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Standardization: A Necessary Support for the Utilization of Sludge/Biosolids in Agriculture

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Abstract: One of the issues facing modern society, regardless of the socio-economic level of the communities involved, is the development of sustainable strategies for the management of sludge/biosolids. Nowadays, it is imperative to replace solutions aimed at simply "disposing of" with those oriented toward "maximizing recovery benefits". It is desirable that agricultural use remains the main option in sludge/biosolids management; however, to ensure effective and safe agronomic benefits, correctly fulfill the legal requirements, and build stakeholder and public confidence, rigorous and sustainable procedures need to be established. The development of realistic and enforceable regulations is crucial, as they represent the right balance between the different aspects of coordinated and effective management. Furthermore, it is important to recognize that regulations must be supported by standardized characterization procedures and good practice guidelines because well-defined procedures allow the legal requirements to be correctly and uniformly met, as well as to reliably compare the results obtained under different conditions and their wide application in different regulatory contexts. In this article, the main aspects for (i) the sustainable application of sludge/biosolids in agriculture and (ii) the development of standardized characterization methods and procedures, thus ensuring effective agronomic benefits and guaranteeing quality/safety of agricultural products, are discussed. Some pieces on the evolution of European legislation in this field are also provided. Details and results of the research activities behind the development of these methods/procedures can be found in the referenced documents.

Keywords: agricultural utilization; biosolids; characterization; land application; sustainable management; sewage sludge; standardization

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1. Introduction

The management of sewage sludge in an economically, environmentally, and socially acceptable manner, i.e., in a sustainable manner, is one of the critical issues facing modern society because of the rapid increase in sludge production as a result of (i) the growing availability of household running water with the consequent production of wastewater, (ii) extended sewerage, (iii) new work installations, and (iv) the upgrading of existing facilities. Subsequently, this has led to increased difficulties in properly locating disposal works and complying with even more stringent environmental quality requirements imposed by legislation [1]. In addition, the management of sludge often requires a considerable amount of the overall operating budget for the entire wastewater treatment plant.

This topic is also well-recognized by Sustainable Development Goal 6 (SDG 6) of the UN Agenda 2030, Tasks 6.2 and 6.3 in particular, which are addressed to "*achieve access to adequate and equitable sanitation and hygiene for all*. . ." and ". . .*substantially increasing recycling and safe reuse globally*. . .", considering that across the world, 2.4 billion people still lack improved sanitation facilities and 1 billion people still practice open defecation [2].

In this regard, it is important to note that the term "*biosolids*" has been introduced into common language to replace the term "*sludge*", which is perceived in a more negative way, in order to emphasize that a waste product can have a beneficial use.

Therefore, there is a need to move from the concept of "*waste*" to that of "*product*" by developing sustainable management strategies aimed at maximizing the benefits of recycling and the consequent need for new resources (Figure 1). Furthermore, it should not be forgotten that the dynamics of recycling flows are substantially different from those of acquiring new resources and/or producing new waste.

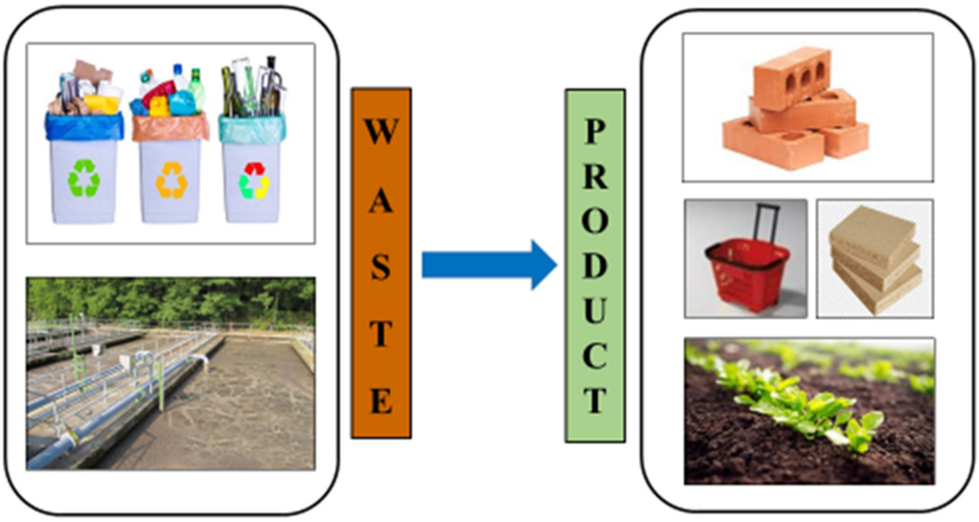


Figure 1. From "*waste*" to "*product*": examples.

With this in mind, the practical application of the sustainability concept for sludge/biosolids management requires the following [3]:

- Considering sludge management as the "*locomotive*", not the "*last wagon*", of any water/wastewater system;
- Taking into account "*technical*" actions aimed at maximizing the recovery benefits;
- Taking into account "*institutional/governance*" actions mainly aimed at issuing appropriate regulations.

Indeed, in traditional approaches, sludge generally plays a minor role in the planning of water/wastewater management systems, as it is at the end of the water cycle; in other words, the "*last wagon*" of the train. However, the selection of the most appropriate sequence for wastewater treatment is strongly driven by the sludge reuse/disposal options available in the specific local context; thus, sludge management should really play the role of "*locomotive*" [4].

In all cases, the adoption of technologies aimed at "*maximizing recoveries*" of materials and/or energy instead of those aimed at the "*simple disposal*" of sludge is important for the development of "*realistic and enforceable regulation*" because optimal and environmentally safe sludge management can only be achieved through objective, transparent, and legally conducted operations. Furthermore, regulations need to be supported by "*standardized characterization procedures*" and/or technical "*guidelines of good practices*" because only well-defined procedures allow for legal requirements to be fulfilled in a correct and uniform manner, thus building stakeholder and public confidence [5].

Additionally, digital transition can play an important role in addressing this management option [4].

Several options at different development levels are available for sludge/biosolids management; however, "*land application*" for agricultural purposes (or even for processing into fertilizers) will likely remain the main option due to its high environmental importance. Within this framework, adequate "*technical*" and "*institutional/governance*" actions are important to guarantee (i) effective agronomic benefits and (ii) the quality and safety of agricultural/food products.

2. Production and Composition

Examples of typical sludge quantities and concentrations of solids and nutrients are summarized in Table 1 [1]. The specific production of sludge ranges from 0.2 to 5.0 L/cap/d, with typical concentrations in the range of 0.7%–10.0%; the typical production of primary plus activated sludge from municipal plants is 2 L/cap/d at 4% solids concentration. The global production of sewage sludge is estimated at 45 Mdry-t/y [6].

Table 1. Typical sludge quantities and characteristics.

Type	Quantity (L/cap/d)	Solids Conc. (%)	Nitrogen (% DM *)	Phosphorus (% DM *)	Potassium (% DM *)
Raw primary	0.9–2.2	2.0–8.0	1.5–5.0	0.3–2.8	<1.0
Raw activated	1.4–7.3	0.2–1.5	3.0–10.0	1.0–7.0	0.1–0.9
Raw pr+act	1.8–2.8	3.0–6.0	4.0–6.0	1.0–1.2	—
Dig. pr+act	0.6–1.0	2.0–12.0	1.0–6.8	0.2–5.7	<4.0
Tertiary	0.2–8.0	3.0–10.0	—	—	—

* DM = dry matter.

In the EU, where the total population is about 500 million people, sludge production amounts to more than 13 Mt/y and shows an average generation rate of about 58.9 g/cap/d, ranging from 19.9 in Greece to 107.6 in Portugal, which depends on the water availability, population served, and level of treatment. There are large differences between Member States; however, on average, more than 60% is utilized in agriculture, approximately 25% treated in thermal processes, and 11% is in landfills.

According to data collected from 2500 larger facilities in the US, about 4.5 Mt of treated sludge or biosolids was generated in 2021, of which about 45% was used for agricultural purposes, 40% was incinerated, and 15% was landfilled [7].

According to China's Statistical Yearbooks, the total population of China is 1.4 billion people, of which the urban population is 689 million. The average sewage treatment rate in cities and county towns is about 97%, while the rural population of 498 million has a sewage treatment rate of about 28%; thus, the total population served by sewage treatment facilities is about 808 million. The total amount of sewage treated is 61.56 Gt/y, with a sludge production of 45.92 Mt/y, of which the land application rate is 14.97% [8].

Table 2 shows, for general information, the average concentrations in sludge/biosolids of organic matter and macronutrients, which are the components of greatest interest for the agricultural use of sludge [9]. Sludge essentially contains nutrients, including nitrogen, phosphorus, and potassium, but unfortunately also bacteria (e.g., Salmonella) and many other polluting substances whose amounts can be very different depending on the type and treatment of wastewaters in which they were originally contained. For this reason, facilities that monitor materials and perform sanitization treatments play a crucial role.

Monitoring and control activities that are already performed at wastewater treatment plants and at sludge treatment plants are even more important with regard to organic compounds, such as halogenated compounds, e.g., polychlorinated biphenyl (PCB) and polychlorinated dibenzodioxins/furans (PCDDs/Fs), perfluorinated compounds (PFCs), linear alkyl benzene sulphonates (LASs), and polycyclic aromatic hydrocarbons (PAHs). Their concentrations can vary depending on the influent characteristics; thus, their control or limitations at the source before they enter the wastewater treatment plant are effective tools to improve sludge quality and reduce health risks and handling costs.

Sludge/biosolids are organic matrices; thus, the degradation of components such as proteins, amino acids, and carbohydrates can lead to the emission of bad odors, which, although not a direct indicator of a health hazard, can cause discomfort, especially during handling. Appropriate stabilization and digestion treatments, as well as proper application techniques, can help reduce this issue.

Table 2. Average concentrations of organic matter and plant macronutrients in sludge/biosolids.

Origin	Industrial		Municipal Biosolids			
Type	Dairy (^)	Paper Mill (^)	Liquid * (^)	Digested (^)	Lime Treated (^)	Composted (^)
Organic matter	60–80	60–80	60–70	40–50	40–50	50–60
Nitrogen (N)	3–8	0.5–2.5	6–7	3–5	3.5–4.0	2–3
Phosphorus (P_2O_5)	2.5–8.0	0.15–1.50	4–7	3–6	4.0–4.5	3–5
Potassium (K_2O)	0.1–0.3	0.05–0.15	0.6–0.8	0.3–0.7	0.4–0.5	1.0–1.5
Sulfur (SO_3)	-	0.15–0.90	2.0–2.5	1.5–2.0	1.5–2.0	2–3
Calcium (CaO)	3–10	10–30	3–7	2–5	20–30	5–15
Magnesium (MgO)	0.5–1.0	0.3–0.5	0.5–0.9	0.6–1.2	0.5–1.5	0.6–1.0

(^) % by mass; * refers to biologically treated sludge (not digested) from small wastewater treatment plants.

3. Recovery Options

The adoption of technical solutions aimed at maximizing the recovery of materials and/or energy is necessary to effectively implement the sustainable management of sludge/biosolids.

The characteristics of the different technologies available for the treatment and management of sludge and the improvement of its quality are well known, so only a generic list is provided below. Details and results of the numerous research activities underlying the development of these treatments can be found in the literature.

The nutrient content of sludge and derived products (e.g., organic fertilizers, compost) is of high value; thus, its utilization in agriculture is a preferred option, especially for sludge/biosolids of better quality. In particular, sludge/biosolids represent a renewable source of phosphorus since white phosphorus (P4) and phosphate rock are included among the 20 critical raw materials (CRMs) for the EU [10]. Phosphorus can be recovered from anaerobically digested sludge or incinerated ash through innovative technologies discussed in [11]. It must also be considered that the use of biosolids directly adds this nutrient to the soil by implementing an important reserve mechanism.

Other possible material recoveries include the production of organic compounds (e.g., volatile fatty acids (VFA), polyhydroxyalkanoates, enzymes), coagulants, adsorbents, bricks, pumice, slag, artificial lightweight aggregates, ceramsite, and Portland cement [12].

Available options for energy recovery range from anaerobic digestion to thermal processes. Technologies such as wet oxidation, pyrolysis, or gasification can generate energy and produce usable/storable fuels and char; however, there are still some uncertainties about their performance and cost. Additionally, the use of microbial fuel cells for the direct conversion of sludge to electricity has been reported [13].

However, it is almost entirely unlikely that raw sludge, as produced in a wastewater treatment plant, already has the characteristics required for its sustainable use. Therefore, it is necessary to perform a series of treatments to obtain the qualitative and quantitative characteristics suitable for its intended use.

As shown in Figure 2, the (i) “*reduction of nuisances*”, i.e., the improvement of quality through stabilization/digestion processes that also involve a reduction in the putrescibility of organic substances and a certain level of inactivation of pathogenic microorganisms, and (ii) the "*reduction of volume*" through thickening/dewatering processes that allow for the obtainment of the most suitable solids concentration, volume, and physical consistency (liquid, paste-like, or solid) for the intended use, represent two unavoidable "*Hubs*" in sludge processing from its origin to the final destination [14].

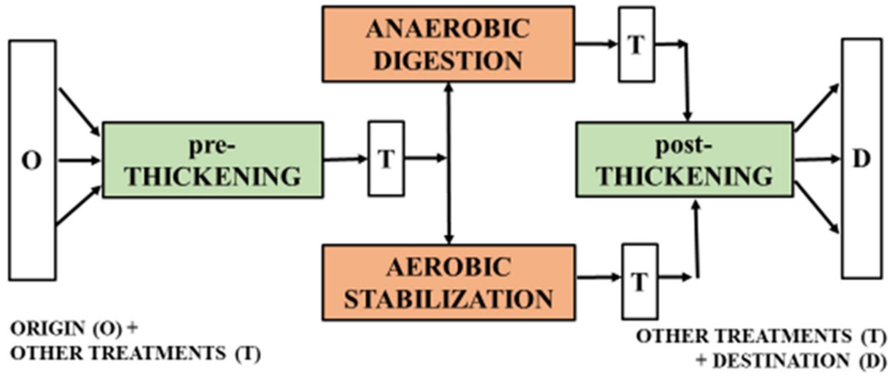


Figure 2. Technical "*Hubs*" in sludge processing from origin to destination.

It seems appropriate to mention that other specific treatments may be imposed by legislation to obtain better final characteristics for the sludge.

4. Agricultural Use

Utilization for agricultural purposes (directly or in the form of other organic products) and other land uses, e.g., reclamation and forestry, is likely to remain the major option for sludge/biosolids management as it involves the better usage of soil by improving its agronomic efficiency. For this purpose, the European Commission has recommended "*...better access to organic fertilizers and nutrients from recycled waste-streams, especially in regions with a low usage of organic fertilizers...*" [15].

This management option is useful for multiple reasons, as it influences many other aspects in addition to the purely agronomic ones, including chemical, physical, biological, sanitary, environmental, and commercial ones [9].

However, as previously mentioned [5], for correct and effective applications in agriculture and to obtain the expected benefits, it is necessary to focus on the development of

- Adequate "*regulation/legislation*", capable of encouraging the correct and safe use of sludge/biosolids;
- "*Standardized characterization procedures*" and/or "*Guidelines of good practices*" to fairly, consistently, and uniformly comply with legal requirements.

Legislation defines the general criteria to be followed for a correct sludge management and establishes the acceptable limit values in sludge and soil of the various parameters of interest. It should also be noted that the legislation develops over time in the full application of the "*precautionary principle*" aiming at providing clear and unambiguous rules.

Furthermore, sludge management is a highly site-specific operation; thus, each country, state, province, or other local institution generally adapts its legislation to the specific local context, including the economy, political and cultural priorities, availability of tools, development level, etc.

With reference, as an example, to the European Union countries, the agricultural use of sludge is currently regulated by the Directive 86/278/EEC, dated 12 June 1986, which is intended to regulate the use of sludge in agriculture in order to avoid harmful effects on the soil, vegetation, animals, and humans, while encouraging the correct use of sludge. This Directive leaves Member Countries the possibility of modifying the limits for the envisaged parameters and/or adding others.

However, the need to increasingly and effectively satisfy the current environmental protection needs and expectations, e.g., the regulation of emerging contaminants present in sludge, such as pharmaceutical products and microplastics, has led the European Commission to activate the revision of the Directive 86/278 from the more general perspective of the sustainability of the recovery activity in relation to the quality of the biomass and the protection of all potentially recoverable resources.

In all cases, a number of requirements, such as guide and/or limit values, are contained in the legislation and regulation, but methods for the determination of the respective parameters are often not available, sufficiently described, or reliable in terms of reproducibility and repeatability. Therefore, the evaluation of sludge properties through standardized methods and procedures is a tool of primary importance to support regulation/legislation for an effective and sustainable application of sludge/biosolids in agriculture to ensure (i) effective agro-nomic benefits and (ii) quality and safety of agricultural products and food.

5. Characterization Parameters

Numerous parameters can be used for the characterization of sludge/biosolids. The contents of total solids, or complementary moisture, suspended solids, volatile solids that are correlated to the organic content of sludge, and organic carbon are the characterization parameters of interest for all sludge/biosolids treatments and management operations [1].

Numerous other characterization parameters, specifically linked to the application of sludge/biosolids to soil/agriculture, are available. The main ones are discussed below, according to the various aspects involved in this operation, which are as follows:

- Agronomic/chemical;
- Physical;
- Biological/microbiological/sanitary;
- Environmental;
- Commercial/logistical/organizational/institutional.

5.1. Agronomic/Chemical Aspects

The use of sludge/biosolids and other organic fertilizers in agriculture generates positive effects that are immediately visible to farmers because they lead to a general increase in agricultural production by nourishing the soil and not only the plants (Figure 3).

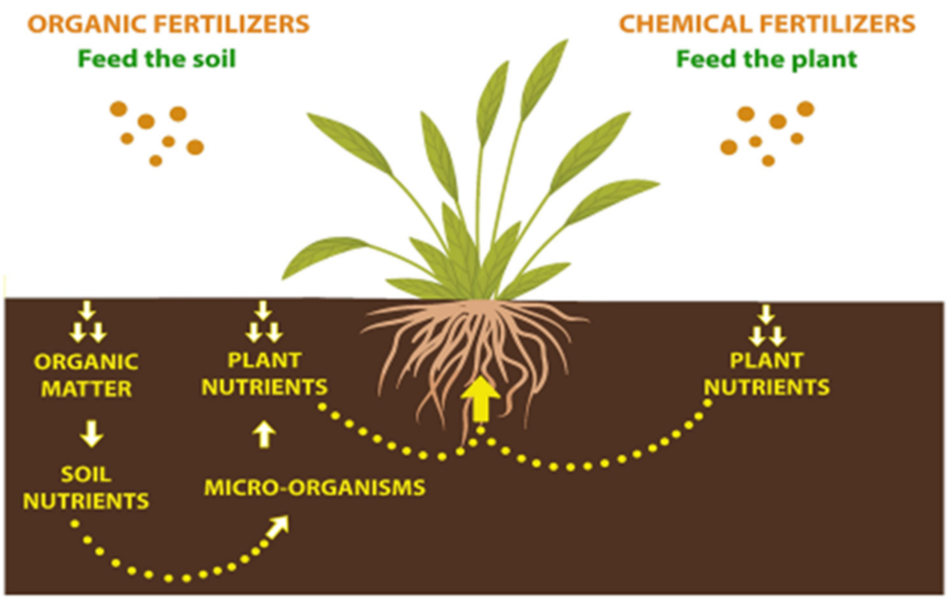


Figure 3. Mode of action of fertilizers.

Regarding agronomic and chemical aspects, the content of nutrients, e.g., phosphorus and nitrogen, and of other parameters, e.g., heavy metals and organic compounds, is of fundamental importance, as those elements affect the amount of biosolids that can be safely spread onto the soil. The main objective in agriculture is to only use sludge/biosolids of higher quality in order to guarantee the quality of soil and agricultural products.

Within this context, the release of nutrients from sludge/biosolids depends on the (i) concentration and properties/forms of the nutrients, (ii) period of application to the soil, and (iii) application techniques.

With regard to nitrogen, its forms in sludge/biosolids are organic N, ammonium (NH^{4+}), and nitrate (NO^{3-}), of which the last two forms are available to plants. Organic N has to be converted to its inorganic form by the mineralization of organic matter; thus, it provides slow-release nitrogen for crops. Once the nitrogen demand has been met, the nitrogen's percolation in the soil to groundwater must be minimized. For this reason, it is necessary to comply with the dosages established by the legislation on the protection of waters from nitrate pollution, which summarizes the agronomic needs of crops required for their growth and water protection.

Phosphorus, whose concentration in biosolids is lower than nitrogen, is currently of great interest because of the scarcity of this matter. The accumulation of this nutrient into the soil through the application of biosolids can play a key role in ensuring continuity of fertilization based on the principles of the "*circular economy*". This mechanism is facilitated by the fact that phosphorus is characterized by reduced mobility.

For agricultural applications, the maximum allowable concentrations of heavy metals (such as mercury, copper, cadmium, chromium, lead, zinc, and nickel) or organic micropollutants, including AOXs (adsorbable organic halogenated substances), LASs (linear alkylsulfonates), NP/NPEs (nonylphenol and its ethoxylates), PAHs (polycyclic aromatic hydrocarbons), PCBs (polychlorinated biphenyls), and dioxins, are defined by legal regulations. Many of the above chemical parameters are often causes for concern. However, it should be considered that the concentration limits imposed by the reference legislation are in favor of prudence and balance the potential environmental risks with the needs of soil and crops. This is the case for zinc, which is an essential trace element for all plants, especially in the early vegetative stages [16]; zinc, similarly to other metals, has been subjected to technical regulations, but only for its necessary limit value.

"*Microplastics*" represent a recent topical issue. They are defined as any synthetic solid particle or polymer matrix, insoluble in water, with a regular or irregular shape, and a size between 1 μm and 5 mm. Plastics are often difficult to trace due to their small size and different chemical properties. It is clear that these components are completely undesirable in any natural environment, whether in the soil or water, and it is equally evident that when an environmental matrix is affected by an abnormal accumulation of these anthropogenic components, the effect inevitably spills over to other compartments.

However, it cannot be denied that this problem is, more than any other, the direct consequence of a production system that has not considered this aspect for a prolonged period of time. As a matter of fact, microplastics are intentionally added to a large number of products, such as plant protection products, cosmetics, domestic and industrial detergents, paints, and other products for industrial use that have been used for years without considering their secondary effects, including a number of bad habits on the part of citizens, e.g., incorrect waste separation or abandonment of waste.

To prevent the possible accumulation of microplastics in the soil, it is, therefore, necessary to first identify what the possible contributions could be, considering both the most impactful ones (e.g., use of fertilizers derived from materials from separate collections) and the secondary ones. This must be considered together with the progressive identification of standardized methodologies and procedures aimed at measuring the content of these components in various matrices. The analysis of the various flows must, therefore, become an indicator for correcting upstream behavior. Simultaneously, the data collected may also serve to implement filtration systems located downstream, for example, at sewage treatment plants [17].

Finally, it should be considered that when using the best management practices and proper organic fertilizers, the yield of an organic system can meet or even exceed that of a chemical system [18].

5.2. Physical Aspects

The knowledge of the physical properties of sludge allows for the prediction of its behavior when handled and submitted to almost all treatment, storage, and utilization/disposal operations. Physical consistency, or physical state, is, therefore, a characteristic of fundamental importance in sludge/biosolids characterization [19,20].

The following three different behaviors have been observed for sludge:

- *Liquid*—the ability to flow under the effect of gravity or moderate pressure and to conform almost instantly to the shape of the vessel containing it (i.e., sludge behaves as a liquid);
- *Paste-like*—the ability to flow under the effect of high pressures and to offer moderate resistance to the forces tending to deform it;
- *Solid*—the tendency to maintain shapes and dimensions while offering consistent resistance to the forces tending to deform it (i.e., sludge behaves as a solid).

A standard method to define the boundary area between liquid and paste-like behaviors (known as the limit of *Flowability*) has already been developed, while one between solid and paste-like behaviors (known as the limit of *Solidity*) is yet to be developed.

Indeed, the selection of the most suitable equipment and procedure for the land application, storage, and transportation of sludge/biosolids is strongly connected to its consistency. Similarly, compacting sludge in a landfill or forming a pile in composting depends on the sludge's consistency rather than its solids concentration [20,21].

Moreover, the actions exerted by sludge/biosolids on the physical properties of the soil are of great importance, as they

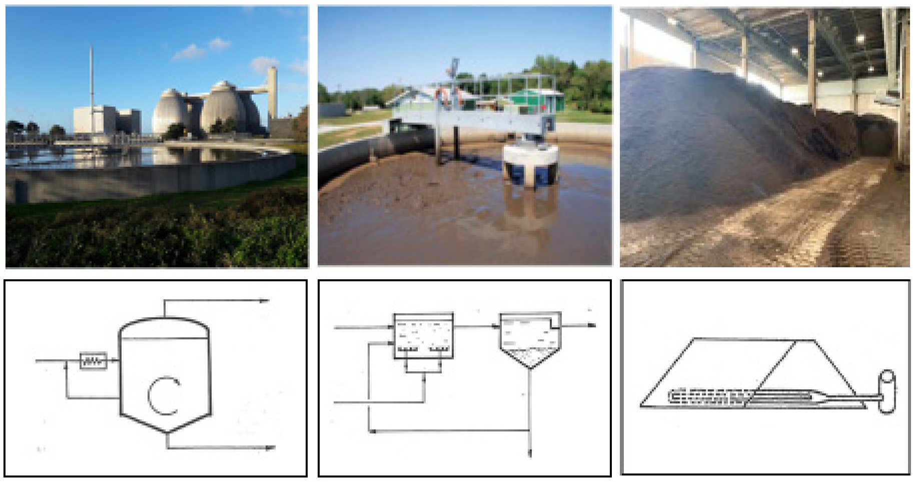
- Improve structure through the formation of clay–humic complexes;
- Increase the thickness of the surface agricultural layer;
- Make the compacted soil porous and lighter;
- Increase the water retention capacity;
- Increase the soil-bearing capacity;
- Increase the nutrient and base retention capacity;
- Favor the chelation of microelements;
- Have a positive effect on the soil microflora and microfauna;
- Perform a carbon sink function;
- Increase the water retention capacity;
- Stimulate root growth;
- Normalize soil pH.

5.3. Biological/Microbiological/Sanitary Aspects

These aspects are linked to the concept of putrescibility, where "*putrescible*" generally means a matrix that contains organic substances that can be decomposed by microorganisms at specific conditions. A stabilized sludge is characterized by "*low putrescibility*", i.e., the level of microbial activity has slowed down to a point where it will not resurge under altered conditions [9].

The evaluation of the biological stability of sludge and derived products (organic fertilizers) is of great importance because it provides indications on the effectiveness of treatments, including the risks of developing bad odors. Odors are not an indicator of danger to health but a characteristic often due to process reagents with discomfort potentially limited to the moment of employment.

Sludge/biosolids can be stabilized by physico-chemical (lime and/or sulfuric acid addition, drying, or irradiation) or biological (aerobic stabilization, anaerobic digestion, or composting) processes (Figure 4).



(**a**) (**b**) (**c**)

Figure 4. View of (**a**) anaerobic digestion, (**b**) aerobic stabilization, and (**c**) windrow composting.

Anaerobic digestion also allows for energy to be recovered by transforming organic matter into biogas. Composting, or, in general, the production of organic fertilizers derived from sludge and/or other organic materials, could be a preferred option in comparison to direct agricultural utilization, mainly because it has the advantage of producing materials that can be more easily stored, transported, and used at times and sites different from those of production. Overall, these materials, following treatment to stabilize their organic components, are characterized by high chemical and microbiological stability; thus, they do not lose their product characteristics over time.

Stabilization results in a reduction of the volatile solids content and makes it possible to obtain safer and more hygienic products because of a certain level of disinfection, i.e., the inactivation of pathogenic microorganisms.

However, a widely accepted parameter and/or procedure to evaluate the biological stability of sludge has not yet been defined, although several have been proposed [22].

The BOD_5/COD ratio can provide a value to define the degree of stabilization for both aerobic and anaerobic treatment processes. A value lower than or equal to 0.15 is an indication of sufficient stabilization. The biological methane potential (BMP) test measures the residual production of biogas from anaerobically treated sludge and is employed to determine stability. However, most of the methods require a number of days for results to be obtained. When more rapid methods are required for operational and technical/legal control purposes, the volatile solids to total solids ratio may be used. Other possible methods include the evaluation of the oxygen uptake rate (OUR) and the specific oxygen uptake rate (SOUR, referred to as the mass unit of volatile solids).

Microbiological parameters are important for the evaluation of hygienic aspects. For this purpose, it must be considered that pathogenic organisms are reduced/killed as a function of time and temperature of the treatment, as well as the consequence of microbial competition with other much more numerous non-pathogenic organisms.

Reference legislation may also provide limit values for those parameters, and, in line with the evolution of scientific knowledge, standards are periodically revised in order to introduce any new parameters of interest.

5.4. Environmental Aspects

Some of the environmental benefits deriving from the use of sludge/biosolids in agriculture have already been highlighted in previous sections. Environmental aspects are very site-specific; thus, the climate, soil characteristics, and, ultimately, the planned land use objectives should all be considered.

In all cases, recycling organic matter after appropriate treatment (i) serves at least as organic soil improver, thus reducing mineral fertilizer applications and decreasing greenhouse gas (GHG) emissions; (ii) helps to replenish depleted soil carbon pools; and (iii) improves water retention capacity and soil structure, thus enabling the closure of the nutrient and carbon cycle and, therefore, fighting against desertification and climate change [23].

From an environmental point of view, the use of sludge/biosolids in the recovery or rehabilitation of disturbed land can include several actions, such as the following:

- Addition of nutrients and organic matter to depleted soils;
- Establishment of new or replenishment of scarce vegetation;
- Improvement of the physical properties of soil;
- Realization of the final cover of exhausted landfills;
- Reclamation of completed mines;
- Creation of wetlands;
- Minimization of erosion and consequent risks of water pollution;
- Improvement of the aesthetic and visual impacts associated with land degradation.

5.5. Commercial/Logistical/Organizational/Institutional Aspects

The availability of potential users and their specific needs, in terms of both location and type of cultivation, are factors of great importance in the management of sludge/biosolids. The main recipient of the products deriving from the recovery of sewage sludge is certainly the agricultural sector, which, today, more than ever, has a high need for organic matter worldwide. It is, therefore, desirable that the soils that increasingly show a lack of organic matter and, thus, a risk of desertification return to their state of fertility.

At the level of spreading machinery or equipment, conventional agricultural equipment, such as manure spreaders, can be used. Alternatively, bio-injectors for direct injection of materials into the soil or for their application to the surface are also available. For more liquid materials, injection nozzles can be used (Figure 5).

Figure 5. Examples of vehicles equipped for handling sludge/biosolids of different physical consistencies.

With regard to the large quantities of sludge/biosolids produced in large plants, which could lead to problems in their use in periods in which agricultural use is not permitted by atmospheric conditions and/or other factors, the availability of adequate storage facilities has to be taken into consideration. The same storage centers could be useful to optimize the handling of sludge/biosolids, depending on the distance between the site of production and that of use. In all cases, the haulage equipment must be suitable for ensuring the maintenance of solids concentration, and to avoid the loss of leachate, or the release of odors.

The institutional aspects are linked to the development of adequate regulations and standardized characterization methods capable of guaranteeing compliance with the regulations in a correct and uniform manner. It is also notable that regulatory institutions (i) cover a range of scales from national to regional and local and (ii) encompass different fields of law, such as water, health, agriculture, planning, and construction. The above implies that regulation should:

- Contain clear and scientifically based indications, parameters, and limits;
- Avoid unjustified prescriptions;
- Include clear rules for penalties and sanctions appropriate to the context of the application;
- Provide incentive mechanisms for the use of biosolids in order to facilitate their diffusion and activate virtuous circular economy mechanisms.

It should also be considered that farmers are by themselves important controllers of the agronomic practices for the valorization of sludge/biosolids, as no one is more concerned about the wellbeing of the soil and the quality of the products than them.

6. Digital Transformation

A useful support to both technical and institutional issues can come from digital transformations. The digital twin process represents a significant way to achieve fault detection and provides a new paradigm for monitoring wastewater treatment processes [24].

A digital twin is a virtual model of physical assets; it runs the lifecycle of the assets and uses real-time data obtained with the application of sensor technology and artificial intelligence on the assets to simulate behavior and monitor operations (Figure 6).

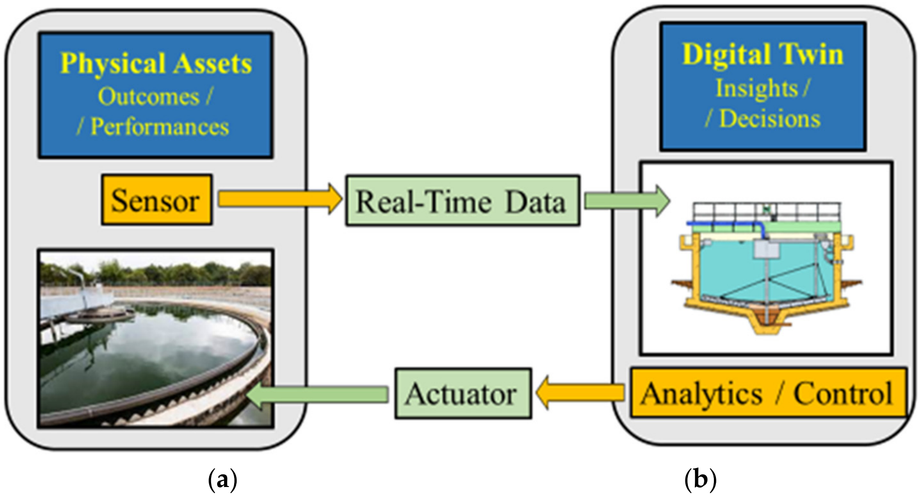


Figure 6. Mode of action of digital twins: (**a**) real plant, (**b**) virtual plant.

From a technical point of view, a greater operational capacity of wastewater and sludge/biosolids management systems can be obtained, and costs can be optimized. This will allow for

- Coping with occasional fluctuations in the flowrate of wastewater entering the treatment plant and/or in the production of sludge;
- The insurance that the concentrations of chemicals entering the plant are below the specified concentrations;
- The control and optimization of energy and chemical consumptions;
- The optimization of the sludge handling/transport system.

One important institutional issue is certainly the management of public perception of the beneficial use of sludge/biosolids, which is strongly related to the correct communication of these practices to the public. Perception in communications relates to values, priorities, culture, and beliefs; however, factors such as inappropriate messaging, word-of-mouth rumors, the credibility of information sources, and media coverage can influence public perception. A high and unwarranted level of concern can generate problems of false perception that are difficult to manage.

Digitalization can be a useful support for proper communication between citizens and public institutions/organizations that would reduce social barriers and ensure greater understanding and total transparency.

7. Standardization Programs

The development of standardized characterization methods and procedures is necessary for all stages of the supply chain to follow one another correctly and sustainably; only this way will it be possible to close the circle of management that runs from the production of sludge/biosolids to the cultivation and production of agricultural products in complete safety and transparency.

However, while the basics of characterization methods and procedures are generally well-known, different laboratories could use different equipment and accessories, thus obtaining results often not supported by any statistical analyses in terms of reproducibility and repeatability. Subsequently, the results cannot be reliably evaluated and compared because they are obtained under different circumstances and conditions. Standardization allows for this issue to be overcome [19].

The main objectives and strategic directions of standardization programs include the following:

- Elaboration of documents on terminology, methods of analysis, good practices for different methods of management, and operational practices for preparing sludge;
- Promotion of sustainable development through good practices for the conservation of organic matter and completion of nutrient cycles;
- Contributions to improvements in public and environmental health and food safety;
- Support issuing legislation relevant to sludge/biosolids;
- Support stakeholders (legislators, public and private companies, control agencies, etc.) in the different communication stages of sludge/biosolids management;
- Orientation to producers and users on how to meet legislation requirements in relation to the area of growing interest, including safety, health, environment protection, etc.

The European Committee for Standardization (CEN) and the International Organization for Standardization (ISO) are two of the international bodies operating in the standardization sector. They work in close collaboration with the corresponding National Standardization Bodies (NSB), such as AFNOR in France, DIN in Germany, and UNI in Italy.

In the context of sludge/biosolids management, CEN and ISO have, respectively, established the Technical Committees CEN/TC308 and ISO/TC275. Table 3 lists the CEN and ISO Technical Committees that are related, directly or indirectly, to the use of sludge/biosolids for agricultural purposes.

Each of the aforementioned TCs has developed, always on the basis of documented scientific and technical research activities, standard procedures or guidelines for the evaluation of the parameters of interest (see Section 5). This allows (i) for the obtaining of comparable results, despite being obtained in different places and situations but under the same conditions, and (ii) the proceeding in a uniform manner with legal control actions.

Examples of published standardization procedures, in addition to methods for the evaluation of individual/specific parameters, are

- The standard ISO 19698 [9], which describes the principles of management of these materials that can be of help if placed in the individual national realities to develop strategies that are increasingly sustainable;
- The standard CEN/TS 13714 [25], which effectively summarizes the entire supply chain from sludge production to the related management strategy, introducing tools and ideas for environmental performance assessments.

However, it must be clear that the work of standardization and that of legislative regulation takes place at different, even if complementary, levels. The task of the standardization bodies is to define evaluation methods and procedures without setting numerical limit values which, instead, fall under the competence of the regulatory bodies at different levels (supranational, national, regional and/or smaller) in relation to the specific local context.

Table 3. CEN and ISO Committees with interactions on sludge/biosolids management.

CEN and ISO Committees that specifically deal with sludge management	
CEN/TC 308	Characterization and management of sludge
ISO/TC 275	Sludge recovery, recycling, treatment, and disposal
CEN and ISO Committees with interactions on sludge management	
CEN/TC 165	Waste water engineering
CEN/TC 183	Waste management
CEN/TC 223	Soil improvers and growing media
CEN/TC 230	Water analysis
CEN/TC 260	Fertilizers and liming materials
CEN/TC 275	Food analysis—horizontal methods
CEN/TC 292	Characterization of waste
CEN/TC 327	Animal feeding stuffs—methods of sampling and analysis
CEN/TC 345	Characterization of soils
CEN/TC 416	Health risk assessment of chemicals
ISO/TC 190	Soil quality
ISO/TC 207	Environmental management
ISO/TC 323	Circular economy
ISO/PC 305	Sustainable non-sewered sanitation systems
ISO/PC 343	Management System for UN Sustainable development goals

An example of a case study relating to the specific topic of sludge management aimed at adapting regulations to technological developments and paying ever-increasing attention to environmental aspects is given by the aforementioned European legislation (Council Directive 86/278/EEC), whose revision process has not yet been concluded.

As requested to all member countries, the directive was implemented by Italy with the Legislative Decret 99/92 of January 1992, which, in cascade, left the individual regions to adopt further regulatory actions appropriate to the local context. This adaptation occurred in the past and continues to occur, with regional regulatory acts.

In any case, all these legislative acts always refer to the characterization methods developed at CEN and ISO level, as well as at the level of the respective National Standardization Body.

However, Directive 86/278/EEC did not consider and, therefore, did not set limits for many pollutants whose importance has become evident over time. To support the policy framework on the EU's Sewage Sludge Directive, a study aiming to assess the impacts of a lot of pollutants on the environment and human health from main sludge management routes was carried out at Joint Research Centre (JRC) [26]. It was concluded that the application of a mix of established and innovative techniques, as a function of local settings and needs, may help to maximize benefits and minimize adverse impacts on the different sustainability dimensions affected by sludge management within the EU.

Details can be found in the literature.

8. Conclusions

The development of sustainable strategies in the management of sludge/biosolids is one of the critical issues facing modern society due to the rapid increase in their production resulting from the growing number of wastewater treatment plants.

A new methodological approach to this problem is required based on the following needs:

- To move from the concept of "*waste*" to that of "*product*" to maximize the benefits of recycling;
- To consider sludge management as the "*locomotive*", not the last wagon, of wastewater treatment systems, thus guiding in the choice of the most appropriate wastewater treatments for improving sludge reuse in the specific context.

The use of sludge/biosolids for agricultural purposes (directly or in the form of organic fertilizers) and other land uses, e.g., reclamation and forestry, is likely to remain the main option in their management because, in addition to the more appropriate use of resources, it brings numerous agronomic benefits involving many aspects (chemical, physical, biological, health, environmental, and commercial).

To guarantee (i) sustainable and effective agronomic benefits and (ii) the good quality and safety of agricultural products intended for animal and human consumption, the adoption of the following is necessary:

- "*Technical*" actions aimed at maximizing the benefits of recovery through "*reduction of nuisances*", i.e., improvement of quality through stabilization/digestion processes, and "*reduction of volume*" through thickening/dewatering processes to obtain the most suitable sludge/biosolids characteristics for the intended use;
- "*Governance/Institutional*" actions aimed at issuing adequate regulations capable of encouraging the correct use of sludge/biosolids in agriculture while preventing harmful effects on the soil, groundwater, and vegetation, as well as the potential contamination of crops for animal and human consumption;
- Correct and balanced "*communication*" mechanisms without distortions and based on scientific data to build stakeholder and public confidence.

In this sense, "*digital transformation*" can be of great help.

Within this framework, the evaluation of sludge properties and characteristics through standardized methods and procedures is a tool of primary importance for the utilization of sludge/biosolids in agriculture, as it allows a reliable comparison of results obtained under standardized circumstances and conditions, thus ensuring correct and consistent compliance with legal requirements and guaranteeing the good quality and safety of agricultural products.

The graphical abstract indicates that it is not desirable (*no direct flight*) to directly use raw sludge, as produced by wastewater treatment plants, for agricultural purposes without the support of specific technical and institutional actions (*flight connections*).

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