglous et al., 2003). Generally, the terms "sewage sludge" and "biosolids" are often used interchangeably but the term "sludge" refers to a liquid, produced by WRRFs, that does not be submitted to further treatments (EPA, 2015; Ukwatta et al., 2015). However, for EPA (2019), the term "biosolids" indicates a sludge that had received one or more treatments, which can be: aerobic or anaerobic digestion, alkaline stabilization, thermal drying, acid oxidation/disinfection, composting, etc. (Ukwatta et al., 2015). Moreover, also Wijesekara et al. (2016) defined BS as stabilized organic solids derived from sewage treatment processes which can be managed safely to be used beneficially for their nutrient, energy, or other values. Therefore, biological SS when properly treated and processed becomes BS and can be reused in many applications due to their high content of nutrient and organic matter (Ashekuzzaman et al., 2019; EPA, 2019).

3.1. From sludge to biosolids

Firstly, according to a conventional WWTP configuration, different kinds of sludge can be found: primary, secondary (also called biological or waste activated sludge – WAS), mixed, tertiary (which is produced when advanced wastewater treatments are used for removing suspended and dissolved substances remained after conventional biological (secondary) treatment) and digested sludge (Fig. 3).

- *Primary sludge* is the residue deriving from primary settlers; it is mainly composed by readily settleable solids and floating material contained in the raw wastewater. Generally, primary sludge is characterized by high putrescibility and a content of total solids (TS) ranging from 2 to 7 wt % (wt%) (Tchobanoglous et al., 2003; Turovskiy and Mathai, 2006).
- *Secondary sludge* is the residue produced during the biological treatment (i.e. activated sludge process or biofilm systems) of wastewater. It is a complex heterogeneous mixture of microorganisms, bacterial constituents (nucleic acids, proteins, carbohydrates and lipids) (Manara and Zabaniotou, 2012) undigested organics (e.g. paper, plant residues, oils, faecal material, etc.), inorganic materials (not removed in the primary basin, if any), and water (Bianchini et al., 2015; Samolada and Zabaniotou, 2014). The types of treatments in wastewater line will determine the different quantities of the sludge inorganic compounds, and thus the extent to which those compounds are associated to the sludge organic fraction (Tchobanoglous et al., 2003). Generally, TS content ranges from 0.5 to 1.5 wt% (Tchobanoglous et al., 2003; Turovskiy and Mathai, 2006). More details on secondary sludge characteristics are reported in Table 1.
- *Mixed sludge* is obtained when different kinds of sludge (e.g. primary, secondary and tertiary) are mixed; its characteristics depend on the sludge characteristics mixed (Fig. 2).

In Table 1 the main properties of municipal biological SS are summarized. Concerning industrial biological SS, its parameters values strongly depend on the characteristics of industrial wastewater treated (Collivignarelli et al., 2015a; Kulkarni et al., 2018).

As concern heavy metals, their content in the biological SS is very variable and affected, as stated above, by processes in water and sludge treatment lines and by influent characteristics. Usually biological SS deriving from wide urban areas, with a substantial industrial influence, shows higher concentrations of metals, especially Cr and Ni, typically of factories (Jordán et al., 2005). High concentrations of iron (III) and aluminium, instead, can be found in the sewage sludge due to the addition of these salts for favouring, for instance, the phosphorus precipitation (Manara and Zabaniotou, 2012). However, the content of heavy metals in the biological SS is a key factor for its reuse and recycling because, as reported in Cusidó and Cremades (2012), they can be a threat for human health (for instance, arsenic is carcinogenic; cadmium probably is carcinogenic, teratogenic and embryotoxic; mercury is teratogenic).

Finally, biological SS contains some compounds with agricultural value, such as: organic matter, nitrogen, phosphorus, potassium and, to a lesser extent, calcium, sulphur and magnesium (Jordán et al., 2005; Manara and Zabaniotou, 2012).

Energy content of sewage sludge is usually expressed by means of the Higher Heat Value or the Low Heat Value (LHV). LHV value mainly depends on: (i) moisture and ash content (high content involves low LHV); (ii) the undigested organic matter (Fonts et al., 2012; Zhang et al., 2015); (iii) the amount of oxygen (high oxygen content leads to low LHV) (Zhang et al., 2015). As reported in Stasta

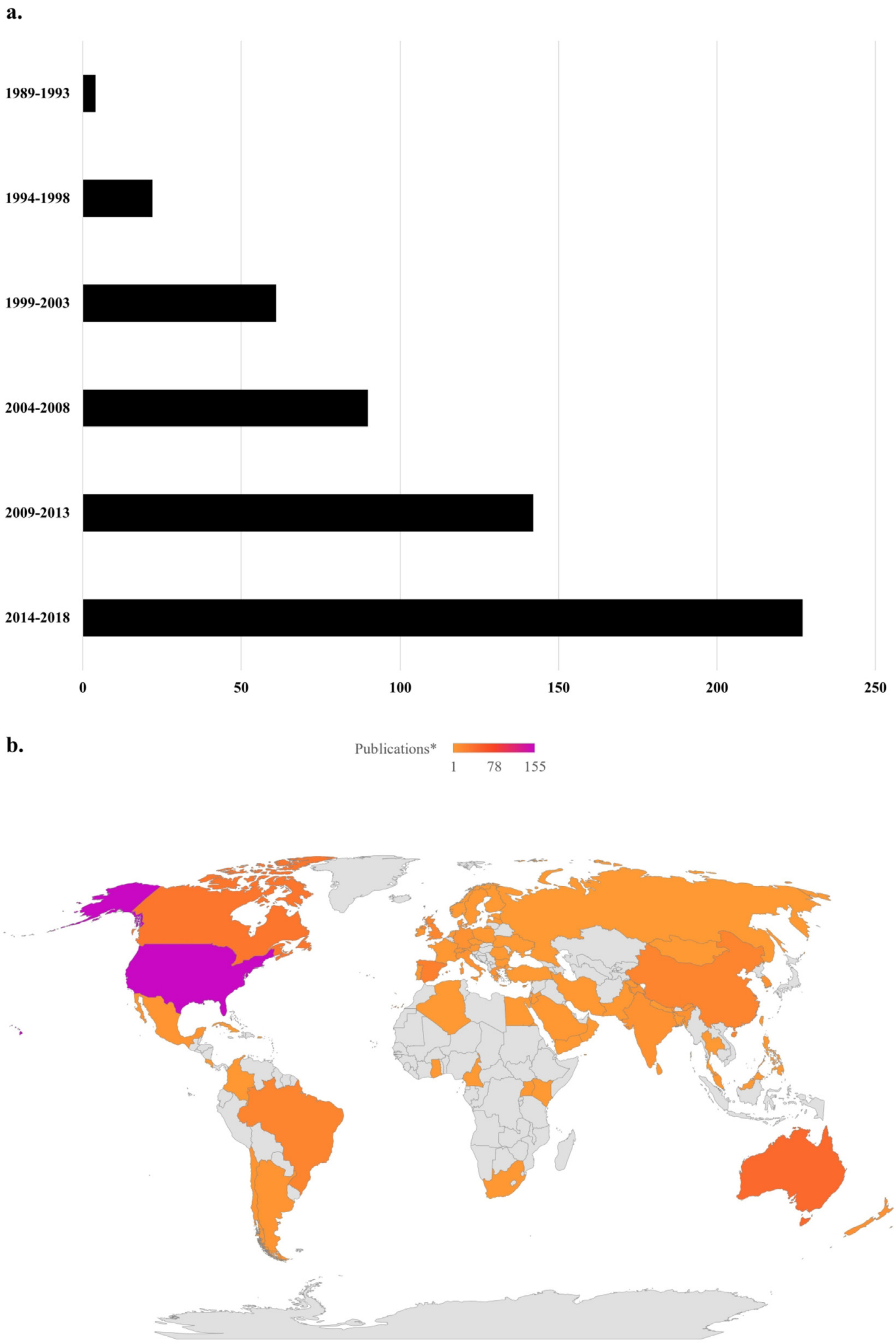

Fig. 1. (**a**) Comparison of the number of research papers, reviews, books and conference proceedings published in last 30 years from 1989 to 2018; (**b**) Distribution of publications on this field in the world from 2009 to 2018. (All data were obtained introducing the words “biosolids reuse” and “biosolids recovery” in SCOPUS). (*) For 15 publications, the country of the first author is not declared in SCOPUS.

Table 1
Main characteristics of municipal biological sewage sludge (SS) before treatments. DM: dry matter; n.a.: not available; (a): Gherghel et al. (2019); (b): Manara and Zabaniotou (2012); (c): Tchobanoglous et al. (2003); (d) von Sperling and Gonçalves (2007); (e) Demirbas et al. (2017); (f): Mininni and Sagnotti (2014); (g): UN-HABITAT (2008); (*): The values reported in Manara and Zabaniotou (2012) on % of volatile matter (%VM) have been multiplied by %VM in the biological SS in order to express it uniformly in %TS.

Parameter	Unit of measure	Primary sludge	Secondary sludge	Mixed sludge
		(a)-(b)-(c)-(d)	(a)-(b)-(c)-(d)	(b)-(e)-(f)-(g)
Total solids	[% TS]	2–9	0.8–3.3	n.a.
Organic solids/volatile solids	[% TS]	60–80	30–88	72–75
Nitrogen	[% TS]	1.5–4	2.4–5	2.8–4.9
Phosphorus	[% TS]	0.2–2.8	0.5–11	1.2–3
pH	[-]	5–8	6.5–8	6.5–8.2
Oxygen	[%TS]	23.1 $^{(*)}$	22.1–25.4 $^{(*)}$	18.5–21.9
Hydrogen	[%TS]	4.6 $^{(*)}$	4.0–5.2 $^{(*)}$	4–4.6
Carbon	[%TS]	33.5 $^{(*)}$	35.2–40.8 $^{(*)}$	n.a.
Organic carbon	[%TS]	n.a.	n.a.	20.5–40.3
Density	[kg m^{-3}]	1003–1010	1000–1020	n.a.
Higher heating value	[MJ kg^{-1}]	23–29	19–23	11.3–20
Manganese	[mg kg_{DM}^{-1}]	n.a.	n.a.	100–200
Iron	[mg kg_{DM}^{-1}]	2000–4000	2000	24,000–38,000
Lead	[mg kg_{DM}^{-1}]	n.a.	n.a.	30–300
Cadmium	[mg kg_{DM}^{-1}]	n.a.	n.a.	<3
Nickel	[mg kg_{DM}^{-1}]	n.a.	n.a.	17–50
Copper	[mg kg_{DM}^{-1}]	n.a.	n.a.	100–200
Chromium	[mg kg_{DM}^{-1}]	n.a.	n.a.	500–900
Zinc	[mg kg_{DM}^{-1}]	n.a.	n.a.	300–3600

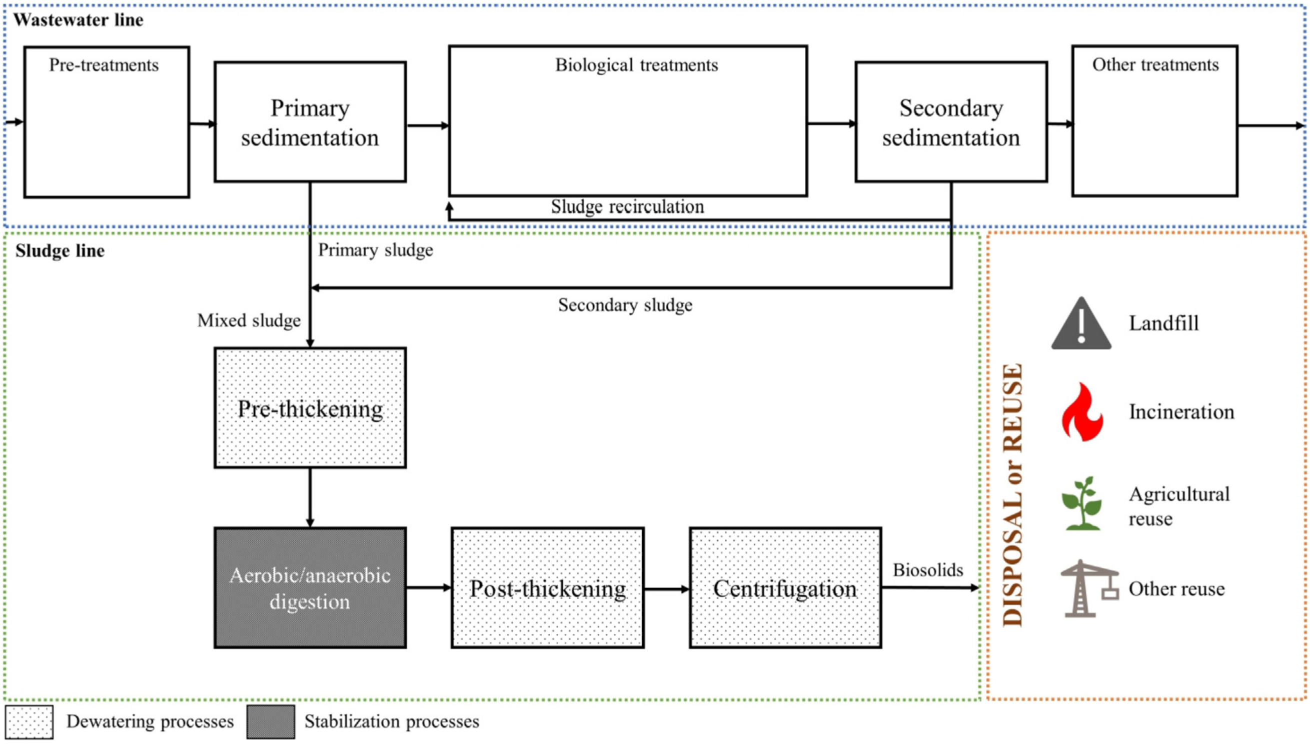

Fig. 2. Scheme example of a conventional WWTP with a sludge line.

et al. (2006) and Manara and Zabaniotou (2012), dry biological SS from WRRFs has a calorific value (12.0–20.0 MJ kg^{-1}) similar to that of brown coal (14.6–26.7 MJ kg^{-1}); therefore, biological SS can be considered suitable as fossil fuel substitute.

According to the size of WWTPs, sludge produced in the wastewater treatment line can be submitted to additional treatments in the so-called sludge treatment line (Fig. 2). Aims of those treatments are to reduce the water content (e.g. thickening) and/or stabilize the organic matter (mainly anaerobic digestion, aerobic stabilization) in order to obtain a solid residue (BS) with a TS content ranging from 12 to 30% by weight (Bianchini et al., 2015; Sanin et al., 2011). Furthermore, biological SS can also be treated in apposite sludge treatment plants in order to provide chemical and/or biological stabilization and remove the pathogens (Collivignarelli et al., 2015a).

3.2. *Biosolids management*

After treatments, the so-called BS need to be managed. Roy et al. (2011) reported that the production of dry BS ranges from 20 to

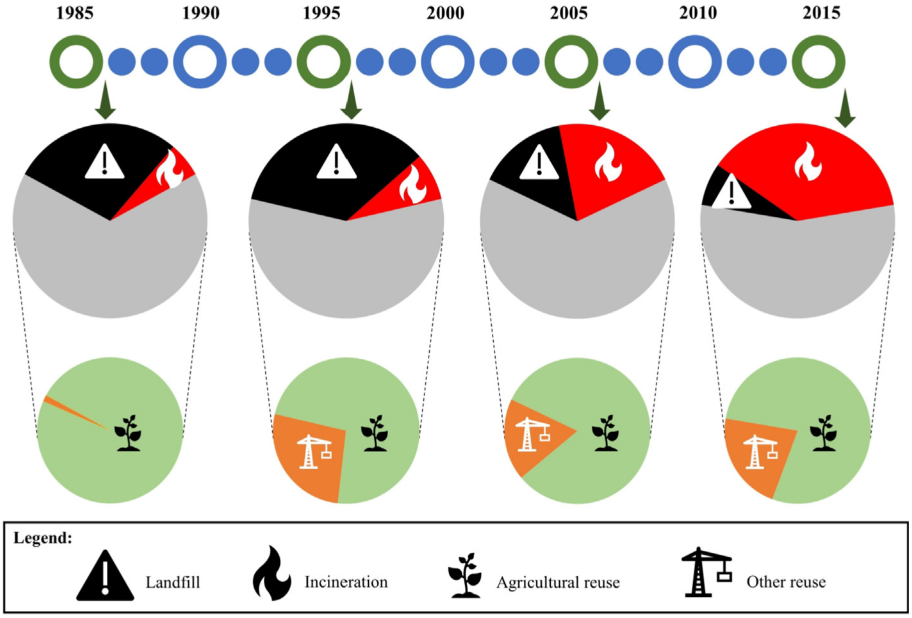

Fig. 3. Comparison of data on biosolids (BS) disposal in Europe in 1985, 1995, 2005 and 2015. Data were obtained from Eurostat (2019).

32.85 kg per person per year. Comparing data of BS disposal in Europe (Eurostat, 2019) in 1985, 1995, 2005 and 2015, two different aspects can be highlighted (Fig. 3). Firstly, the percentage of landfill disposal decreases consistently despite of a significant increase in incineration and energy recovery. Moreover, the percentage of matter recovery remains almost the same during the years but the types of reuse adopted have changed. While in 1985 recovery in agriculture represented the primary solution of matter reuse (98.6%), in 2015 it represents only 78%. In fact, 22% of BS subjected to matter reuse are destined for other applications (i.e. for engineering applications). Therefore, matter reuses in agriculture, engineering applications and others remain the main solutions in Europe for BS (Eurostat, 2019).

4. Biosolids reuse in agriculture and abandoned mine sites

Land application involves the spreading, spraying, injection, or incorporation of BS, including a material derived from BS (e.g. compost and pelletized BS), onto or below the surface of the land (USEPA, 1995). Mine site rehabilitation is another opportunity for BS reuse. In these cases, BS are used for restoring contaminated soil (e.g. heavy metals) and mine areas. In Table 2 some recent experiences are summarized.

In some countries (e.g. in Australia, the USA, China, and some European countries) the BS reuse as soil amendment/fertilizer in arable crops represents the most used disposal option (Mininni and Dentel, 2013). Also in this case, biological SS needs to be treated by processes which included biological (aerobic or anaerobic), thermal and/or chemical stabilization (e.g. with lime) in order to convert it into BS which met standards required for agricultural reuse (Al-Gheethi et al., 2018a). Indeed, high stabilization and reduction of the pathogen level represents essential requirements for land application (Al-Gheethi et al., 2018b; Ashekuzzaman et al., 2019). For instance, Collivignarelli et al. (2015a) carried out a regional study to investigate the BS reuse on agricultural land in Lombardy and reported that more than 90% of the Italian BS reused in agriculture are applied to the soils of five regions (i.e. Lombardy, Emilia Romagna, Puglia, Tuscany and Veneto). In Table 3 other experimental investigations on BS application in agriculture are reported.

4.1. Benefits

Land application of BS can represent an interesting strategy for improving site productivity by increasing soil organic matter (SOM) content and fertility; moreover, BS can also improve soil physical properties, particularly when applied to heavy textured and poorly structured soils (Alvarenga et al., 2015; Castán et al., 2016). For instance, Fuentes et al. (2017) combined traditional planting technique with the addition of composted BS for recreating sink areas on semiarid slopes. Their tests have been an effective technique to improve the establishment and growth of seedlings planted on semi-arid slopes, improving the availability of water and the accumulation of organic matter. The advantages related to the application of BS are well known: mainly, they: (a) improve soil structure, (b) decrease bulk density, (c) increase soil porosity (d) increase soil moisture retention, (e) and hydraulic conductivity (Ojeda et al., 2003). In addition, thanks to the nitrogen and phosphorus content, BS can significantly increase crop yield (Sigua et al., 2005; Wang et al., 2006). In Nelson (New Zealand), for example, aerobically digested BS were applied to more than 1000 ha of pine plantation forestland with low soil nitrogen fertility. Results from a long-term trial showed that the application of BS has significantly improved forest productivity (Kimberley et al., 2004; Wang et al., 2006) with minimal adverse effects on the ecosystem (Su et al., 2008; Wang et al., 2004). Moreover, as reported in Wang et al. (2006) applying BS to nutrient-deficient plantation forestland can reduce the risk of contaminants entering in the human food chain and it can increase tree growth.

4.2. Problematic issues and barriers

In the scientific literature, no agreement can be found about the adverse effects caused by land application of BS; according to Wang et al. (2008), they mainly refer to: (i) raising of the levels of persistent toxins in soil, vegetation and wild life, (ii) potentially slow and long-termed biodiversity-reduction through the fertilizing nutrient pollution operating on the vegetation, and (iii) greenhouse gas emissions (e.g. CH_4 and N_2O).

Considering the literature results, the following problematic

Table 2
Examples of biosolids (BS) reused in degraded areas and abandoned mine sites. n.a. = not available.

Problems	Biosolids applied	Results	Drawbacks	References
Heavy metal-contaminated soil	Municipal Waste Compost/Biosolids compost (Wastewater sludge mixed with green wastes)	Increase of pH; reduction heavy metals (As, Pb, Cd, Cu, Zn); increase the total organic carbon and hydro soluble carbon content in soil	–	Mora et al. (2005)
Areas of mine activities	Stabilized BS	Increase of pH, electrical conductivity, organic carbon and dehydrogenase activity	BS may contain organic pollutants and potentially toxic elements	Mingorance et al. (2014)
Tailings sites	Anaerobically digested BS	Improve physical (increase gravimetric water retention and reduction of soil erosion), chemical (increase electrical conductivity, soil organic matter, total carbon and cation exchange capacity) and biological (increase total aerobic, total anaerobic, iron reducing, sulphate reducing and denitrifying microorganisms) properties	Heavy metal accumulation and N and P loading	Gardner et al. (2010)
Abandoned opencast mining areas	BS and nitrogen fertilizer	Increase total microorganism population, organic matter, total nitrogen, available nitrogen, phosphorus and potassium, soil biological fertility; prevent soil erosion (with vegetative cover)	Decreased C/N ratio	Li et al. (2013)
Semiarid soil polluted with Cadmium	Dehydrated aerobic BS	Reducing inhibitory effects of Cd on biological parameters, increase biodiversity of soil microorganisms and their metabolic activity	–	Moreno et al. (2002)
Highly disturbed sites by fires and grazing	Anaerobically digested biosolid	The application of BS, when applied at adequate doses, represents an improvement in the C balance in the reforestation of degraded Mediterranean sites	–	Valdecantos and Fuentes (2018)
Areas of mine activities	n.a.	Improve biological, chemical, and physical properties of degraded lands, enhance the nutrient cycling, water purification, and restoration of plants and increase the recreational value of the land	–	Wijesekara et al. (2016)

Table 3
Examples of experimental investigations on biosolids (BS) reuse in agriculture. n.a. = not available.

Type of crop	Biosolids applied	Results	Drawbacks	References
Bermudagrass	Anaerobically digested, air-dried BS	Increase soil concentrations of organic carbon, nutrients and heavy metals. Biomass production and nutrient uptake were increased due to BS. Heavy metals were not significantly transferred from soil to above-ground plant tissue	–	Sloan et al. (2016)
Lettuce, radish, tomato, pepper and cabbage	BS rich of Carbamazepine, diphenhydramine, and triclocarban	Diphenhydramine and triclocarban were only detected in the fruits of tomato and pepper plants, with the concentration in tomatoes being higher compared to that of peppers, while the concentration of these CECs in shoots of all plants did not displayed significant variations	Compounds were taken up and accumulated in crop	Christou et al. (2019)
Corn	Anaerobically digested, lagoon stabilized, air-dried BS	The use of BS as phosphorus nutrient for corn would not cause a major impairment to water sources even phosphorus applied through BS was not completely used by annual crop	Further studies are necessary to investigate the interactions of BS phosphorus mobility with soil type	Tian et al. (2016)
Spinach	Dehydrated BS	Contents of metals below the maximum levels permitted for soils in India. The most agronomic performance and biochemical components of the crop were found at 50% concentrations of BS in both seasons	Significantly increase of Cd, Cu, Mn, and Zn in the soil and crop	Brisolara et al. (2017); Kumar et al. (2016)
Cabbage	n.a.	Rhizosphere conditions (presence of dissolved organic matter in the planting matrix) might be one of the critical factors determining mobilization and bioavailability of xenobiotic compounds such as pharmaceuticals and personal care products	–	Christou et al. (2019); Holling et al. (2012)
Carrot, radish, lettuce, spring wheat and soybean	Dewatered anaerobically digested municipal BS	The presence of the chosen pharmaceuticals and personal care products in plant tissue poses only a minimum risk to human health	–	Prosser et al. (2014)

issues will be discussed: social acceptance (section 4.2.1), presence of heavy metals (section 4.2.2), possible spreading of human pathogens (section 4.2.3), possible toxic effects (section 4.2.4), presence of organic contaminants (section 4.2.5) and greenhouse gas emissions (section 4.2.6).

4.2.1. *Social acceptance*

In recent years, agricultural reuse faces strong public opposition by local stakeholders (Liu et al., 2018b; Mininni et al., 2015). Therefore, in last few years, BS reuse in agriculture has declined or even stopped in some European countries such as Finland, Slovenia, Sweden, the Netherlands, Greece and Belgium and stricter regulations have been introduced (Praspaliauskas and Pedišius, 2017; Tyagi and Lo, 2011). This aspect is due to consumer's demand on food safety and quality (Zhang et al., 2019). Moreover, the potential presence of organic and inorganic micropollutants caused a strong opposition from the farmers and food industries, fearing that the soil would be contaminated and not utilizable for food production (Aemig et al., 2019). Moreover, land application of BS releases odorous, volatile organic compounds (VOCs) (e.g., terpenes, alcohols, ketones, furans, sulphur-containing compounds, and amines) and ammonia (Maulini-Duran et al., 2013). Odours depend on initial substrate chemical composition, pH, moisture content, redox potential, atmospheric temperature, microbial activity, and physical and chemical properties of VOCs (Rosenfeld et al., 2001) and are released during their biodegradation. In many cases odours cause only discomfort to people living around fields where they are applied although Lleó et al. (2013) report that exposure to high concentrations of odours produced by BS lead to toxicological effects (e.g. sensory irritation) and psychogenic effects.

4.2.2. Presence of heavy metals

In the WWTPs, heavy metals contained in wastewater are concentrated into biological SS and therefore can be present in the BS after treatments (Collivignarelli et al., 2019a). As reported by Sharma et al. (2017), heavy metal concentration in BS produced in different countries may differ due to dissimilar wastewater or sludge treatment technologies adopted.

Despite some heavy metals are considered as essential micronutrients for plant growth, high concentrations of these compounds could be toxic to food crops, domestic animals, and humans (Shamuyarira and Gumbo, 2014; Singh and Agrawal, 2008). It is also known that heavy metals are no biodegradable and their persistence in soil is much longer than any other reactive components of the terrestrial ecosystems. Therefore, the fate of heavy metals in post-BS-applied soil is of great importance with respect to interactions with the biological processes, their release and mobility, and transferability to the food chain.

In the soil, the bioavailability of heavy metals can increase and causes their excessive uptake by plants (which is correlated with extractable forms of metals rather than the total metal contents in soil) or leaching down. It must be highlighted that some plant species can protect the food chain by providing an effective barrier against the uptake of most heavy metals (Lu et al., 2012). The influence of BS on the availability of heavy metals and their effects on seed germination has been reported in literature. For instance, Islam et al. (2013) investigated the effects due to the repeated application of BS to a silt-loam soils sited in Ohio (USA). Results revealed that the extractable fractions of Pb, As, Zn, and Cu were significantly higher at 0–15 cm soil depth. Consequently, the accumulated heavy metals may mobilize from the soils to groundwater and surface water bodies. Other authors, such as Alvarenga et al. (2015), Cai et al. (2007), Hargreaves et al. (2008) and Moretti et al. (2016) point out that the use of compost produced by the mixing of municipal solid wastes and BS can exceed, in some cases, the limits settled by *EU ECO Label for Soil Improvers* and by the *Proposed limit values for compost for the heavy metals,* especially for Ni, Pb and Zn (Cai et al., 2007; Hargreaves et al., 2008). Therefore, in order to immobilize heavy metals, alkaline stabilization of BS is identified as a better strategy, as well as the control of heavy metal concentration in BS before their reuse in agriculture. In Table 4, examples of experimental investigations on the content of heavy metals in BS reused on land are reported.

4.2.3. Possible spreading of human pathogens

Land application of BS may be also responsible for spreading human pathogens. The transmission of *pathogens* from application of BS to humans, animals or plants is still a major concern on public health (Al-Gheethi et al., 2018a). Different physicochemical and biological parameters such as temperature, moisture content, oxygen, pH, sunlight, soil type, texture, and predation may influence the inactivation of pathogens in BS (Sidhu et al., 2001).

At present, specific limits for microbiological sludge quality or disinfection treatment requirements are not indicated in the Council Directive 86/278/EEC (CEU, 1986), which regulate the recovery of BS in the agricultural field. However, limits on microbial and organic compounds in the BS should be introduced; prevision concentration limits are reported in the *EU Working Document on sludge - 3rd draft* (EWA, 2000) and *EU Working document on sludge and biowaste* (DGEEC, 2010).

As concern the microbial parameters, DGEEC (2010) and EWA (2000) state that the treated sludge should fulfil the limits of *E.coli* < 500 CFU g^{-1} and the absence of *Salmonella* spp. in 50 g (wet weight). Additionally, sludge produced by conventional treatment shall, at least, achieve a 2-Log reduction in *E.coli* while any new sludge treatment process shall be initially validated through a 6-Log reduction of a test organism such as *Salmonella senftenberg W775*. As reported by Mininni et al. (2015), the feasibility and reliability of these tests on sludge are still amply debated and seriously questioned because conventional indicators (e.g. *E. coli,* faecal coliform bacteria, clostridia, somatic coliphages, etc.) and/or pathogen index (*Salmonellae*) are used as surrogate of pathogen presence for routine evaluation of treatment plant performances and sludge microbial quality. The problem is that viral pathogens show a different persistence in the environment with respect to other microbial pathogens; therefore, the use of bacterial indicators is not providing reliable information of viruses reduction in sludge processing. The results of EU project ROUTES (CORDIS, 2014) proved that pathogens control should be focused on *Salmonellae*, *E. coli* and somatic coliphages, the latter ones resulted a very good indicator of enteric viruses. Since BS can be applied on land once or twice a year, pathogens can regrowth during the storage period (Fytili and Zabaniotou, 2008) and in the scientific literature there is an open discussion on the survival or regrowth of pathogens after sludge processing. Several studies have been focused on survival patterns and potential growth of inoculated organisms in sterile and non-sterile sludge; only few studies have reported survival and regrowth of indigenous pathogens in BS. For instance, Moce-Llivina et al. (2003) reported that somatic coliphages were significantly more resistant to thermal inactivation than other bacterial indicators. In fact, the phages survived significantly better than *Salmonella choleraesuis* and *E. coli*. Moreover, Pourcher et al. (2005) indicated that the use of faecal *E. coli* or enterococci as indicators of hygienization could be questioned, as the resistance of pathogenic bacteria differs from one pathogen to another, similar to that observed with *Salmonella* and L. *monocytogenes*.

In order to obtain a pathogen-free BS, thermal pre-treatments such as thermophilic anaerobic digestion, pasteurization, and thermal hydrolysis can be used (NZWWA, 2003; Wang et al., 2008). Performances of innovative sludge treatments are under study; for instance, Levantesi et al. (2015) evaluated the performances of several advanced sludge treatment solutions monitoring microbial indicators (*Escherichia coli*, somatic coliphages and *Clostridium perfringens* spores) and pathogens (*Salmonella* and enteroviruses). As expected, they found that a better microbiological quality of BS was obtained with thermal treatments (e.g. thermal hydrolysis and thermophilic anaerobic digestion) even if the anaerobic/aerobic digestion process greatly contribute to the reduction of microbial load, allowing the achievement of the microbial quality levels proposed for the reuse of BS in agriculture. Only a limited microbial load reduction was obtained by anaerobic digestion at 37 °C temperature and by mild sonication pre-treatment. Yin et al. (2018) studied the thermal inactivation of faecal indicator bacteria, present at high levels in biological SS. They showed that thermal pretreatment with mixing allowed to completely inactivate (100%) faecal coliform, *Salmonella* spp. and faecal Streptococcus within 80 min following a first-order kinetics. Moreover, Al-Gheethi et al. (2018a) reported that the inactivation of *Salmonella* spp. has been significantly greater than the inactivation of total coliforms at 80 °C for 90 min. After heat treatment at 80 °C for 120 min, total coliforms were reduced by 5.5 $\log_{10}$ while faecal coliforms and *Salmonella* spp. were undetected.

4.2.4. Possible toxic effects

As reported by Manzetti and van der Spoel (2015) BS-based fertilization seems imprudent because of toxic compounds (e.g. heavy metals, endocrine disruptors and persistent organic compounds) that may accumulate in the vegetation and then transferred to feeding herbivores and their predators. Therefore, intoxication of foetuses, reduction in the reproductive potential as well as other long-term effects can compromise biodiversity and

Table 4
Examples of experimental investigations on the content of heavy metals in biosolids (BS). DM: dry matter; n.a.: not available.

Type of biosolids	Heavy metals concentration	Results	References
n.a.	$Cd = 0.3-1$ mg kg_{DM}^{-1}; $Cr < 5.6$ mg kg_{DM}^{-1}; $Cu = 141-156$ mg kg_{DM}^{-1}; $Ni = 22.6$ mg kg_{DM}^{-1}; $Pb < 5.6$ mg kg_{DM}^{-1}; $Zn = 581-757$ mg kg_{DM}^{-1}; $Hg < 1.3$ mg kg_{DM}^{-1}	The BS in this study comply with the requirements of the legislation (Portugal) on heavy metals content.	Alvarenga et al. (2015)
Anaerobically stabilized	$Cd = 9.2$ mg kg^{-1}; $Cr = 280$ mg kg^{-1}; $Cu = 465$ mg kg^{-1}; $Ni = 150$ mg kg^{-1}; $Pb = 164$ mg kg^{-1}; $Zn = 3657$ mg kg^{-1}	After 500 d of anaerobically stabilization, the BS appeared to be suitable to be used in abandoned sites and degraded areas, while its application on land should be managed to ensure that certain heavy metals would not accumulate in soil (Cr, Ni and Zn). Other investigation about of transformation of heavy metals are needed	Yang et al. (2017)
n.a.	$Ag = 2.3$ mg kg_{DM}^{-1}; $Cd = 1.0$ mg kg_{DM}^{-1}; $Hg = 0.6$ mg kg_{DM}^{-1}; $Pb = 22$ mg kg_{DM}^{-1}; $Cu = 350$ mg kg_{DM}^{-1}; $Zn = 600$ mg kg_{DM}^{-1}	Significant reduction of the concentrations of heavy metals in BS over time (1970–2010). Currently the average measured concentrations in BS are:	Kirchmann et al. (2017)
Air-dried	$Cu = 115$ mg kg^{-1}; $Pb = 207$ mg kg^{-1}; $Zn = 306$ mg kg^{-1}; $Cr = 100$ mg kg^{-1}; $Co = 20$ mg kg^{-1}; $Mn = 56$ mg kg^{-1}	The BS have been subsequently pyrolyzed and, under field conditions, the results confirmed the heavy metals immobilization. The total heavy metals contents obtained with the pyrolysis of BS up to 500 °C did not exceed the limits established in EU legislation	Figueiredo et al. (2019)
Composted	$As = 14.2$ mg kg^{-1}; $Cd = 0.8$ mg kg^{-1}; $Cr = 98$ mg kg^{-1}; $Cu = 194$ mg kg^{-1}; $Ni = 108$ mg kg^{-1}; $Pb = 48.7$ mg kg^{-1}	Applying composted BS to soil annually and continuously might cause fresh release of heavy metals and accumulation of some metals in the soil horizon	Fang et al. (2017)
Dewatered	$Cu = 146-4567$ mg kg_{DM}^{-1}; $Pb = 69.9-104$ mg kg_{DM}^{-1}; $Ni = 74-148$ mg kg_{DM}^{-1}; $Mn = 214-1844$ mg kg_{DM}^{-1}; $Cr = 49.6-121$ mg kg_{DM}^{-1}; $Zn = 609-987$ mg kg_{DM}^{-1}; $Cd = 3.1-6$ mg kg_{DM}^{-1}	The total concentrations of Cu, Ni exceeded the allowable values for agriculture land use (in China). Promise results with respect to agricultural applications for some samples have been highlighted. In other samples, the total contents of heavy metals were high. Further treatments by remediation are necessary before a possible application on land.	Liu J. et al. (2015)

animal (human) proliferation. In general, in order to test the possible toxic effect, diplopods (e.g. *Rhinocricus padbergi*) have been considered excellent bioindicators of soil contamination (Christofoletti et al., 2016; Rastetter and Gerhardt, 2017). For instance, Christofoletti et al. (2016) used *Rhinocricus padbergi* to assess toxicity in samples of BS. The behavioural analysis, mortality rate, and histological, histochemical, and ultrastructural analyses of the midgut of diplopods has been the parameters evaluated. They evidenced that after 30 days of exposure, diplopods showed an accumulation of compounds. Conversely, several studies state that significant environmental or health risks connected to the use of BS on land have not been widely demonstrated (Clarke and Smith, 2011; Samolada and Zabaniotou, 2014). Tejada et al. (2014) studied over two experimental seasons the effect of a biofertilizer obtained from BS on the yield and on the quality of maize crops (*Zea mays* L.). The results show that the application of BS had no effects on the soil, maize nutrition, grain quality or yield. In addition, they found that, in order to improve agricultural maize yields, quality and nutritional, BS should be applied as a foliar fertilizer instead of applying it to soil. In laboratory tests, Rastetter and Gerhardt (2017) used three species (*Lemna minor*, *Gammarus fossarum* and *Eisenia foetida*) in order to evaluate the acute effects of two types of BS samples on all environmental compartments: water, sediment and soil. They highlighted that the BS tested must be classified as toxic at high concentration levels under laboratory conditions but will most likely not have any acute toxic effect on the test organisms in the field. Prosser et al. (2014) studied the risk for human health due to the consumption of vegetables cultivated adopting BS as soil improvers. They demonstrated that the absorption of some pharmaceuticals and personal care products (triclosan, triclocarban, miconazole, carbamazepine, and diphenhydramine) in plant tissue did not pose significant risk to human health.

4.2.5. *Presence of organic contaminants (OCs)*

Over the past couple of decades, significant attention has been given to selected groups of persistent organic contaminants *(OCs)* in BS, including chlorinated dioxins/furans, polychlorinated biphenyls, and polycyclic hydrocarbons (Clarke and Smith, 2011). Most of these compounds do not affect human health when BS are reused in farmland, possibly because of effective source control (Hundal et al., 2008). In EU about 143,000 chemicals are registered for industrial use; therefore, all of them could be potentially found in BS. Residual concentration of OCs depends, over their lipophilicity, on the initial concentration and on the extent of destruction during wastewater and sludge treatment. Clarke and Smith (2011) reported that, in the BS, OCs accounted for few ng kg^{-1} to some percentage in the dry solids.

Research on organic contaminants in BS has been undertaken for over thirty years; recently, as reported in EWA (2000), limit thresholds have been proposed for the so-called sum of halogenated organic compounds (AOX), linear alkylbenzene sulphonates (LAS), di(2-ethylhexyl)phthalate (DEHP), nonylphenole and nonylphenole ethoxylates (NP/NPE), polynuclear aromatic hydrocarbons (PAH), polychlorinated biphenyls (PCB), and polychlorinated dibenzo-p-dioxins and -furans (PCDD/F).

Several emerging organic contaminants were identified in BS based on environmental persistence, human toxicity, and evidence of bioaccumulation in humans and in the environment. For instance, perfluorinated chemicals (PFOS, PFOA), polychlorinated alkanes (PCAs), polychlorinated naphthalenes (PCNs), organotins (OTs), polybrominated diphenyl ethers (PBDEs), triclosan (TCS), triclocarban (TCC), benzothiazoles, antibiotics and pharmaceuticals; synthetic musks, bisphenol A, quaternary ammonium compounds (QACs), steroids, phthalate acid esters (PAEs) and polydimethylsiloxanes (PDMSs) were recognised for priority attention because they can enter into living organisms via BS-amended soil (Brunetti et al., 2015; Clarke and Smith, 2011; Smith, 2009). Among those compounds, PFOS, PFOA and PCAs were identified for priority attention because they are environmentally persistent and potentially toxic or can be found in large concentrations in BS. Therefore, BS-amended soil can make theoretically possible to these compounds entering into human and ecological food-chains. However, as reported by Clarke and Smith (2011) and Smith (2009), there is a growing number of evidences demonstrating that most of the studied compounds do not endanger human health when BS are reused on land.

Recently, Braguglia et al. (2015) investigated the performances of different enhanced sludge stabilization processes on a broad class of conventional (EOX, LAS, NPEs, PCBs, PAHs, and phthalates) and emerging organic micropollutants contained in digested sludge. Processes studied were: (i) thermophilic digestion integrated with thermal hydrolysis pretreatment, (ii) sonication before mesophilic/thermophilic digestion, and (iii) sequential anaerobic/aerobic digestion. Results indicated that the concentrations of the conventional organic pollutants in the feed just in few cases exceed the recommended thresholds set in the DGEEC (2010). Removals of conventional and emerging organic pollutants were greatly enhanced by performing double-stage digestion (sonication before mesophilic/thermophilic digestion and sequential anaerobic/aerobic digestion treatment) if compared to a single-stage process (such as thermal hydrolysis pretreatment). Concerning the toxicity reduction, the authors found similar results.

4.2.6. Greenhouse gas (GHG) emissions

Sablayrolles et al. (2010) studied the GHG emitted by BS reused in agriculture. They found that the BS stockpiles and the spreading stage on land produced an emission of 282 $Kg_{eq}CO_2\ t_{DM}^{-1}$ similar to 345 $Kg_{eq}CO_2\ t_{DM}^{-1}$ produced by a hypothetical biological SS treatment stage (composting) and greater than 11 $Kg_{eq}CO_2\ t_{DM}^{-1}$ produced by transport phase. Therefore, considering only the GHG emitted by BS reuse (and not from the previous biological SS treatments), stockpiles and land application represents the main source of emissions (Aguilar-Chávez et al., 2012; Maulini-Duran et al., 2013; Nkoa, 2014). For instance, Majumder et al. (2014) studied the direct emission of GHG generated from BS stockpiles in Melbourne (Australia) and found that the youngest BS (<1 year) released higher amounts of methane (CH_4) and nitrous oxide (N_2O). In comparison, stockpiles aged between 1 and 3 years emitted higher overall GHGs compared with the oldest stockpiles. Studies revealed that GHG emissions were dominated by CO_2 and N_2O while CH_4 is emitted in low concentration (accounted for less than 2%) and generally its contribution can be considered negligible (Majumder et al., 2014). In order to minimize the impact of GHG emissions from BS applications, some actions such as selecting remote sites, minimizing the length of time for storage of BS can be undertaken. Despite this, increase land application and decrease disposal of BS in landfills and incinerators can significantly reduce GHG emissions, as land application contributes low GHG impacts (Miller-Robbie et al., 2015).

5. Reuse of biosolids in construction sector: applications

BS reuse for producing bricks, lightweight artificial aggregates, and cement-like materials is considered a good strategy because it converts the wastes into useful materials by the concomitant reduction of disposal issues (Ukwatta et al., 2015). Moreover, reusing, reprocessing, or recycling materials reduces extraction of raw resources (Calkins, 2009).

Construction industry is a suitable technological activity sector to employ solid wastes (Fig. 4), due to the large amount of raw materials and final products used (Martínez-García et al., 2012; Ukwatta et al., 2015). As reported Calkins (2009), each year more than three billion metric tons of raw materials are used to manufacture construction materials and products worldwide. In addition, the construction industry faces the problem of the depletion of natural materials such as pumice, scoria, crushed stones, and clay. In some countries, the exploitation of raw material is becoming severely regulated; for instance, in order to protect the clay resource and the environment, China have started to limit the use of bricks made from clay (Chen et al., 2011). Following, the prospective benefits deriving from the use of BS in the construction and building materials as well as the mechanical proprieties of the obtained materials are reported. In Fig. 4 the applications of BS in the construction sector are presented.

5.1. Road construction

The feasibility of BS reuse in the field of road engineering is reported in several works (Lucena et al., 2014; Kanari et al., 2016). The studies were focused on performances assessment of different kinds of BS that are mainly employed in the road base layer or as a fill material in road embankments as substituted of raw materials.

Engineering properties of BS have been studied in recent years in several countries such as UK, Hong Kong, USA, South Korea, Turkey, Spain, Poland and Singapore (Arulrajah et al., 2011; Świerczek et al., 2018). In literature, some tests such as California Bearing Ratio (CBR), unconfined compressive strength, indirect-tensile strength, resilient modulus, and deterioration tests were conducted for investigating mechanical properties of BS (pure or blended) (Arulrajah et al., 2013, 2011; Lucena et al., 2014).

Arulrajah et al. (2013) report that BS tested have similar properties to soil, such as moisture content, cation exchange capacity, and moisture retention as well as geotechnical engineering properties (e.g. plastic behaviour, acceptable shear strength parameters and compaction ability). However, several research studies show that BS is generally associated with high compressibility (Disfani et al., 2009), high rates of creep, and possible unsatisfactory strength characteristics, which increases the risk of excessive settlements in case of their application as load bearing media (Santagata et al., 2008). As reported in some researches, bearing capacity can be improved submitting BS, before the use, to a stabilization process even if best results can be obtained blending BS with additives such as cement, lime, and emulsion (Lucena et al., 2014; Disfani et al., 2009). For instance, Lucena et al. (2014) investigated the possibility of using 10 wt% of BS in pavement base layers, adding, in different percentages (2, 4, 6, and 8% by weight), three additives (i.e. cement, lime, and emulsion). Results indicated that the CBR gains when using lime and cement as additives and decreases when using emulsion. In particular, the addition of 8 wt% cement to the mixture of soil BS supplied the highest increments of resistance. Similar results were also obtained

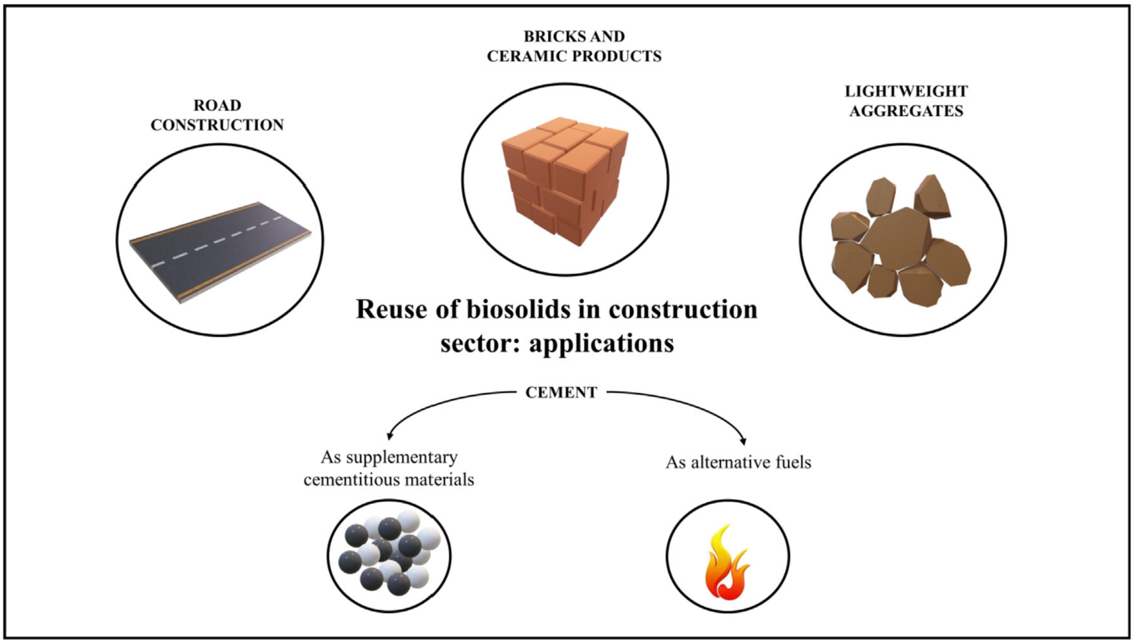

Fig. 4. Applications of biosolids (BS) reuse in construction sector.

by Suthagaran et al. (2010). Wójcik et al. (2018) studied the properties of an aggregate obtained mixing BS, glass powder and a quartz glass related hydraulic binder. They demonstrated that this aggregate can be used in road pavement base layers. Moreover, Mohajerani et al. (2017) studied the combination of BS and brown coal fly ash and they found that had the potential to be used in road embankments or as a stabilized subgrade material. Their researches highlighted that the addition of brown coal fly ash (10%, 25% and 50% by dry weight) significantly improved the California Bearing Ratio (CBR) values and reduced the organic content of the mixtures, demonstrating a good indication of the general strength and load bearing capacity (Mohajerani et al., 2017).

Moreover, the growth of plants on road embankments is of great importance because they protect the roadbed from erosion (Lucena et al., 2014; De Oña et al., 2011). Generally, embankment soil is basically selected according to its resistance characteristics; therefore, in some cases, its agronomic characteristics are very limited (e.g. immature, bad soil structure, and low nutrient content) (De Oña and Osorio, 2006; Pengcheng et al., 2008).

De Oña and Osorio (2006) and Pengcheng et al. (2008) studied the effects on the growth and development of plants due to the BS utilization. Both authors investigated the addition of BS-compost to a natural soil. Results show that the use of this compost improved the chemical-physical properties of the soil, increased the growth of the plants (they tested the perennial ryegrass), reduced the volume and the total mass flux of sediments in runoff. Moreover, De Oña et al. (2009) report that BS-compost mixtures worked better than the use of BS only or compost only.

As concern the potential threat related to the use of BS in the road construction field, the available researches suggest that BS, if treated properly and managed in accordance with existing regulations and standards, is safe for the environment and human health (Arulrajah et al., 2011; Pengcheng et al., 2008). For instance, Arulrajah et al. (2013) indicated that heavy metals, dichloro diphenyl trichloroethane (DDT) and organochlorine pesticides concentration along with pathogens (bacteria, viruses, or parasites) were within acceptable limits for usage in geotechnical applications.

5.2. Bricks and ceramic products

Conventional bricks are produced from clay and shale with high temperature kiln firing or from ordinary Portland cement (OPC) concrete (Calkins, 2009; Zhang, 2013).

Brick-making sector is characterized by low energy efficiency (CCAC, 2015); for instance, Calkins (2009) reported that clay bricks require from 150% to 400% more energy to produce than concrete paving bricks. Low technological levels are highly related with pollutant air emissions; in fact, brick production contributes with greenhouse gases (GHG) and black carbon (BC) emissions, with a significant impact on human health and climate change. Moreover, bricks-making sector is characterized by an intensive quarry activity; in the 2014, only in the USA, about 10 million tons of common clay have been mined (Jewell and Kimball, 2015). In order to reduce the impacts related to quarry activities, saving the costs and for a sustainable development, The Brick Industry Association (2015) reported that almost 50% of manufacturers incorporate some kind of waste into their bricks.Many researchers evaluated the use of a wide variety of waste materials, including, for instance: fly and bottom ash (Arıöz et al., 2010; Chen et al., 2012), fly ash from coal-fired generators (Freidin, 2007), mine tailings (Ahmari and Zhang, 2012), cigarette butts (Abdul Kadir et al., 2009), and rice husk ash (Hegazy et al., 2012a, 2012b).

The incorporation of BS into the bricks, possibly blended with other materials (e.g. fly ash, circulating fluidized bed combustion bottom ash, agricultural wastes, forest wastes, etc.), was proposed and researched since the eighties of the last century for instance by Alleman and Berman (1984).

Researches are mainly focused on investigating the effects of the addition of BS in different percentages; typically, they are blended from 2% up to 50% by weight (Ingunza D. et al., 2011; Kadir and Mohajerani, 2011). For instance, Ukwatta et al. (2015) studied the effects of the addition of 25% of BS. However, other authors investigated also the proprieties of bricks made with 100% of BS (Weng et al., 2003; Tay et al., 2004).

Tests conducted by many authors indicated that the proportion of BS in the mixture and the firing temperature are the two key factors affecting the brick quality (Weng et al., 2003). In general, the addition of BS in proportions of 2 up to 20 wt% does not induce significant changes in the relevant functional characteristics of bricks (Martínez-García et al., 2012); on the contrary, a significant number of researches demonstrate that a higher amount of BS in the mixture could compromise characteristics of bricks (Ingunza D. et al., 2011; Tay et al., 2004; Weng et al., 2003). For instance, Liew et al. (2004a, 2004b) reported that bricks with a BS content of up to 40 wt% can satisfy the relevant technical standards although bricks with more than 30 wt% BS addition are not recommended (they are brittle and easily broken even when handled gently). In addition, Ingunza D. et al. (2011) found that bricks with 35 wt% of BS were reduced in some dimensions between 1 mm and 7 mm.

Despite many authors have demonstrated the feasibility, by a mechanical point of view, of the utilization of BS for brick construction (Table 5), some sectors of public opinion are against to put in practice that process due to unfamiliarity and lack of information about this novel practice (Cremades et al., 2018).

The environmental behaviour of construction product is assessed by the study of the properties that influence its environmental sustainability, such as *leaching behaviour*. As there is no harmonization in the tests and components to be studied to determine the environmental performance of the waste-based ceramic products so far, the leaching tests selected in each case are different (Pacheco-Torgal et al., 2015). The most used tests are the Toxicity Characteristic Leaching Procedure (TCLP) (Martínez-García et al., 2012; Weng et al., 2003) and the Diffusion Leaching Test – NEN 7345 (Cusidó and Cremades, 2012; Cusidó and Soriano, 2011). In general, authors agreed that heavy metals are the main compounds which can be found in the leachates from bricks made with BS; authors highlighted that heavy metals were originally present in BS or in the clay and the leaching from the bricks was very low (Liew et al., 2004a; Martínez-García et al., 2012). Weng et al. (2003) have recorded that chromium and zinc were leached in greater amount with respect to the other heavy metals, although the concentrations were much lower than those of the Taiwan-EPA regulated TCLP limits; moreover, organic compounds from BS did not appear in leachates. Cusidó and Cremades (2012) investigated the potential health risks related to people who live in houses built with materials made from BS. Tests were conducted according to ESA PSS-01-729 (1991) and ESA PSS-01-702 (1994). By means of these tests it is possible to evaluate the gases (i.e outgassing and offgassing) and particles emitted by the bricks in a simulated time frame equivalent of 10 years. Also in this case, tests show that there are no environmental restrictions on the use of clay bricks made with BS.

Finally, *the visual appearance* of bricks can be influenced by many factors such as the firing temperature and the amount of BS in the mixture although authors did not find the same results. Liew et al. (2004b) and Cusidó and Cremades (2012) found that a high amount of BS addition in mixture has a pronounced effect on the pore structure of the amended clay bricks, involving uneven and rather poor surface textures. Moreover, Kadir and Mohajerani (2011) reported that the firing process can cause black coring to the final product. Authors concluded that BS-bricks might not be suitable to replace conventional bricks due to their poor surface texture and finishing, unless wall plasters (cladding or rendering) are applied. On the contrary, Ingunza D. et al. (2011) found that there is no sign of alteration in color or odour in the bricks made with up to 20 wt% of BS in the mixture.

5.3. *Lightweight aggregates (LWAs)*

Nowadays, in the construction sector there is a great interest for the use of natural materials and/or aggregates that undergo thermal expansion under controlled conditions for the production of *lightweight aggregates (LWAs)*. The perlite and some lamellar minerals (i.e. vermiculite, clay, schist, shale, slate) are the most used raw materials for the thermal synthesis (Kanari et al., 2016). An excessive exploitation of these non-renewable natural resources will lead to their depletion in the future. Thus, in order to preserve the reserves in granulates, the use of residues derived from waste industry could represent an interesting solution.

Several studies investigated the effects of using BS in the production of LWAs (Franus et al., 2016; González-Corrochano et al., 2016; Tuan et al., 2013). Most previous studies have focused that the use of dewatered biological SS involves the production of porous and loose aggregates due to high organic matter and water content. Thus, generally, no greater than 30% BS should be used. In practice, in order to improve the performance of manufactured LWAs, BS could be mixed with suitable materials such as coal ash (Wang et al., 2009), inorganic waste (Tuan et al., 2013), organic waste (Chiang et al., 2009), river sediments (Liu et al., 2018a) and clay (Ayati et al., 2018).

Regarding the application of BS as a substitute of sand/stone, LWAs need to satisfy the strength requirement of ASTM C330 and ACI 318 for structural lightweight concrete, which requiring a minimum 28-day compressive strength of 17.2 MPa (Tuan et al., 2013). *Compressive strength*, as reported by several research, varies between 24 and 60 MPa, these results complies the value limit. This parameter is affected by (i) temperature and (ii) material mixed with BS. Wang et al. (2009) and Chiang et al. (2009) showed an increase (more than double) of compressive strength when sintering temperature goes up to 1050 °C–1100 °C. Chiang et al. (2009) also investigated the effect of organic residues mixed with BS: the results showed an increase of compressive strength with a decrease of rice husk added. Nevertheless, this result was not confirmed by Wang et al. (2009), that did not report any linear correlation between these parameters.

As concern the *bulk density*, different authors (Huang and Wang, 2013; Tuan et al., 2013) measured different values (0.5–1.5 g cm^{-3}), which is mainly related to sintering temperature and percentages of material mixed with BS such as compressive strength. As reported by Tuan et al. (2013) an increasing of temperature, for instance from 850 °C to 1100 °C, and percentages of waste glass powder mixed with BS, from 30% to 50%, involved a reduction of bulk density about 20–30%. In opposite, with the same sintering temperature, but with a 10% of waste glass powder mixed with BS, they showed an increase (of 10%) of bulk density.

Several authors also investigated the *water absorption*. For instance, Huang and Wang (2013) observed that the water absorption rates of the LWAs ranging from 0.5% to 15%. The increase of different materials/residues, such as clay (Ayati et al., 2018), rice husk (Chiang et al., 2009) and coal ash (Wang et al., 2009), mixed with BS involved a growth of water absorption. However, Tuan et al. (2013) highlighted that the water absorption decreases when increase the amount of waste glass powder mixed with BS.

The most important parameter that affects the water absorption of LWAs is the sintering temperature. Generally, as reported by Tuan et al. (2013), the water absorption of sintered samples decreased when the heating temperature increased. Moreover, higher sintering temperatures are advantageous for the stabilization of heavy metals, that can be stabilized in LWAs, preventing their release and secondary pollution of the environment (Xu et al., 2013). In fact, Lynn et al. (2018) demonstrated that for the lightweight aggregates made by BS ash and sintered at 1050 °C, the leached concentration of As, Ba, Cd, Cr, Pb, Hg and Se has been below detection limits.

Table 5
Summary of literature information regarding the main mechanical properties of bricks and ceramic products made with the addition of biosolids (BS). wt%: weight %; n.a.: not available.

Properties	Biosolids [wt%]	Results	References
Brick mass	n.a.	During the firing process brick mass can significantly decrease due to the BS organic matter reduction; the weight loss on ignition increase according to the percentage of sludge within the bricks	Liew et al. (2004a), Ukwatta et al. (2015)
	5	The decomposition of organic matter occurred between 200 and 550 °C. The first exothermic peak (200–400 °C) is associated with biodegradable materials, undigested organics, and dead bacteria, as well as the emission of semivolatile compounds	Martínez-García et al. (2012)
Firmness and compaction (measured by water absorption behaviour)	n.a.	The water absorption of the bricks increases with increased BS addition and therefore leads to decreased resistance to weathering	Martínez-García et al. (2012), Ukwatta et al. (2015)
	25	The bricks absorbing capability has increased to an average of 160% more than control brick	Ingunza D. et al. (2011)
	n.a.	The water absorption increases with BS percentage with a linear relation	Liew et al. (2004a), Jordán et al. (2005)
Shrinkage	0–20	It is affected by firing temperature and the proportion of BS in the mixture	Weng et al. (2003)
	n.a.	Shrinkage grows with the increase of BS in the mixture since the swellability and the organic content of the sludge are much higher than those of clay	Martínez-García et al. (2012), Ukwatta et al. (2015)
	n.a.	Decrease with the increase of BS in the mixture	Liew et al. (2004a), Jordán et al. (2005), Monteiro et al. (2008)
Compressive strenght	n.a.	Greatly dependent on the amount of sludge in the brick: higher amounts of BS in the mixture involve lower strength	Martínez-García et al. (2012), Ukwatta et al. (2015)
	25	Reduction of more than 50% of the compressive strength of the brick samples	Ukwatta et al. (2015)
	0–25	All bricks satisfied (14–42 MPa) the minimum requirement (5 MPa) for the compressive strength. The organic content present in the raw mixture has a significant impact on the compressive strength of the final product	Mohajerani et al. (2019)
	5–20	5% addition of BS in the mixture can significantly affect the compressive strength performance of bricks. Their lost up to 70% of maximum strength in the bricks manufactured with 20 wt% of BS	Ingunza D. et al. (2011)
Firing temperature	0–10	Greatly dependent on the amount of BS in the bricks. With 1000 °C, strength values close to those of standard clay bricks (roughly 20 MPa) are obtained	Weng et al. (2003)
Freezing resistance	0–15	No cleavage, fissure or scalping have been encountered in samples; superficial deterioration has been observed in the case of samples with higher sludge content	Martínez-García et al. (2012)
Thermal conductivity	25	Decreased from 1.08 (control) to 0.81 W m^{-1} K^{-1} in the bricks with positive implication in terms of energy savings	Ukwatta et al. (2015)
	25	It decreased up to 39% (control: 1.09 W m^{-1} K^{-1})	Mohajerani et al. (2019)

5.4. Cement

Concrete is one of the most commonly used construction materials in the world (Khatib, 2016). Portland cement, the primary constituent of concrete, is produced and used in large quantities: for instance, about 237 million tons only in the European Union. It is well known that the production of OPC (Ordinary Portland Cement) is highly energy intensive and releases significant amount of greenhouse gases such as CO_2 (Zhang et al., 2018). Currently, as reported by Kupwade-Patil et al. (2018), OPC production accounts for approximately 5% of the CO_2 emissions in the world.

Three different strategies for minimizing the environmental impacts can be adopted: (i) the reduction of the cement use in a concrete mixture, and the cement replacement with appropriate alternative (ii) raw materials and (iii) fuels. *Reduction in cement use* in a concrete mixture is most easily achieved through the replacement of OPC with other pozzolanic or hydraulic materials (Aï;tcin, 2000).

5.4.1. Biosolids as supplementary cementitious materials

The most common *supplementary cementitious materials* (SCMs) are industrial by-products used in the concrete mixture; these include, for instance: ground-granulated blast-furnace slag, silica fume, metallurgical slags, siliceous and calcareous fly ashes, circulating fluidized bed combustion fly and bottom ashes, spent foundry sand, chemical gypsum and sewage sludge (Khatib, 2016; Strigáč, 2015).

As reported in many researches, BS can be used as *substitute of raw materials* (Ahmad et al., 2016; Liu G. et al., 2015; Valderrama et al., 2013). Among the sludge derived from WWTPs, dried biological SS is the most investigated for raw materials recovery in the cement kilns factories (Husillos Rodríguez et al., 2012; Samolada and Zabaniotou, 2014). Moreover, waterworks sludge (Chen et al., 2010), and dried industrial sludge (Arsenovic et al., 2012) have been investigated.

The use of BS in the cement production is influenced by many factors although the co-processing of BS in cement kilns has yet been widely employed at the full-scale plants in the United States, Europe, Japan and other developed countries (Lv et al., 2016; Rahman et al., 2015).

According to Stasta et al. (2006), BS can be used in the cement kilns if comply, at least, with the following characteristic parameters: (i) maximum moisture content of 20%, (ii) low heat value (LHV) of 9 MJ kg^{-1} and (iii) granulometry between 0 and 5 mm.

BS produced in WWTPs contains useful compounds that can be used for the production of OPC; for instance, SS contains CaO, SiO_2, Al_2O_3 and Fe_2O_3 that represent, since as a first approximation, the four major oxides of Portland cement clinker (Valderrama et al., 2013; Yen et al., 2011). Other useful compounds that can be find in the BS and that could affect the burning process (clinkering, cooling, and emission) of the Portland cement are chlorides (typical concentrations of those compounds are reported in Table 1) and phosphate. Chlorides, as reported by Kwon et al. (2005) and Maki (2006), increase the burnability of the raw meal and allows higher contents of alite (tricalcium silicate, 3CaO SiO_2, called as C_3S) at the same clinkering temperature. Moreover, chlorides have a great capacity for reducing the viscosity of the liquid phase and can improve the solubility of CaO (CaO is highly soluble in liquid phases rich in halogen).

Phosphate in Portland cement should range between 0.3 and

0.5 wt%, typically it is in the order of 0.2%. In laboratory experiments performed by Fukuda et al. (2010) and Pacheco-Torgal et al. (2013), it was shown that the addition of a small amount of P_2O_5 suppress the 'dusting effect' due to the transformation of β-C_2S to γ-C_2S. Authors agreed that BS incorporation into cement raw meal was effectively limited by the phosphate content which, up to 0.7%, began to increase belite (dicalcium silicate, 2CaO SiO_2, called as C_2S) formation at the expense of alite causing increased setting times and lower strength development in pastes. Moreover, also the Sulphur (S^{6+}) content can influence the characteristics of cement; Pacheco-Torgal et al. (2013) reported that SO_3 and P_2O_5 decrease both the viscosity and surface tension of the liquid as well as the polymorphic form of C_3S. In addition, Naamane et al. (2016) showed that the high amounts of P_2O_5 and SO_3 in BS calcined in temperature range 700–800 °C increase water demand and setting time compared to the control mortar. The addition of SO_3 or $SO_3 + HPO_4^{3-}$ simultaneously reduces the burnability, whereas it is improved with the addition of $SO_3 + HPO_4^{3-}$ and F^- (Maki, 2006). Finally, alkali metal oxides (Na_2O and K_2O) increase the viscosity and decrease the surface tension of the liquid phase (Pacheco-Torgal et al., 2013).

As shown in Table 1, *heavy metals* can be found in the biological SS and therefore in BS. Many authors investigated the effects of heavy metals on cement properties (Espinosa and Tenório, 2000; Gineys et al., 2011; Stephan et al., 1999). For instance, Gineys et al. (2011) explored the maximum amount of Cu, Ni, Sn, and Zn that could be incorporated in a laboratory clinker and found the following threshold limits: 0.35% of Cu, 0.5% of Ni, 1% of Sn and 0.7% for Zn. Murat and Sorrentino (1996) and Espinosa and Tenório (2000) studied the effects on cement properties when adding BS containing Cr as the predominant heavy metal. Authors concluded that the largest amount of Cr was trapped in Portland cement. All authors also concluded that Cr, Ni, and Zn in the BS had no impact on cement mortar strength or initial setting time or hydration of cements because are typically lower than threshold limits.

The amount of BS that can be added as raw material substitute can range from 5 to 15 wt% (Johnson et al., 2014; Lin et al., 2012). Different authors studied the effects of BS, in this case dried biological SS, as additive on cement property in the process of clinker burning. Authors refer that, due to the organic content of the BS, in order to avoid undesirable changes in the mechanical and rheological properties of pastes and mortars, BS replacement may not exceed a replacement rates greater than 10%.

5.4.2. Biosolids as alternative fuels

The inclusion of BS in cement production kilns allows this material to be used not only as supplementary cementitious material but also as an alternative fuel with substantial energy and environmental savings. In fact, its CO_2 emissions are lower than coal (Husillos Rodríguez et al., 2012; Liu G. et al., 2015). Moreover, co-combustion of BS in cement kilns represents an advantage for a low investment cost and rapid implementation (Zabaniotou and Theofilou, 2008). Indeed, usually there are no additional investment costs for off-gas cleaning (Stasta et al., 2006). Wang et al. (2008) reported that dewatered BS can be utilized; approximately 5 wt% may be co-fired together with coal without compromising the temperature of the combustion process.

The effects on the air emissions due to the co-processing of BS in cement kiln are complicated. For instance, Cao et al. (2013), Liu G. et al. (2015) and Fang et al. (2015) showed that BS can be used as a reducing agent for NO_x removal. Fang et al. (2015) investigated, especially, the influences of BS feed rate, feed point, feed method, and air-staged combustion on NO_x removal. Results indicate that the use of BS as a secondary fuel is conducive to NO_x reduction, which depends primarily on the feed rate and feed point.

Conversely, BS can also make the pollutants more complex, even cause the emission of unconventional air pollutants, such as PAHs, dioxins and heavy metals (Lv et al., 2016; Rovira et al., 2014). For instance, when BS is co-processed in cement kiln, PAHs emission shows a trend of increase although its emission is small (Conesa et al., 2011; Gálvez et al., 2007).

Some authors mainly focused on investigating the effects on human health risks derived from the exposure to PCDD/Fs and metals emitted by a cement kiln that co-process BS. For instance, Rovira et al. (2011) found that PCDD/Fs emission slightly increases when BS is co-processed although they were within the ranges considered acceptable by international regulatory organisms. As concern heavy metals, Stasta et al. (2006) and Rulkens (2008) agreed that they are immobilized within the cement.

6. Other reuse options

6.1. Adsorbent materials

An alternative route of BS reuse is the conversion into adsorbent material with sustainable methods to allow its reuse in water treatment applications (Wu et al., 2015; Xu et al., 2015). The first to recognize BS potential as a feedstock for producing activated carbon was Kemmer et al. (1971), since then different study analysing the production of adsorbent from BS by its carbonisation (Cheng et al., 2016; Smith et al., 2009).

Adsorbent material is obtained from conversion of BS via pyrolysis, which allow to achieve, therefore subjecting to an activation process, the production of char, a low cost adsorbent with good adsorption properties in water treatment applications (Hadi et al., 2015; Kimbell et al., 2018; Liu et al., 2010).

Numerous methods of activating carbons are available, but it's possible grouped them in two categories: physical activation and chemical activation (Smith et al., 2009).

Physical activation of BS is commonly carried out with carbon dioxide (Marques et al., 2011), steam (Li et al., 2011; Smith et al., 2012) or air (Monsalvo et al., 2011) and prescribes two steps: carbonisation and activation (Alvarez et al., 2016). Carbonisation allows breaking down the cross-linkage between carbon atoms in order to increase the Brunauer–Emmelt–Teller (BET) surface area of the resulting char (Alvarez et al., 2016). The main parameters that influence this process are: heating rate and dwell time (Seredych and Bandosz, 2007; Yilmaz et al., 2011), mesoporosity, macroporosity and feedstock type (Ding et al., 2012; Xu et al., 2015). The transformation of BS in char is completed by activation with gas at high temperature (800–1200 °C) for further development of the BS-based adsorbent's (BBA) porosity (Alvarez et al., 2016). Lots of activation agents are reported in literature, including N_2, CO_2, steam, O_2/Air, etc.; in general, steam and CO_2 are the most commonly used (Alvarez et al., 2016; Smith et al., 2009).

Another possibility is chemical activation, which depends on temperature, activator type and concentration and binder addition. There are a wide variety of activators with different activation temperature, but the most common used include KOH, NaOH, $ZnCl_2$ and H_3PO_4 (Alvarez et al., 2016). In particular, KOH was proved to be an effective activator in producing BBAs with high BET surface areas when is obtained through carbonisation and activation (Alvarez et al., 2016; Smith et al., 2009).

Results of conversion of BS to adsorbent depend on different treatments (physical or chemical) and parameters (temperature, time, acid washing). Generally surface areas of char ranges from 100 to 2000 $m^2\,g^{-1}$, where the best results are obtained with chemical activation. The use of KOH gives the opportunity to reach BET surface areas between 1000 and 1900 $m^2\,g^{-1}$ (Lillo-Ródenas et al., 2008; Smith et al., 2009), but high value can be achieved from activation with NaOH, 1224 $m^2 g^{-1}$ (Ros et al., 2006), or $ZnCl_2$, 700 $m^2 g^{-1}$ (Chen et al., 2002; Tsai et al., 2008), too.

BET surface areas obtained with physical activation vary from 100 to 500 $m^2 g^{-1}$ due to temperature, time and acid washing (Bandosz and Block, 2006). Acid washing with HCL, which dissolve inorganic content with a consequence increase of surface of char, is investigated by Ros et al. (2007).

The adsorbent material obtained from BS may be used for different applications, the most applied is the adsorption of volatile organic compounds (VOCs) (Anfruns et al., 2011; Benintendi, 2016); removal of NO_x (Pietrzak and Bandosz, 2008, 2007) and H_2S (Bandosz and Block, 2006; Sioukri and Bandosz, 2005) are typical examples. The adsorbent could be used for adsorption of dyes, phenolic compounds and antibiotics too (Kimbell et al., 2018). In recent years, dyes represent a significant problem (Collivignarelli et al., 2019b). The removal of anionic and cationic dyes with BS derived adsorbent materials is reported in different articles (Bandosz and Block, 2006; Rozada et al., 2003). As regards the adsorption by carbonaceous adsorbents of phenol/phenolic compounds and antibiotics are describes by Dąbrowski et al. (2005) and Ding et al. (2012), respectively. Another important application is the adsorption of heavy metal: cadmium (Gutiérrez-Segura et al., 2012), hexavalent chromium (Agrafioti et al., 2014; Deng et al., 2010), mercury (Bandosz and Block, 2006) are typical examples.

The two most significant factors for the BBAs to evaluate their economically feasible application are adsorption capacity and cost. The cost of BBAs depends on various factors, including local availability, nature of BS, processing required, preparation conditions and both recycle and lifetime issues (Xu et al., 2015). The production of BBAs costs approximately 0.1–0.2 US \$ kg^{-1}, which is cheaper than commercial activated carbon (2.0–2.2 US \$ kg^{-1}) (Ahmaruzzaman, 2011; Lin and Juang, 2009), in addition to a good capacity of adsorption: for examples high methylene blue adsorption capacity (260 $mg g^{-1}$) is connected with a low cost (365 US \$ t^{-1}) (Xu et al., 2015).

6.2. Source of phosphorus

Considering that the phosphorus reserves will run out quickly, finding alternative sources of phosphorus is an urgent matter (Lin et al., 2018). BS have a high phosphorus content (approximately 8% w/w), making it a potential source of nutrients. Phosphorus recovery process from BS is composed in relation to the different technologies and different characteristics of organic matter used (sludge liquor, digested or non-digested sludge). Direct extraction of phosphorus from BS allows to reduce the high energy associated with ashing of BS, that represents a commonly practiced in most European countries (Shiba and Ntuli, 2017). Recovery from BS requires a prior hydrolysis, disintegration and dissolution, while from liquid phase the principal treatments concern the precipitation or crystallization (Blöcher et al., 2012).

6.2.1. Recovery by precipitation

P-recovery through precipitation can be subdivided in different group: precipitation in the BS with or without prior leaching, adsorption to a carrier and pellet formation (Sartorius et al., 2011). These techniques are based on minerals precipitation in the form of struvite, hydroxyapatite or calcium phosphate. The most important advantage is the ability to obtain high-quality phosphoric minerals and the use of BS for direct applications in agriculture (Cieślik and Konieczka, 2017). Furthermore, precipitation of struvite allows to improve the compost quality (if composting is the final reuse of BS) through conservation of nitrogen: it is shown a gradually increased and stabilized concentration of NH_4^+ when struvite precipitation is applied in composting process. Also for this reason, precipitation is the major process adopted for BS P-recovery (Kataki et al., 2016). Shiba and Ntuli (2017), by means of acid leaching followed by ion exchange and precipitation using magnesium hydroxide and ammonium hydroxide, shown a technique for recovering the P nutrient (about 82% of P was extracted as calcium phosphates and aluminium phosphates). Moreover, Nakagawa and Ohta (2019) recovered up to 40% of P as calcium hydroxyapatite with a full-scale plant that treated BS ash.

6.2.2. Recovery by wet chemical process

P-recovery from digested BS is obtained also through wet-chemical process, applying extraction chemicals, pressure and temperature in relation to the starting material used. That approach provides adding a strong acid to decrease the pH in order to dissolve the initially bound of the phosphorus. The amount of chemicals consumed depend on BS characteristics (e.g., water content) and the P-recovery rate is associated to the operative parameters (Egle et al., 2015). The principal issue is concerned the metals dissolved during this wet-chemical extraction, that requires an intensive use of chemicals for separate they before the metal ions and the phosphate product can be precipitated (Sartorius et al., 2011). Other questions from this approach are: (i) complexity of treatment due to BS composition (in particular from chemical precipitation with Fe or Al) (ii) possible production of waste (i.e. acidified sludge), that required further treatments and (iii) high chemicals consumption (wet chemical) and their costs (Egle et al., 2015). The use of a P-recovery process also depends on the pollutant content in the BS (mainly heavy metals): wet-chemical leaching and wet oxidative approaches shows a depollution potential up to 98% of all heavy metals for BS (Egle et al., 2016).

6.2.3. Recovery by crystallization

In recent years, nutrients recovery from BS via crystallization was developed for the final production of magnesium ammonium phosphate (struvite) and calcium phosphate. In order to recovery P-nutrient via crystallization, a solubilization of P to release of phosphate to the supernatant is necessary (Tyagi and Lo, 2013). Up to 85% of dissolved P can be recovery from digested supernatant by crystallization or instant precipitation (Egle et al., 2016).

7. Summary of the reuse options

As pointed out in this work, land application of BS improves soil properties, but requires further investigation, especially for effects connected with OCs. On the other side, as showed, the presence of heavy metals and pathogens does not imply problems for human health. Heavy metals can be immobilized by some plants species protecting the food chain and human health; pathogens can be inactivated in particular by thermal processes and aerobic/anaerobic digestion. In opposition several authors highlighted than, in some cases, it is better to prevent the spreading on land for the consequence connected with human health.

Furthermore, several studies have examined materials with BS, as a substitute of raw material, in engineering application, for instance as base layer, and sometimes as load bearing media, in road construction. Results highlighted the good qualities of cement, LWAs and bricks, obtained with BS addiction; moreover, no problems have been shown for human health. However, obstacles to their use are due to: (i) opposition of population due to “unfamiliarity” about these novel practices, and (ii) stringent limit values imposed on waste, which are more restrictive than other materials.

Although lack of social acceptance, the reuse of BS in the engineering sector would allow energy and environmental savings, emission reduction and immobilization of heavy metals.

Regarding the reuse of BS as adsorbent materials, the low

Table 6
Biosolids (BS) reuse options and their respective advantages/disadvantages.

Type of reuse		Advantages	Disadvantages
Agriculture and abandoned mine site		✓ Improve soil structure	✗ Release odorous volatile organic compounds (VOCs)
		✓ Decrease bulk density	✗ Raising of the level of toxins in soil
		✓ Increase soil porosity	✗ Potential reduction of biodiversity in the slow and long term
		✓ Increase soil moisture retention and hydraulic conductivity	✗ Greenhouse gas emissions
		✓ Increase crop yield	✗ Possible spread of human pathogens
Construction sector	*Road construction*	✓ Similar properties to soil	✗ Present high compressibility
		✓ Increase growth of the plants on embankments	✗ Possible high rates of creep
	Bricks and ceramics products	✓ Low costs	✗ High percentages of sludge in the mixture are not recommended
		✓ Reduce impact related to quarry activities	✗ Increase the degree of shrinkage
		✓ With low percentage of sludge, products respect mechanical requirements	✗ Possible very low release of substances
		✓ No environmental restrictions	
	Lightweight aggregates	✓ Saving of non-renewable materials	✗ Generally requires high sintering temperature
		✓ Aggregates satisfying strength requirement	
	Cement production	✓ Property similar to cement	✗ Probable change in the characteristics of the final product
		✓ Energy and environmental saving	✗ Possible emission of PAHs, dioxins and heavy metals.
		✓ Low investments cost and rapid implementation	
Other	*Adsorbent materials*	✓ Low cost compared to commercial activated carbon	✗ Great variability of the adsorption capacity depending on the type of activation
		✓ Generally good adsorption capacity	
		✓ Adsorption also of dyes, heavy metals and antibiotics	
	Source of phosphorus	✓ High-quality phosphoric minerals	✗ Pre-treatments necessary
		✓ Reduce high energy associated with ashing of biosolids	✗ Some processes are complex
		✓ After P precipitation, the use of biosolids for direct applications in agriculture	
		✓ Improve the compost quality	

production costs, compared to traditional adsorbent materials, represent the main advantage. Moreover, many studies have also shown the feasibility of using BS as source of phosphorus for a subsequent recovery, but the P-recovery processes could be complex. These reuse options are a very significant result that reduces the high energy associated with the incineration of BS, which is still a common practice in most European countries.

Table 6 shows the main routes for BS reuse. They are classified in three macro categories: agriculture and abandoned mine sites (section 4), engineering applications (section 5) and other types of reuse (section 6). For each type of reuse option, the main advantages and disadvantages are reported.

8. Conclusions

In the context of a circular economy, this paper discussed the main routes for BS reuse in order to increase the matter recovery. Around 250 papers, reviews, books and conference proceedings have been examined. The applications of BS on land, on engineering fields, as adsorbent materials, and as a source of phosphorus are explored. Certainly, considering the large amount of BS produced and the results reported by literature, their reuse represents a suitable and necessary long-term solution.

Regarding the BS reuse on land, this work highlights the importance of the continued monitoring and data collection in order to evaluate the significance and implications of emerging OCs. The reuse of BS in the engineering fields is certainly interesting and it would allow energy and environmental savings, emissions reduction and immobilization of heavy metals. This sector, together with the production of adsorbent from BS, should be further studied in future in order to achieve a significant reduction in the use of natural raw materials. Furthermore, considering that the phosphorus reserves will run out quickly, finding alternative sources represents one of the main challenges that must be addressed. With their high nutrient content, the BS can represent a viable solution but further studies on this topic are needed in order to achieve the goal.

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