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Article

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

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Abstract: One of the issues facing modern society, whatever the socio-economic level of the communities involved, is the development of sustainable strategies in the management of sludge/biosolids. Today, it is imperative to replace solutions aimed at simply “disposing of” with those oriented towards “maximizing recovery benefits”. It is desirable that agricultural use remains the main option in sludge/biosolids management, but 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 regulation is crucial as it represents the right balance between the different aspects of a coordinated and effective management. Furthermore, it is to recognize that regulation needs to be supported by standardized characterization procedures and guidelines of good practices, because well-defined procedures allow legal requirements to be correctly and uniformly met, thus ensuring reliable comparison of results obtained under different conditions. In this article, main aspects to consider for a sustainable application of this management practice are discussed, together with the parameters that need to be evaluated for the characterization of sludge/biosolids, according to the various aspects related to the agricultural use.

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

1. Introduction

The management of sewage sludge in an economically, environmentally, and socially acceptable manner, i.e. sustainable manner, is one of the critical issues facing modern society, due to the fast increase in sludge production as a result of (1) growing availability of household running water with the consequent production of wastewaters, (2) extended sewerage, (3) new work installations, and (4) upgrading of existing facilities. This leads to increased difficulties in properly locating disposal works and complying with even more stringent environmental quality requirements imposed by legislation that require higher levels of treatment for the final use/disposal of sludge [1].

In addition, the management of this unavoidable by-product of any wastewater treatment plant often requires a considerable amount of the overall operating budget for the entire plant.

This topic is also well-recognized by the 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...”, following the consideration that across the world 2.4 bn people still lacks improved sanitation facilities and 1 bn people still practices open defecation [2].

In this regard, it is important to first note that, from a terminological point of view, the term “biosolids” has been introduced into common language to replace that of “sludge”, which is perceived in a more negative way, to make it clearer that a waste product can have a beneficial use, especially in agriculture.

From the foregoing, it clearly emerges the need to move from the concept of “waste” to that of “product” by developing sustainable sludge management strategies aimed at maximizing the benefits

of recycling through the reduction of the amount of losses, and the consequent need for new resources (Figure 1). Furthermore, it should not be forgotten that the dynamics of the recycle flows are substantially different from those of acquiring new resources and/or producing new waste.



Figure 1. From solid/liquid “waste” to “product”: examples.

Within this framework, the practical application of the sustainability concept to sludge/biosolids management requires [3]:

- considering sludge management as the “*Locomotive*”, not the “*last wagon*”, of any water/wastewater system;
- taking into account “*Technical*” actions aimed to maximize the recovery benefits;
- taking into account “*Institutional*” actions mainly aimed to issue appropriate regulation.

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 the wastewater treatment is strongly driven by the sludge reuse/disposal options available in the specific local context, so sludge management should really play the role of “*Locomotive*” [4].

In any case, whatever the envisaged method for reuse/disposal, the adoption of technologies to “*maximize recoveries*” of useful materials and/or energy, instead of those aimed at simply disposing of sludge, is a major pillar, together with the development of “*realistic and enforceable regulation*” because an optimal and environmentally safe sludge management can only be achieved through objective, transparent, and legally conducted operations.

It is also to be recognized that regulation needs to be supported by “*standardized characterization procedures*” and/or technical “*guidelines of good practices*”, because only well-defined procedures allow legal requirements to be fulfilled in a correct and uniform manner, thus building stakeholder and public confidence [5].

Several options are known for sludge/biosolids management, some of which are still being developed; in any case, “*land application*”, mainly for agricultural purposes (or also by transformation into fertilizers) is likely to remain the major option. For this reason, the aforementioned “*technical*” and “*institutional*” actions are particularly important in order to ensure effective and safe agronomic benefits, and guarantee the quality of agricultural products.

Finally, yet importantly, the support that the “*digital transition*” can give in tackling this management problem must not be forgotten [4].

2. Production and composition

Typical sludge quantities and concentrations of solids and nutrients are reported in Table 1 [1]. Specific production of sludge ranges from 0.2 to 5.0 L/cap/d with typical concentrations in the range

0.7%–10.0%, being 2 L/cap/d at 4% solids concentration the typical production of primary plus activated sludge from municipal plants.

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

The global production of sewage sludge is estimated at 45 Mdry-t/y [6].

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

According to data collected at 2,500 larger facilities in US, about 4.5 Mt of treated sludge or biosolids were generated in 2021. About 45% was used for agricultural purposes, 40% incinerated and 15% landfilled [7].

According to China Statistical Yearbooks, the total population of China is 1.4 billions, of which the urban population is 689 millions. The average sewage treatment rate in cities and county towns is about 97%, while the rural population of 498 millions has a sewage treatment rate of about 28%, so the total population served by sewage treatment facilities is about 808 millions. 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 the average concentrations in sludge/biosolids of organic matter and macronutrients, which are the components of greatest interest for the agricultural use [9].

It can be noted that the sludge contains essential nutrients, such as nitrogen, phosphorus and potassium but, unfortunately, also bacteria (e.g. Salmonella), the concentration of which depends on the origin and treatment of the wastewater. For this reason, the role of facilities that monitor materials and carry out sanitization treatments is crucial.

This monitoring and control activity already carried out at wastewater treatment plants and then at sludge treatment plants, is even more important in relation to organic compounds, such as halogenated compounds, e.g. polychlorinated biphenyl (PCB) and polychlorinated dibenzodioxins/furans (PCDD/F), perfluorinated compounds (PFC), linear alkyl benzene sulphonates (LAS), polycyclic aromatic hydrocarbons (PAH) and others. Their concentrations can vary depending on the influent characteristics, so their control or limitation at the source before they enter the wastewater treatment plant is an effective tool to improve sludge quality and reduce health risks and handling costs.

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

Origin	Industrial			Municipal biosolids		
	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 ₂ O ₅)	2.5-8.0	0.15-1.50	4-7	3-6	4.0-4.5	3-5

Potassium (K ₂ O)	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. * Referred to biologically treated sludge (not digested) from some small wastewater treatment plants.

Finally, since biosolids are organic matrices, 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 health hazard, can cause discomfort especially during handling. Appropriate stabilization and digestion treatments, as well as proper application techniques, can help in reducing this problem.

3. Treatment options

As already mentioned, the adoption of technical solutions aimed at maximizing the recovery of useful material and/or energy is necessary to effectively implement a sustainable management of sludge/biosolids.

3.1. Recovery of materials

The nutrient content of sludge and derived products (e.g. organic fertilizers, compost, etc.) is of high value, so utilization in agriculture is a preferred option especially for better quality sludge/biosolids.

Sludge/biosolids could represent a renewable source of phosphorus, since white phosphorus (P₄) and phosphate rock are included among the 20 critical raw materials (CRM) for the EU [10]. Phosphorus can be recovered through anaerobic digestion or from incinerated ash. Innovative technologies for P recovery from sewage sludge ash are discussed in [11].

It must also be considered that the use of biosolids directly adds this nutrient by implementing an important reserve mechanism to the soil.

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

3.2. Recovery of energy

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, but there are still some uncertainties about their performance and cost. The use of microbial fuel cell for direct conversion of sludge to electricity has been reported [13].

However, it is almost entirely unlikely that the raw sludge, as it is produced in a wastewater plant, already has the characteristics required for its disposal, much less for its sustainable use, for which it is necessary to carry out a series of treatments, among the many available, to obtain the *quali-* and *quanti-*tative characteristics suitable for the intended use.

As shown in Figure 2:

- the “*reduction of nuisances*”, i.e. the improvement of quality through stabilization/digestion processes which involve, in addition to the reduction of the putrescibility of organic substances, a certain level of disinfection, i.e. the inactivation of pathogenic microorganisms, and
- the “*reduction of volume*”, through thickening/dewatering processes which allow to obtain the optimal level of solids concentration, volume and physical consistency (liquid, paste-like, solid)

most suitable for the intended use/disposal, represent two unavoidable “hubs” in sludge processing from its origin to the final destination [14].

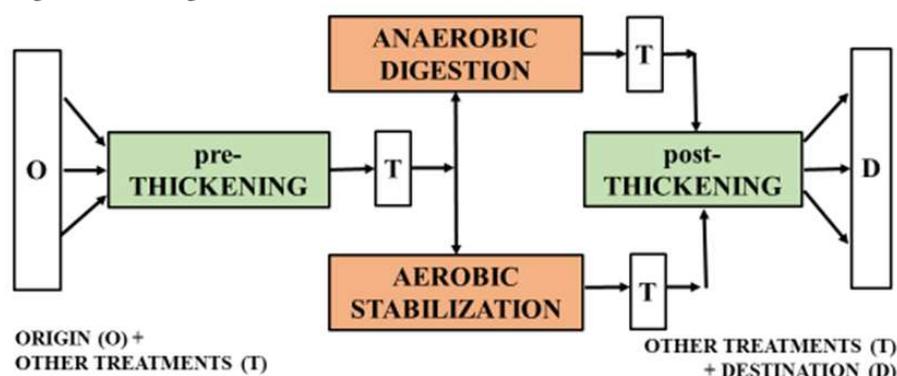


Figure 2. Technical “hubs” in sludge processing from origin to destination.

It seems appropriate to mention that the effects on sludge/biosolids quality are very different depending on the type of treatment (e.g. the degree of pathogens reduction ranges from “high” for processes that increase temperature and/or pH to “low” for secondary sludge or after mesophilic digestion).

4. Agricultural use

Utilization for agricultural purposes (directly or in form of other organic products) and other land uses, e.g. reclamation, forestry, etc., is likely to remain the major option in sludge/biosolids management because it involves a better use of the soil by improving its agronomic efficiency.

It also seems interesting to mention the European Commission document [15] where, among the measures regarding fertilizers, a “...better access to organic fertilizers and nutrients from recycled waste-streams, especially in regions with a low usage of organic fertilizers...” is recommended.

This management option can be useful in many ways as it influences a multiplicity of aspects in addition to the purely agronomic ones, including the chemical, physical, biological, sanitary, environmental and commercial ones [9].

However, as previously mentioned [5], for a correct and effective application of this option, and to obtain the expected benefits, it is necessary the development of:

- adequate “regulation/legislation” capable of encouraging the correct and safe use of sludge/biosolids in agriculture;
- “standardized characterization procedures” and/or “guidelines of good practices” to fairly, consistently and uniformly comply with legal requirements.

The task of the legislation is to define the general criteria to be followed for a correct management by establishing, at the same time, the limit values acceptable in the soil and sludge/biosolids of the various parameters (heavy metals, pathogens, organic compounds, moisture, odor generation, etc.), as well as the responsibilities of the various actors/operators of the system. To this purpose, it must be clear to all stakeholders that the legislation, supported by technical standardization, was born and develops over time in the full application of the “precautionary principle”, with the aim of giving clear and unambiguous rules and taking preventive attitudes.

It should also be highlighted that sludge management is a highly site-specific operation, so each country, state or province or local Institutions can/must adapt its legislation to the specific local context, including economy, political and cultural priorities, availability of tools, development level, etc.

In conclusion, the evaluation of sludge properties through standardized methods and procedures is a tool of primary importance for an effective and sustainable sludge/biosolids management.

5. Characterization parameters

Numerous parameters can be used for the characterization of sludge/biosolids.

The contents of total solids, or the complementary moisture, suspended solids, volatile solids, which are correlated to the organic content of sludge, and organic carbon are the characterization parameters of interest for all sludge/biosolids treatment and management operations including, therefore, the use for agricultural purposes [1].

There are numerous other characterization parameters specifically linked to the application of sludge/biosolids to soil; the main ones are discussed below, according to the various “-aspects” involved in this operation, which are:

- agronomic/chemical-;
- physical-;
- biological/microbiological/sanitary-;
- environmental-;
- commercial/logistical/organizational-;
- institutional-.

5.1. Agronomic/chemical aspects

The use of biosolids, and other organic fertilizers, for agricultural purposes 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 just the plants (Figure 3).

Regarding agronomic and chemical aspects, the content of nutrients, e.g. phosphorus and nitrogen, and that of other parameters, e.g. heavy metals and organic compounds, is of fundamental importance, as these elements affect the amount of biosolids to be spread on soil within the limits set by the legislation.

For some time now, the reference legislation has in fact set itself the objective of allocating only biosolids characterized by higher quality to agricultural use, to guarantee the quality of the soil and agricultural products.

Within this context, the release of nutrients from sludge/biosolids depends on:

- concentration and properties/forms of nutrients;
- period of application to soil;
- application techniques.

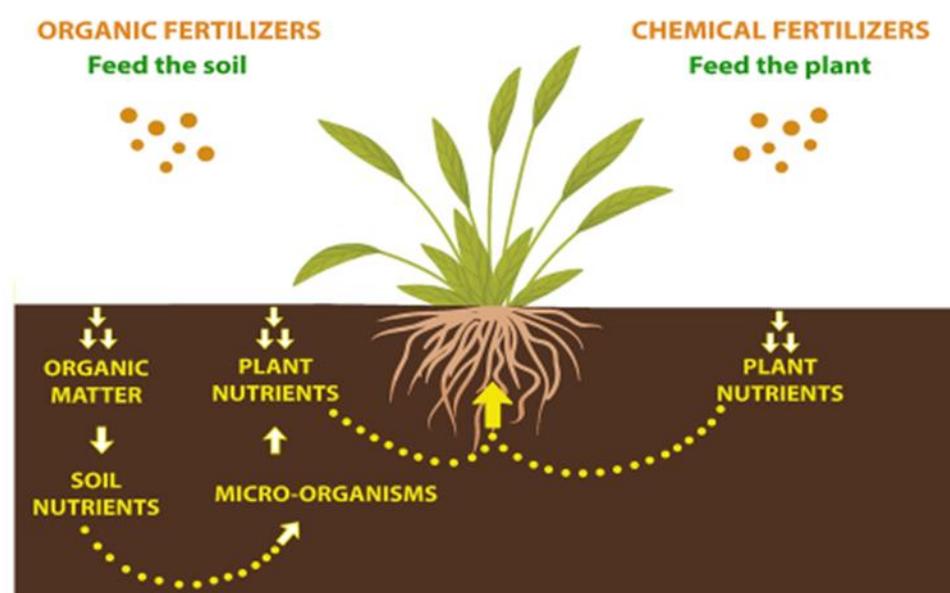


Figure 3. How fertilizers act.

As regards nitrogen, its forms in sludge/biosolids are organic N, ammonium (NH_4^+), and nitrate (NO_3^-), being the last two forms available to plants. Organic N has to be converted to inorganic forms by mineralization of organic matter, so it provides slow release nitrogen for crops. Once the nitrogen demand has been met, the nitrogen percolation into soil to groundwaters 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 the water protection.

On the other hand, phosphorus, which is contained in biosolids in concentrations lower than nitrogen, is currently of great interest because of the scarcity of this matter. For this reason, the accumulation of this nutrient into the soil, through the application of biosolids, can play a key role and ensure 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.

When sludge is used for agricultural purposes, the maximum allowable concentrations of heavy metals (such as mercury, copper, cadmium, chromium, lead, zinc and nickel) or organic micropollutants, such as AOX (adsorbable organic halogenated substances), LAS (linear alkylsulfonates), NP/NPE (nonylphenol and its ethoxylates), PAH (polycyclic aromatic hydrocarbons), PCB (polychlorinated biphenyls), and dioxins, are defined by legal regulations.

Many of the above chemical parameters are often a cause 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 risk with the needs of soil and crops; this is the case of zinc that is an essential trace element for all plants, especially in the early vegetative stages [16]. Zinc, like other metals, has been subject to technical regulations, but with the necessary limit value.

A very topical issue are also "microplastics". 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, be it 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 too long. 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, included a number of bad habits on the part of citizens, e.g. incorrect waste separation, abandonment of waste, etc.

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 collection) and the secondary ones. This must go hand in hand with the progressive identification of standardized analysis methodologies and procedures aimed at measuring the content of these components in the various matrices. The analysis of the various flows must therefore become an indicator for correcting upstream behavior; at the same time, the data collected may also serve for the implementation of filtration systems located downstream, for example, at sewage treatment plants [17].

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

5.2. Physical aspects

The knowledge of physical properties allows the prediction of sludge behavior when handled and submitted to almost all treatment, storage and utilization/disposal operations, including storage, pumping, transport, land-spreading, dewatering, drying, incineration, landfilling [19].

The physical consistency, or physical state, is a characteristic strictly linked to the rheological properties, and is a parameter of fundamental importance in sludge/biosolids characterization. In particular, for sludge/biosolids three different behaviors have been observed, i.e.:

- *liquid*, ability to flow under the effect of gravity or moderate pressure and to conform almost instantly to the shape of the vessel containing it;
- *paste-like*, ability to flow under the effect of high pressures and to offer moderate resistance to the forces tending to deform it;
- *solid*, tendency to maintain shapes and dimensions while offering consistent resistance to the forces tending to deform it, so methods to define the boundary area between liquid and paste-like behaviors (known as limit of *flowability*) and that between solid and paste-like behaviors (known as limit of *solidity*) need to be set up [19].

Actually, the selection of the most suitable equipment and procedure for 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 is depending on sludge shear strength rather than on its solids concentration [20].

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 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 basically linked to the concept of putrescibility, where "*putrescible*" generally means a matrix that contains organic substances that can be decomposed by microorganisms in specific conditions. A stabilized sludge is characterized by "*low putrescibility*", i.e. the level of microbial activity has slowed 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 gives indications on the effectiveness of treatments, including risks of developments of bad odors. Odors are not an indicator of danger to health, but a characteristic often due to process reagents, e.g. lime, with a discomfort potentially limited to the moment of employment.

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

Anaerobic digestion allows also 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 has the advantage of producing a material, which can be more easily stored, transported and used on times and sites different from those of production. Generally speaking, these materials, following the treatment undergone to stabilize the organic component, are characterized by high chemical and microbiological stability, so they do not lose product characteristics over time.

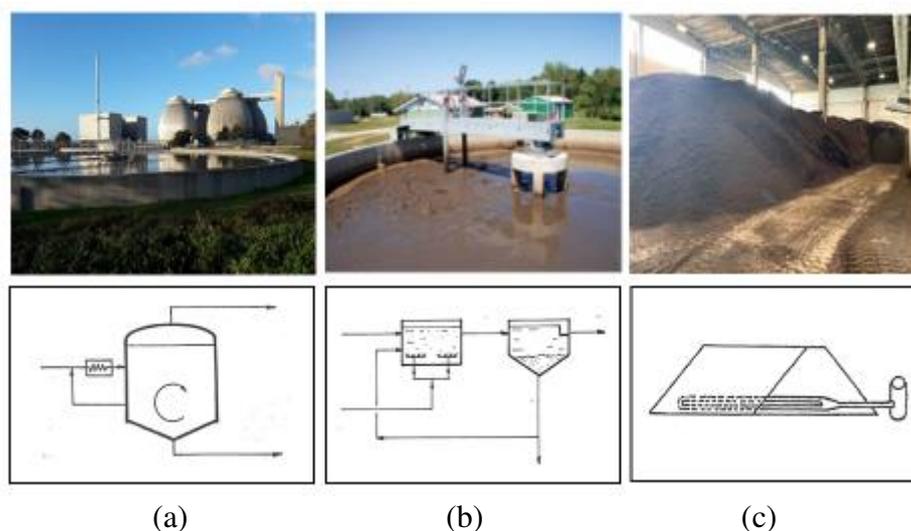


Figure 4. View of (a) Anaerobic digestion, (b) Aerobic stabilization, and (c) Windrow composting.

Stabilization results in a reduction of the volatile solids content and also make it possible to obtain safer and more hygienic products thanks to a certain level of disinfection, i.e. 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 [21].

The BOD₅/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 allows the residual production of biogas from anaerobically treated sludge to be measured and employed to determine stability. However, most of the methods require a number of days for results to be obtained. In the case that faster methods are required for operational and technical/legal control purposes, the volatile solids to total solids ratio may be measured.

Other possible methods include the evaluation of the oxygen uptake rate (OUR), the specific oxygen uptake rate (SOUR, referred to the mass unit of volatile solids), the odor intensity.

The microbiological parameters are important for the evaluation of hygienic aspects; to this purpose, it must be considered that pathogenic organisms are reduced/killed as a function of time and temperature of 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 for agricultural purposes have already been highlighted in previous sections, as they are correlated to other aspects.

The environmental aspects are very site-specific, so climate, soil characteristics and ultimate land use objectives shall all be considered.

In all cases, recycling organic matter after appropriate treatment (i) serves as organic soil improver at least, thus reducing the mineral fertilizer application, 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 [22].

Summarizing 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:

- addition of nutrients and organic matter to depleted soils;

- establishment of new, or replenishment of scarce vegetation;
- improvement of physical properties of soil;
- realization of 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 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 in many areas of the planet a high need for organic matter. It is therefore desirable that the soils, which increasingly show a lack of organic matter and, therefore, 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).

As regards 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 the solids concentration and the loss of leachate or release of odors.



Figure 5. Types of vehicles equipped for handling sludge/biosolids of different physical consistency.

5.6. Institutional aspects

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 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 valorisation of sludge/biosolids, as no one is more concerned about the well-being of the soil and the quality of the products than they are.

6. Digital transformation

A useful support to both technical and institutional issues can come from the digital transformation.

From a technical point of view, a greater operational capacity of wastewater and sludge/biosolids management systems will be obtained, and costs optimized, thanks to the processing by digital twins of the real-time data obtained with the application of sensors technology and artificial intelligence (Figure 6). This will allow to:

- cope with occasional fluctuation in the flowrate of wastewater entering the treatment plant and/or in the production of sludge;
- ensure that the concentration of chemicals entering the plant are below the specified concentration;
- control and optimize energy and chemicals consumptions;
- optimize sludge handling/transport system.

One of the institutional issues to be addressed 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, 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, thus reducing the social barriers and ensuring greater understanding in total transparency.

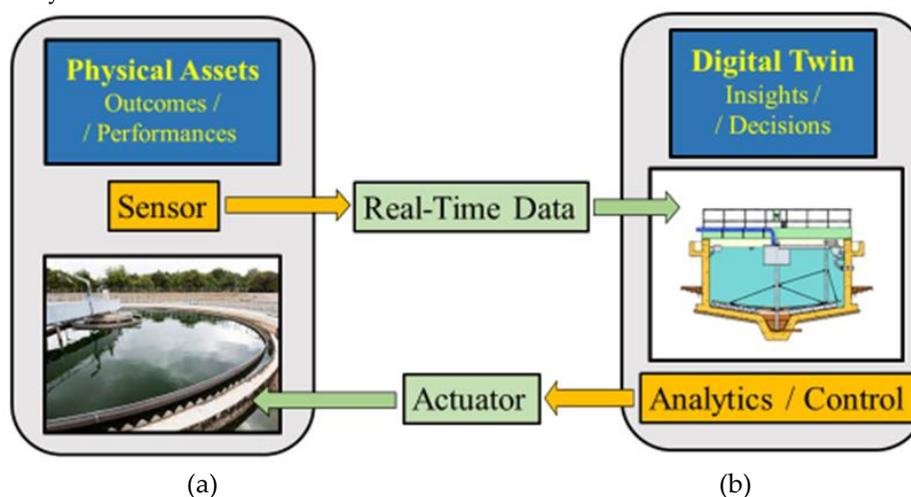


Figure 6. How digital twins work: (a) real plant, (b) virtual plant.

7. Standardization programmes

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 in this way will it be possible to close the circle of management that goes from the production of sludge/biosolids to the cultivation of agricultural products in total safety and transparency.

However, while the basics of methods and procedures of characterization are generally well known, it could happen that each laboratory uses different equipment and accessories, thus obtaining results often not supported by any statistical analysis in terms of reproducibility and repeatability.

It follows that the results cannot be reliably evaluated and compared because obtained under different circumstances and conditions which standardization allows overcoming [19].

Main objectives and strategic directions of standardization programmes include the:

- elaboration of documents on terminology, methods of analysis, good practice for different methods of management, and operational practices for preparing sludge;
- promotion of sustainable development through good practice for the conservation of organic matter and completion of nutrient cycles;
- contribution to improvements in public and environmental health and food safety;
- support to 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, like safety, health, environment protection, etc.

To this end, CEN (European Committee for Standardization) and ISO (International Organization for Standardization) have, respectively, established the Technical Committees CEN/TC308 and ISO/TC275 specifically devoted to the sludge/biosolids management.

Table 3 lists other CEN and ISO Technical Committees that are directly or indirectly related to the use of sludge/biosolids for agricultural purposes.

Just to give some examples, the standard ISO 19698 "*Sludge recovery, recycling, treatment and disposal - Beneficial use of biosolids - Land application*", describes the principles of management of these materials that can be of help, if placed in the individual national realities, to develop strategies increasingly sustainable, and the standard CEN/TS 13714 "*Characterization of sludges - Sludge management in relation to use or disposal*" effectively summarizes the entire supply chain, from sludge production to the related management strategy, introducing tools and ideas for environmental performance assessment.

Table 3. List of CEN and ISO Technical Committees related to agricultural use of sludge/biosolids.

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 308*	Characterization and management of sludge
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 275*	Sludge recovery, recycling, treatment and disposal
ISO/PC 305	Sustainable non-sewered sanitation systems

ISO/TC 323	Circular economy
ISO/PC 343	Management System for UN Sustainable development goals

8. Conclusions

The sustainable management of sludge/biosolids from an economic, environmental and social point of view is one of the critical issues that modern society has to face due to the rapid increase in their production resulting from the ever-increasing number of wastewater treatment plants, as an element essential to increase the well-being of the community and the environmental sustainability.

However, the management of this unavoidable by-product is both difficult and expensive.

In this context, the need to move from the concept of "*waste*" to that of "*product*" emerges, so that the adoption of "*Technical*" actions, aimed at maximizing the benefits of recovery, and "*Institutional*" actions, mainly aimed at issuing adequate regulation, is required.

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

To ensure (i) sustainable and safe agronomic benefits, and consequent quality of agricultural products, and (ii) correct and consistent compliance with legal requirements, the development of adequate:

- "*regulation/legislation*", capable of encouraging the correct use of sludge/biosolids in agriculture, while preventing harmful effects on the soil, groundwaters and vegetation, as well as potential contamination of crops for animal and human consumption;
- "*standardized characterization procedures*" and "*guidelines of good practices*", to reliably compare characterization results obtained under standardized circumstances and conditions, is necessary, thereby building the stakeholder and public confidence through correct and balanced communication mechanisms, based on scientific data and without distortions.

The Graphical Abstract indicates that it is not possible (no direct flight) to directly use raw sludge, as produced by the treatment plant, for agricultural purposes without subjecting it to specific technical and institutional actions (flight connections).

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