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REVIEW

Characterization of Solid Digestates: Part 1, Review of Existing Indicators to Assess Solid Digestates Agricultural Use

C. Teglia · A. Tremier · J.-L. Martel

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Abstract Anaerobic digestion of organic wastes is clearly encouraged by current regulations in Europe. In complement to the energy supply it represents, this biological treatment process also allows the recycling of organic matter and nutrients contained in biodegradable wastes. Indeed the digestion residue can be further promoted as soil improver or fertilizer. The sustainability of anaerobic digestion plants partly depends on the management of these digestion residues. Digestates present particular characteristics that can reduce their direct agricultural valorization and minimize by the way the benefit of such a biological treatment. Thus the first part of this two part paper aims at reviewing and discussing a wide range of biochemical, biological and physical indicators used to assess the agronomic quality of organic products and the feasibility of an aerobic treatment by composting. The definition of agronomic quality is very complex and no single parameter can be picked out to assess the quality of solid digestates coming from different sources. A relevant choice of these parameters will lead to state on digestates agricultural use, whether they can be directly used on soil after digestion or if they need a composting post-treatment before utilization. The second part of this two part paper will choose indicators to characterize several digestates in order to assess their future agricultural use.

Keywords Anaerobic digestion · Composting · Digestates · Quality indicators · Agricultural valorization · Aerobic treatability

C. Teglia (✉) · A. Tremier
Cemagref, UR GERE, 17 avenue de Cucillé, CS 64427, 35044 Rennes, France
e-mail: cecile.teglia@cemagref.fr

C. Teglia · A. Tremier
Université européenne de Bretagne, Rennes, France

J.-L. Martel
Suez Environnement, 38 rue du Président Wilson, 78230 Le Pecq, France

Introduction

The constant increase in waste volume and the consideration of environmental issues related to its management (such as soil contamination or gaseous emissions) has led European countries to adopt various regulatory measures in order to minimize waste and to enforce good management. Reducing quantity of waste landfilled is considered as a priority objective in European waste management policy. Lately directive 2006/12/EC specified that member States shall take appropriate measures to encourage recycling of organic substances, including composting and other biological transformation processes [1]. The revision of the Waste Framework Directive adopted on June 2008, confirmed the following waste hierarchy in descending priority for waste prevention and management: prevention, preparing for re-use, recycling, other recovery (energy recovery for instance) and disposal [2]. Furthermore in the last few years, green energy demand has strongly increased requiring that waste management options should include energy recovery.

In this context, biological treatment of wastes by anaerobic digestion (AD) seems to be a promising technology. Firstly, AD allows the production of renewable energy through biogas. In addition, AD offers several technical benefits since this fully enclosed process reduces odorous pollution and is known to be a very flexible technology treating a wide range of organic wastes. Finally, AD recycles organic matter and nutrients contained in wastes into a digestion by-product, i.e. digestate, which could be used in agriculture as soil amendment or fertilizer. According to the nature of the treated waste and the technology of digestion used, this digestate can be liquid or solid. When it's possible liquid digestates are often managed through direct spreading on agricultural lands. In other cases, AD can be followed by a solid/liquid separation phase to produce different by-products with different uses. The liquid phase can be valorized after a biological treatment and used as liquid fertilizer or undergo ammonia stripping in order to separate and use specifically the nutrients contained. The solid fraction can be used as organic amendment. The continuous reduction of available arable lands and the risks of groundwater pollution by nutrients leaching lead AD sites to move towards digestion techniques that produce a solid residue presenting in addition the benefit to be more economically handled and transported. High solid operation and/or post-treatment of the digested sludge (centrifugation, pressing, drying) allow to obtain solid phase residues that can be used as organic soil amendment. This paper will only deal with the quality of solid digestates.

The recent development of AD led to different environmental issues regarding the quality and innocuousness of these organic residues. Indeed the high adaptability of this technology and the search for an optimum energetic yield in biogas plants lead to use a wide range of organic wastes and mixtures of different wastes to feed the digesters. This results in the production of continuously varying digestates that are for the moment not fully characterized. If digested sewage sludge have been largely studied, digestates coming from other organic wastes such as biowastes or municipal solid wastes (MSW) are not well known yet. Nonetheless digestates present several particular characteristics which can reduce their potential for valorization. Digestates result from a first step of biological treatment and are sometimes not fully stabilized: they can present a residual biodegradability and contain complex organic elements such as ligno-cellulosic compounds as they are not degraded during digestion. Digestates are also rich in nitrogen as total nitrogen is conserved during AD. The nitrogen speciation is of particular interest as it can bring management issues. During digestion, a large part of nitrogen is converted into ammonium [3] which can lead to potentially phyto-toxic digestates or to ammonia emissions stripped after digestion. Digestates can also be odorous, too wet or too concentrated in phyto-toxic volatile fatty acids, preventing a direct land application [4]. Thus, AD residues may have to be subjected to an appropriate post-treatment in order to insure characteristics suitable with an agricultural use, i.e. efficiency and safety [5, 6]. Composting can be an adequate post-treatment for digestates since it can stabilize their residual organic matter, reducing by the way their phyto-toxicity [7] and improving their humic potential [8].

Few data are nowadays available concerning the characterization of different type of digestates [9–11] and concern essentially the evaluation of digestates stability [12, 13] or the effects of an aerobic post-treatment [6, 14]. Currently available data on digestates characterization are usually not dedicated to assess the digestate potential for an agricultural use. However a relevant characterization of digestates organic matter composition is essential to assure a sustainable and reliable way to manage and recycle these biodegradable residues. As for composts or commercial amendments which characterization and classification are standardized, specifications have to be defined to assess a safe use of solid digestates. Therein the characterization suggested in this paper aims at defining the agricultural use of solid digestates: whether they can be directly returned to soil as amendement or fertilizer or if they need an aerobic post-treatment to improve their quality. Quality indicators and standards for an agricultural use of organic residues essentially exist for composts. Thus, this review revisits indicators used to define compost quality in order to identify relevant parameters that will characterize a direct agricultural use of solid digestates and their treatability through an aerobic post-treatment. The classification of indicators described in this review will be applied in the second part of this two-part paper to characterize solid digestates coming from different types of organic wastes.

Characterization of Solid Digestates for a Direct Agricultural Use After AD

Application on soil of biologically treated wastes is a way to recycle organic matter contained in biodegradable wastes. In order to promote an agricultural use, biological treatment, in our case AD, must lead to a product presenting the required quality to be directly used on soil. This quality can be defined by three main aspects:

1. organic amendment properties: addition of organic amendments has been proven useful to restore the quality of degraded soil that can limit agricultural productivity [15]. A soil amendment is a material added to soil that will improve its physical properties, such as water retention, permeability, water infiltration, aeration or structure. The goal is to provide a better environment for roots and thus enhance the plant development.
2. fertilizing effect: fertilizers are applied on soil to promote plant nutrition thanks to the provision of

macronutrients (nitrogen, phosphorus and potassium) and other micronutrients. The major goal of fertilizer is thus to improve soil fertility and production yield of crop cultivation.

3. Innocuousness: the safe use of organic wastes on land depends on several factors including its potential impacts on general environment (soils, water resources, air…) and possible impacts on animal and human health (infections for compost handlers and users, odour issues…). Using organic residues on agricultural land can bring environmental impacts such as groundwater pollution or harmful gaseous emissions. These later issues will not be properly discussed in this paper. They can be related to parameters presented here but they are predominantly influenced by the dose used on land and the period of application.

In the following section will be presented and discussed parameters usually applied to compost quality in order to determine relevant indicators to qualify digestates and state on their potential direct use on agricultural lands.

Organic Amendment Properties

A soil amendment is defined as a material added to soil whose principal aim is to maintain or improve soil physical properties and which can improve its chemical and/or biological properties or activity. This section lists the indicators defining an amendment product.

Organic Matter, Dry Matter

The main characteristic of an organic amendment is to assure the addition of organic matter to soil. OM content is thus essential to describe an amendment and is the main indicator that must fulfill specification in order to define a soil amendment or a constituent of a soil amendment according to the European Committee for Standardization [16]. Several minimal requirements in OM content are thus reported in European standards and will be presented and discussed in the last paragraph of this sub-section. Using OM content to estimate organic amendment properties can however be questioned. The effective amount of valuable organic matter for soil can actually be overestimated since the measurement method of organic matter content (combustion at high temperature) does not differentiate biodegradable and non biodegradable compounds. For instance, plastics will be combusted during the measure and included in organic matter content. Moreover, potential kinetics of biodegradation in soil of the different organic fractions of the amendment are not given by the measurement of the total organic matter content. For example, lignin is also quantified by this measure despite the fact that this organic compound is hardly biodegradable. Table 1 gives examples of organic matter content of different digestates characterized in literature. Digestates OM content varies widely from almost 40 to more than 85 (% of dry matter) according to the nature of the input waste.

Dry matter is also important to determine on organic amendment and has to be assessed to state on a potential and practical use of the amendment. Actually important moisture can bring particular issues such as odours, higher transport costs and difficulties to store and distribute the amendment. Concerning digestates, dry matter content is highly dependent on the digestion process applied and/or on the potential post-treatment sustained by the digestion residues.

Carbon and Nitrogen Content

The quantity of organic matter brought to soil is a major characteristic of an organic amendment, but the

Table 1 Digestates organic matter content

Nature of input wastes	VS (%DM)	Reference
Dairy manure + biowaste	69–76	[10]
Organic fraction of MSW + pig slurry	68–71	[11]
Pig slurry + milk serum + cow slurry + maize silage + rice residues	70	
Pig slurry + blood industry residues + maize silage	67–74	
Primary sludge	55	[12]
Organic fraction of MSW	55	
Mixture of primary sludge + organic fraction of MSW	58	
Pharmaceutical industrial sludge	70	[13]
Cattle manure	86	
Mixture of primary sludge + organic fraction of MSW	70	
Food wastes + landscape wastes	39–43	[14]
Energetic crops + cow slurry + agro-industrial waste + organic fraction of MSW	75	[26]

Table 2 Digestates carbon and nitrogen composition

Nature of input wastes	TOC (g/kgDM)	TKN (g/kgDM)	N-orga (g/kgDM)	$N\text{-}NH_3$ (%TKN)	Reference
Dairy manure + biowaste	–	50–60	19–27	52–62	[10]
Energetic crops + cow slurry + agro-industrial waste + organic fraction of MSW	404	65	32	51	[26]
Organic fraction of MSW + pig slurry	378–397	135–151	48–53	63–68	[11]
Pig slurry + milk serum + cow slurry + maize silage + rice residues	367–383	83–103	38–41	54–61	
Pig slurry + blood industry residues + maize silage	387–421	85–92	31–34	61–67	

composition of this organic matter is also relevant. Carbon and nitrogen are the most important constituents of organic matter. Rather than total concentration, the balance between organic and mineral forms will influence the agronomic use of the waste. Products rich in organic carbon and nitrogen will rather be used as soil amendments in order to improve soil biological properties. It must be noted that the biological treatment applied on organic waste can influence the balance between mineral and organic matter and thus the agricultural use of the residue. Indeed Kirchmann et al. showed that if the main concern is soil protection and improvement, addition of aerobically treated material should be preferred over anaerobically treated substrates [17, 18]. Table 2 presents the carbon and nitrogen composition of several digestates. The total organic carbon of these digestates is about 400 g/kgDM while total nitrogen content is more variable according to the digestates between 50 and more than 150 mg/kgDM. These data showed that the majority of the nitrogen contained in digestion residues is present under mineral form as $N\text{-}NH_3$ always represents more than 50% of the total nitrogen. The predominance of mineral nitrogen could reduce the digestates potential of valorization as organic amendment and enhance their use as fertilizers.

Measuring kinetics of carbon and nitrogen mineralization during soil incubation is an effective way to estimate the uptake or stocking of organic matter and nutrients in the soils. The restoration of soil properties (soil structure, microbial activity, soil fertility) partly depends on the storage of the carbon brought to soil through organic matter application on land. Mineralization test is a good indicator of the organic matter decomposition rate and consequently of the carbon sequestrated in the soil. The proportion of organic carbon mineralized during 3 days of incubation was used recently to define a new indicator of potential residual organic carbon in soils [19]. This indicator also defined as a function of soluble, cellulose and lignin fractions, estimates the proportion of exogenous organic matter contributing to soil organic carbon storage. No values indicating the minimum agronomic benefit for an organic amendment was yet provided by the authors. On these mineralization aspects, rather no data on digestates have been published.

Biochemical Fractionation

Besides the quantity and the composition of organic matter applied on land, organic amendment properties are defined by the structural nature of the organic matter added to soil. The biochemical fractionation of organic matter according to Van Soest methodology defines a soluble fraction containing proteins and carbohydrates, and fractions constituted with cellulose (CEL), hemicellulose (HEMI) and lignin (LIGN) [20]. Nonetheless, it must be noted that this fractionation method is not representative of pure compounds but quantifies categories of soluble compounds in the same conditions. Biochemical fractionation is often used to assess wastes biodegradability [21–24] and leads to define different maturity indices. (CEL + HEMI)/LIGN ratio is suggested as an indicator of humification degree, since the transformation by micro-organisms of cellulose, hemicellulose or lignin leads to the synthesis of humic substances [25]. Authors reported values of 3–4 for fresh wastes and lower values after biological treatment while Tambone et al. [26] reported values of 0.8 for digestates of different organic wastes. Komilis and Ham [27] used CEL/LIGN ratio to distinguish fresh and mature wastes, and observed a decrease from 2.3 to less than 0.5 at the end of a composting process. In coherence, Tambone et al. [26] observed a decrease from 1 to 0.5 during AD. Lignin can partially decompose, but cellulose and hemicellulose are more biodegradable compounds. Indeed, their losses during biodegradation are greater and thus CEL/LIGN and (CEL + HEMI)/LIGN ratios decrease. Nevertheless there is not a linear relationship between these biochemical ratios and the biodegradation of organic matter, meaning that these indicators could be uncertain to state on the extent of decomposition and thus on the product maturity. Actually, variation of biochemical fractions during biodegradation may be ever-changing according to the nature of the substrate. Nonetheless biochemical fractions are used to define standardized stability indices for French amendments as

IBS (index of biological stability) or Tr (proportion of residual organic matter) but no indication of limit value is provided [28].

Humic Substances

Concentration of humic substances is also used to assess amendment quality as these substances, the main and more stable component of the organic matter, are essential to improve global soil fertility and health [29, 30]. The amount of humic substances in organic products is thus considered as an important indicator of their biological maturity, warrantee for safe impact and successful performance of amendments in soils. Fulvic acids (FA) and then humic acids (HA) are produced during biosynthesis of humic substances. Humic acids can contribute to the soil buffer capacity and soil cation exchange capacity. Humic acids content consequently affects the behaviour of heavy metals through the formation of complexes with different solubility and thus mobility [31]. HA/FA is often used to characterize humification processes and has been proposed as maturity indicator [32]. This ratio increases during aerobic biodegradation mainly due to a great increase in HA content [33], and a value of 1.9 has been proposed as a maturity threshold for composts [34]. Humic acids analyses are also used to characterize the degree of decomposition of the organic matter. Elemental composition leads to determine the ratio between hydrogen content and carbon content (H/C) of humic substances as an estimation of maturity. Campitelli et al. noted that organic amendments with low H/C ratio are more mature as they present humic acids more condensed and substituted in aromatics rings [30]. The authors also used the ratio of absorbance at 465 and 665 nm which is frequently used in soil science to assess the humification degree. A decrease of this quotient indicates the progressive humification processes. Nevertheless, the non-specific techniques used for the extraction of humic substances, leading to the co-extraction of non-humic compounds, could prevent the use of these indices as maturation degree indicators [35]. Moreover there is no minimal degree of humification recommended for amendment utilization. Data on digestates humic composition were not found.

Cation Exchange Capacity

Determination of cation exchange capacity (CEC), that addresses generally soil quality characterization, can be applied to organic products when they are used as growing media. CEC determines a substrate ability to absorb specific cations (Ca, Mg, K, Na…) and can be used as a maturity indicator as it rises during aerobic biological treatment along with organic matter reorganization and humification processes. This process reflects humic substances synthesis during maturation according to several authors who suggest a maturity threshold at 60 meq/100 g [36]. Besides, the increase in CEC is of agronomical interest as it gives a chance for a longer soil fertility and improves contaminants retention avoiding leaching to groundwater [37]. Other authors rather use the ratio between CEC and carbon content (CEC/C) to characterize composts, as this indicator reflects also changes in carbon concentration during biodegradation. A CEC/C ratio of 2 mmol/g is for instance the minimum value required for compost commercialization according to Normative Instruction of the Brazilian Ministry of Agriculture Livestock and Food Supply [38]. However, the initial values of CEC at the beginning of a biological treatment of organic wastes can sometimes be higher than these limits. Therefore, these maturity thresholds cannot be used for all composts although the evolution of CEC is a good indicator of organic matter humification process [35].

Existing Standards

Different European standards exist on organic amendment properties in order to standardize and control their quality and enhance these products' image for sale. The ECS report on labeling and specifications on soil amendment and growing media details the list of products which can be considered as soil amendments [16]. It appears that the main specification for soil amendments concerns minimal organic matter content between 20 and 90% of dry matter according to the nature of the product. For digested material, the minimal requirement in organic matter is 20% of dry matter. Data available on digestates (Table 1) show that these organic products could all be considered as soil amendments on the sole criterion of organic matter content. Other parameters are compulsorily specified on soil amendments such as the organic matter content, pH, electrical conductivity or granulometry for some of them. Facultative declarations can also be made: dry matter content or bulk density. Concerning digested materials, essential constituents (i.e. higher than 10% in volume), organic matter content and pH must be specified. It must be noted that this ECS report is only informative but does not consist in a European standard for soil amendment as each European country possesses its own legislation.

Quality requirements and quality assurance of composts and digestion residuals are controlled and monitored by the RAL quality label in Germany [39]. RAL GZ 251 on compost quality exists since the early 1990's. Minimum quality criteria for digestate products are defined in RAL GZ 245 and include hygienic aspects, impurities maximal contents, degree of fermentation or organic matter content. Indeed, digestates must present minimal organic matter content of 30% of dry matter (determined by loss on ignition).

In Spain, specific legislation on soil amendment does not exist but some regulations control organic products such as humic or non humic amendments, composts and peat. These regulations define the name of the products, minimal contents or quality requirements. Spanish legislation defines for example maximal content in heavy metal in sludge used in agriculture [16].

Austrian ordinance on quality and sales of composts coming from wastes defines several quality requirements (maximal heavy metal contents, type and origin of input wastes, specification rules) [16].

In France, standards NF U44-051 and NF U44-095 regulate the agricultural use as soil amendments defining the compliance of chemical characteristics with limits of quality [40, 41]. French organic soil improvers must present dry matter content higher than 30 or 50% of the fresh weight according to the type of compost considered. Moreover, amendments must contain minimal organic matter content of 20% of fresh matter to be normalized according to French standards. French organic soil improvers shall also have a C/N higher than 8, except for sludge composts [40]. Finally, sum of nitrites, ammonium and urea have to be specified and together represent less than 33% of total nitrogen while total N, K_2O or P_2O_5 shall not exceed 3% and the sum of these elements 7% of fresh weight. The 8 digestates characterized by Tambone et al. [11] comply with these criteria as they presented on average total N, K_2O or P_2O_5 of 0.5, 0.2 and 0.3% of fresh weight.

Fertilizing Effect

The fertilization potential of an organic product is not only estimated by the total content of the three main nutrients (nitrogen, phosphorus, potassium) but rather by their availability for plant nutrition. Using the necessities of the crops as a reference and taking into account the content and availability of these macronutrients are also essential to determine the doses of organic fertilizers to be applied on soils. Agronomic measures of nutrient availability by crop growth tests (plants N uptake for instance and available nutrients in the soil) are thus essential to determine the fertilizing effect of an organic product. This section details the indicators used to qualify fertilizing products.

C, N, P, K

A proper use as fertilizer requires assessing the potential release in soil of inorganic nutrients from their organic forms. The C/N ratio, which is an important tool to assess total nutrient balance, cannot explain all differences in nitrogen mineralization. Organic wastes with similar C/N may mineralize different amounts of nitrogen due to chemical differences in their composition [31]. Mineralizable carbon and soluble mineral nitrogen (ammonium) are important characteristics for fertilizer as they constitute a potential of available nutrients for plant growth. Mineralization test of nitrogen allows the quantification of mineralized nitrogen. The ratio between mineralized nitrogen and total nitrogen is indicative of nitrogen availability for plants uptake. Biological treatment of organic wastes influence their future agricultural use and digested organic wastes are preferentially used as organic fertilizers as their proportion of available N is more important than in composts. For anaerobic sludge the proportion of available N in the first, second and third year of application is 20, 10 and 15% while for composts these figures are 10, 5 and 2.5% respectively [42].

Water soluble concentrations in N, P or K can assess the availability of these elements for plant uptake as soluble compounds are easily assimilated. However, it is very important to adapt the fertilizer use to crop requirements because excessive addition of fertilizing product on soils can lead to degrade water quality by nitrate leaching and runoff nutrient loads. In particular, P extractable content is of considerable interest as P leaching lead to nutrient input in water sources stimulating algae and rooted aquatic plant growth leading to accelerated eutrophication [43]. High soil P accumulation under continuous fertilization may also increase the risk of P transport from soil to surface water [15].

Other Mineral Content

The determination of mineral content estimates the fertilizing potential of the waste through the quantification of potential nutrients brought on soil [29]. Increased mineral concentrations can result in increased plant uptake but the extraction of minerals by the crops, and thus the potential increase in production, is essentially influenced by the pH. For instance organic fertilizers with pH close to neutrality can reduce the alkalinity of basic soils and thus favour calcium and magnesium extraction by the crops [42]. Acid soils will also present a larger amount of available manganese than neutral or alkaline soils [43]. Data available showed that digestates pH was close to neutrality as it ranged between 6.7 and 8.5 [6, 10, 12–14].

Existing Standards

For an organic fertilizer to meet French standards, total N, K_2O and P_2O_5 have to show a minimum content in fresh matter of 3% and the sum of these compounds have to be higher than 7%. Also, organic nitrogen content from animal and/or vegetable origin has to be higher than 1% [44]. German regulation on fertilizers specifies that nutrient contents in dry matter must be higher than 0.5% of N, 0.3% of P and 0.5% of K_2O [16].

Innocuousness

Innocuousness of organic products used in agriculture includes impacts on potential users (and the exposed human population in general), environment (flora, fauna and largely ecosystems including soil and water) and plants growing in the amended or fertilized soil. Innocuousness of organic residues is complex to define and depends on a combination of several factors. For instance, Walter et al. attributes the potentially phyto-toxicity nature of the organic wastes to the combining action of a high salinity, any excess of ammonium ions or organic compounds such as fatty acids, and heavy metal presence [45]. Digestates innocuousness has been very rarely studied so far and only few data concerning organic contaminants or toxic elements have been found in literature [9].

Inorganic Impurities

The presence of contaminants in organic products designed to agricultural use can induce adverse impacts on the general environment. Absence of inert material, such as plastics or sharp particles of glass, is a quality requirement both for sanitary issues (harmless contact through manipulation) or visual aspect of a soil conditioner. Kapanen and Itävaara estimated that compost may contain impurities (plastic and glass) equivalent to only 0.5% of its fresh weight [46]. Table 3 gives national guidelines in European countries for several impurities in compost, digestates or fertilizers [47].

Table 3 National guidelines for impurities in organic residues (based on [47])

Country	Impurities	Maximal values in %DM
Austria (ordinance project on compost (10/98)	Total	0.5–2
	Plastics	0.02–1
	Metals	0.2
Austria (ON S2200)	Glass, metal, plastics	0.5
	Glass	2
	Plastics	0–0.2
Austria (ON S2022)	Glass	2
	Plastics	4
	Iron metals	0
	Non iron metals	0.5
Belgium (Flanders)	Total	0.5
	Stone > 5 mm	2
Finland (fertilizer regulation)	Total	0.5
France (NF U44-051)	Plastics > 5 mm	0.3–0.8
	Glass + metals > 2 mm	2
Germany (ordinance on biowaste)	Glass, plastics, metals	0.5
	Stone > 5 mm	5
Germany (RAL GZ251)	Glass, plastics, metals	0.5
	Stone > 5	5
Germany (RAL GZ245)	Glass, plastics, metals	0.5
Italy (fertilizer regulation 748/84)	Plastics	0.05–0.45
	Other inert material	0.9
Netherlands (BRL K256/02)	Glass, metal, plastics	0.5
	Glass > 16 mm	0
	Stone > 5 mm	3
Netherlands (BOOM)	Total	0.2
	Glass	0–0.2
	Stone > 5 mm	2
Norway	Impurities	0.5
Spain (ministerial order)	Plastics and other inert materials < 10 mm	0

Potentially Toxic Elements

The risks due to potentially toxic elements are usually associated with toxicity when their concentration is too important and with a deficiency in plant growth when their concentration is too low. Heavy metal content must be watched closely as it may induce metal accumulation on soils when the amendment is repeatedly applied. The solubility and thus availability for plant of these elements influence mostly the potential toxicity of the product rather than the total metal concentration [31]. Actually potentially toxic elements become toxics once absorbed by plants, animals or micro-organisms. And the absorption occurs usually when the element is solubilized. Thus chemical speciation of heavy metals provides valuable information on metal mobility, bioavailability and leaching rates when amendment is applied on soil [45]. Nevertheless, investigations into bioavailability of trace elements could be expensive and very time consuming [43] therefore guidelines are usually established on total content of heavy metals. Table 4 shows some guidelines proposed for heavy metal concentration in products designed to an agricultural use. Concentration thresholds are comparable in European [39, 40, 48] and Canadian regulations [49], but higher in US EPA specifications [43]. Cadmium should be particularly watched as Diacono and Montemurro deem that this element is one of the most significant potential contaminants of food supplies on arable lands as it is quite toxic to humans and relatively soluble on soils and thus readily taken up by crops [31]. The data available on digestates heavy metals content reported that concentrations in Cd, Co, Cr, Cu, Hg, Ni, Pb and Zn in digestates coming from biowaste were lower than standardization guidelines [9].

Table 4 Guidelines for potentially toxic elements

Specification	British PAS [48]	RAL GZ251 [39]	NF U44-051 [40]	CCME [49]	US EPA (cited in [43])
Element	Concentration mg/kgDM				
As	–	–	18	13	41
Cd	1.5	1.5	3	3	39
Cr	100	100	120	210	–
Cu	200	100	300	400	1,500
Hg	1	1	2	0.8	17
Ni	50	50	60	62	420
Pb	200	150	180	150	300
Se	–	–	12	2	100
Zn	400	400	600	700	2,800
Co	–	–	–	34	–
Mo	–	–	–	5	–

British PAS British Public Available Specification; *RAL GZ251* German standards for compost; *NFU44-051* French standards for organic amendments; *CCME* Canadian Council of the Ministers of the Environment; *US EPA* United States Environmental Protection Agency

Other potentially toxic compounds can exist in organic wastes. These elements are usually determined on aqueous extracts of solid organic products. For instance, high levels of water-soluble phenolic compounds may have adverse effects on environment because polyphenols induce nitrogen immobilization on soil and inhibit seed germination [35]. Walter et al. [45] also list ethylene oxide, short-chain aliphatic acids, phenolic compounds and ammonia as phyto-toxic agents. In particular, ammonium concentration can help to evaluate a potential phyto-toxic effect and a minimum concentration of ammonia will assure to reach a more stable status and a comfortable use of the soil conditioner. A maximal concentration of 0.4 mgN-NH_4/g DM has been suggested as a potential phyto-toxic threshold [35, 50].

Organic Contaminants

Organic contaminants such as pesticides are also to be quantified before an agricultural use. French standards for organic amendment and more recently a 2010 British Public Available Specification on digestates gives threshold values to insure innocuousness of the organic by-product [40, 41, 48]. Persistent organic pollutants are of particular interest as they are highly chlorinated and known to be persistent in the environment [43]. French normalization for fertilizing material coming from waste water treatment specifies upper limits for the sum of seven biphenyl polychlorinated compounds at 0.8 mg/kgDM. Upper limits are also set at 4, 2.5 and 1.5 mg/gDM for the following polycyclic aromatic hydrocarbons: fluoranthen, benzo(b)fluoranthen and benzo(a)fluoranthen respectively [41].

Stability

Stability is an important characteristic of organic products. Stability avoids management issues such as further fermentation leading to odorous emissions but also limits further decomposition in soil that may lead to nitrogen immobilization depending on the period of use during the year. Stability is thus an important condition to reach to assure innocuousness of organic products once applied on soil. Stability can be described either by biological or chemical parameters.

Biological Indicators

Biological parameters are the most accurate indicators of biodegradability as they measure the respiration rate due to microbial activity during the biodegradation of organic matter. Table 5 summarizes different biological indicators along with their limit established to determine stability [51–57]. Several respirometric methods, either in aerobic or anaerobic conditions, exist to assess the biological stability of organic products. During aerobic biodegradation process, microorganisms oxidize the biodegradable organic matter in presence of oxygen leading to the production of metabolites such as carbon dioxide. Therefore evolution of oxygen consumption and/or carbon dioxide production allows the estimation of the aerobic stability of the product. These measures can be done in liquid or solid phase, in static or dynamic conditions. Among data available, only Drennan and DiStefano gave values of digestates biological stability. The OUR measured for food wastes and landscape wastes digestates are included between 0.7 and 0.9 mgO_2/gOM/h [14]. These digestates could thus be considered as stable organic residues but estimating their agronomic benefit can not be based only on biological stability as many other factors impact soil improvers' quality as previously described.

Microbial activity also leads to heat production. The self-heating potential is a measure of the heat released during the biodegradation of a defined quantity of organic

Table 5 Stability thresholds for biological indicators

Respiratory index	Biological stability limit	Reference
AT_4	5 mgO_2/gDM	[51, 52]
AT_4	10 mgO_2/gOM	[53]
DRI	1,000 mgO_2/kgOM/h	[53, 55]
OUR	1 mgO_2/gOM/h	[54, 56]
Self-heating potential	0–10°C ⟺ very stable and mature compost	[57]
	10–20°C ⟺ moderately stable compost in maturation	
	20–30°C ⟺ active compost in fermentation	
	30–40°C ⟺ fresh compost at the beginning of fermentation	
	40–50°C ⟺ raw wastes	
GB_{21}	20 Nl/kgDM	[53]
BMP_{21}	10 Nl/kgDM	[53]
BI	10 d^{-1}/kgDM	[51]

AT_4 respiration activity in 4 days; *DRI* Dynamic Respiration Index; *OUR* Oxygen Uptake Rate; *GB_{21}* gas formation test in 21 days; *BMP_{21}* Biochemical Methane Potential in 21 days; *BI* Black Index

product in a closed vessel under controlled conditions of temperature and moisture. Table 5 gives the classification proposed by Brinton et al. [57] to determine organic residues stability based on the self-heating potential.

In anaerobic conditions, the degradation of carbonaceous matter leads to the production of biogas essentially composed of methane and carbon dioxide. Measurement of biogas production in a hermetically closed vessel under controlled conditions of temperature and time gives an estimation of anaerobic biodegradability. An other biological indicator has been recently proposed: the black index provides an indication of waste biological stability based on the observation of the colour change of a lead acetate test paper in an enclosed vessel containing the product [51]. Authors deem that this index would be an economically preliminary test to characterize waste stability. Table 5 gives stability limits proposed for anaerobic indicators.

Chemical Indicators

Organic matter concentration is often used as a stability criterion for organic wastes or by-products since its decrease illustrates microbial activity [51]. Organic matter determination is important to assess stability since a product containing insufficiently degraded organic matter could evolve once applied on land hence leading to nitrogen immobilization, odorous emissions or pathogen regrowth in the soil [58]. In addition, excess of available organic matter may lead to nutrient deficiency in plants and oxygen deficiency in the root zone since oxygen will be consumed to degrade the residual organic matter [46].

Another way to estimate organic matter concerns chemical oxygen demand (COD). COD measures the degradability of organic matter under strong oxidizing conditions. This parameter is sometimes used as a stability criterion and a threshold value of 700 mgO_2/gDM was proposed to define municipal waste composts as stable [59]. Nevertheless as for organic matter concentration, COD may overestimate biological reactivity as it measures total (i.e. biological and chemical) oxidation of organic matter. Consequently Cossu and Raga proposed a stability indicator integrating the biological oxygen demand measured at 5 days [51].

The biological degradation of the organic matter depends essentially on the metabolic use of carbon and nitrogen. During biodegradation organic carbon is utilized for energy by decomposer microorganisms and is either assimilated into cell wall or released as metabolic products as carbon dioxide. Organic nitrogen is predominantly converted into inorganic forms that are either used in new microbial synthesis or released into the soil once the product is applied on land. The amount of nitrogen required by microorganisms for their growth is 20 times smaller than that of carbon [31]. If there are both a low concentration of organic carbon and a larger quantity of nitrogen in respect to the requirements of microorganisms, nitrogen will be mineralized and released in soil. On the contrary, if nitrogen quantity is smaller than microbial requirements, inorganic nitrogen contained in soil will be used to complete the biodegradation process leading to nitrogen immobilization. Thus C/N of organic residues must be well balanced in order to assure their stability once applied on soil. Stability threshold ranges between 10 and 20 according to authors and wastes considered [5, 24, 50, 60]. For MSW compost, Bernal et al. [34] defined a stability threshold for a C/N of 12 and specified that a compost with C/N higher than 15 may alter microbial equilibrium in soil. For agricultural wastes, Kirchmann et al. estimate that products with C/N higher than 18 may lead to nitrogen immobilization in soil [17]. However, using C/N for stability assessment does not gain consensus as this ratio can vary widely according to waste nature. The particular characteristics of the soil can also influence the effect of organic amendments and an amendment with a specific C/N could be beneficial to one soil and detrimental to another.

Several authors proposed stability indicators based on soluble carbon and nitrogen content measured on aqueous extracts of solid wastes. Indeed, organic solid waste can be described as a three-phase matrix: solid, liquid and air. Micro-organisms grow preferentially in the aqueous biofilm surrounding solid particles of organic matter [61]. Microbial activity is thus mainly located in the aqueous biofilm and quantification of solubilized organic compounds is supposed to assess more accurately waste reactivity. In Germany, total organic carbon in elution test is considered as the most important stability criterion before landfilling organic wastes and must be lower than 250 mg/L [52]. Dissolved organic carbon have also been suggested as an indicator of compost stability with threshold varying between 0.5 and 17 mg/gDM according to authors [34, 35, 62]. Concerning soluble C/N, stability thresholds between 0.55 and 5–6 have been proposed [34].

C/N for digestates are found to be very variable between 7 for digestion residues coming from a mixture of energetic crops, cow slurry, agro-industrial wastes and organic fraction of MSW [26] and almost 25 for digestates of food and green wastes [6]. Despite the variability of the C/N ratio according to the nature of the feed mixture, digestates C/N are commonly lower than 20. Tambone et al. [11] observed that C/N of 8 studied digestates were between 7 and 14, much lower than those of 3 characterized composts. The lower C/N ratio for digestates are essentially due to the digestion process as carbon is degraded during AD while total nitrogen is conserved. Thus these low values for C/N do not inevitably assure digestates stability.

pH, Salinity, Conductivity

Other chemical characteristics can be detrimental to the environment. pH is important to determine innocuousness as it controls the behaviour of metals and many other soil processes [46]. Indeed, low pH causes higher heavy metal solubility that can cause phyto-toxicity issues on plant growth. A low pH can indicate immaturity of a compost because of the intensive production of organic acids during the prior thermophilic stage of composting [43]. Lasaridi et al. [58] report that in most national standards, compost should have a pH value within the range 6.0–8.5 to ensure compatibility with most plants. Data available in literature reported adequate pH for digestates as they presented values ranging from 6.7 to 8.5 for mixtures of food wastes and green wastes [6, 14] and about 7.5 for agricultural wastes mixed with municipal wastes [10, 12, 13].

Plants are also negatively affected by excess salt concentration in soils [43]. Electrical conductivity, measuring the content of dissolved solutes on aqueous extracts of organic solid products, is an estimation of salt content. Products with high electrical conductivity can potentially inhibit seed germination and impact the soil biological activity but the absence of correlation between electrical conductivity, biodegradation and effective phyto-toxic effects prevent to use conductivity to assess potential phyto-toxic impacts [43, 63].

Phyto-Toxicity

Because it is difficult to assess the impact on the environment only on potentially toxic chemical compounds, biotests are also needed to estimate the ecotoxicity of organic products before their use on land [46]. These ecotoxic tests can consist in the estimation of growth inhibition for different living organisms such as bacteria or algae which are quite sensitive bio-indicators. Phyto-toxicity essays can measure either the immediate toxicity of the product thus inhibiting the germination or the latent toxicity inhibiting the root growth.

Immediate toxicity tests usually consist in the determination of potential seed germination inhibition measured on an aqueous extract of the organic product. Germination tests measure both germination percentage and root growth of a particular species and lead to determine a germination index. Innocuousness thresholds for the germination index vary from 50 to 80% according to authors and wastes. For instance, municipal composts are estimated safe when the germination index is higher than 60% while for a mixture of food and green wastes a minimum limit of 70% has been proposed [6, 29, 53]. Nevertheless, a recent study showed that the germination index was highly dependent on the plant used for the germination test [54]. The authors proved that a compost could be phyto-toxic for one plant and beneficial to other. Thus, it appears difficult to establish a general limit of the germination index to assess amendment maturity.

The latent toxicity can be assessed by growing tests. These tests are usually performed on mixtures of compost and soil or sometimes on compost alone and consist in studying the development of plants or mushrooms on the organic media. No threshold value exists to define stability of organic substrate by growth trials [64].

Pathogens

Health risks for humans or animals must also be estimated before an agricultural use of organic waste. The presence of faecal coliforms is often used as an indicator of the overall sanitary quality of soil and water environments as they generally occur at higher frequencies than the pathogens and are simpler and safer to detect [65]. Potential

Table 6 Upper limit values for microbiological indicators

Specification	NF U44-051 [40]		NF U44-095 [41]		CCME [49]	British PAS [48]
	a	b	a	b		
Helminth eggs	abs. in 1.5 g*		abs. in 1 g*	abs. in 25 g*	–	–
Lysteria monocytogenes	–	–			–	–
Salmonella	abs. in 1 g*	abs. in 25 g*			abs.	abs. in 25 g*
Fecal coliforms	–	–	–	–	<1,000 MPN	–
E. coli	–	–	–	–	–	<1,000 CFU

a all cultivation except market garden produces; *b* market garden produces; *abs* absence of the pathogen; * expressed by gram of fresh matter; *MPN* most probable number per gram of total solids on a dry weight basis; *CFU* colony forming unit per gram of fresh matter

NFU44-051 French standards for organic amendments; *NF U44-095* French standards for fertilizing material coming from waste water treatment; *CCME* Canadian Council of the Ministers of the Environment; *British PAS* British Public Available Specification

impacts on human health can be assessed through the quantification of coliform bacteria. *Escherichia coli* is reported to be the most representative bacterium in the group of faecal coliforms (Le Minor (1984) cited in [65]) but faecal streptococci are commonly considered as the best indicators of faecal pollution. *Staphylococcus aureus* is one of the main cause of collective infections of food and can also induce cutaneous infections hazardous for compost handlers and farmers. Among pathogens, *Salmonella* are the most studied and the most frequently found so they have been proposed as indicator of pathogens behaviour in sludge and composts [66]. Helminth eggs are also currently quantified as they present a high resistance to environmental factors. Hygienization of waste after biological treatment will be then assured by the reduction of several bacteria or pathogens in the end-product [67–69]. The quantification of these microbiological indicators along with upper limits assuring a safe use of organic by-products are specified in different national regulations and reported in Table 6 [40, 41, 48].

For Lasaridi et al., sanitized compost is defined by the following criteria: 5×10^2 CFU/gDM for faecal coliforms, 5×10^3 CFU/gDM for faecal streptococci and absence of *Salmonella* in 100 g [58]. The digestates studied by Paavola and Rintala could consequently be considered as sanitized as they showed 0–3 $\log_{10}$ cfu/g of faecal coliforms [10]. In German standards, the quality requirements for digestates are a maximum of 2 germinable weeds and sprouting plants per liter and that *Salmonella* are not traceable. Moreover the proof for a successful sanitization during the digestion process has to be made (i.e. heating of the input material to 70°C for at least 1 h or input/ouput control) [39].

Conclusions

The agricultural use of an organic product depends on its innocuousness towards general environment (soils, crops, humans…) and its agronomic contribution to soil improvement or crop growth.

Organic amendment quality firstly depends on a minimal quantity of organic matter brought to soil. The composition (nature and structure) of this organic matter is then important to determine through several indicators (carbon and nitrogen content, biochemical fractionation, humic substances…). The fertilizing effect is mostly influenced by the bio-availability of essential nutrients (N, P, K). Innocuousness can be estimated by chemical parameters (heavy metals, organic contaminants, impurities…) but it is difficult to assure a safe use of an organic amendment or fertilizer only on chemical composition. Biological stability estimated by respirometric indicators must be reached before an agricultural use as it avoids further decomposition that may lead to negative impacts (odours, nutrient deficiency for plants…). Eco-toxic tests such as phytotoxicity estimation or pathogens determination must also be carried out before any agricultural use. At the end, the profit of organic wastes application on soil depends on a variety of factors such as the concentration in different elements, the contribution of each one to soils as well as the period and the type of soil on which amendments or fertilizers are spread. Many impacts (release of nutrients, accumulation of heavy metals) need time to be tested as their effects are present only when repeated applications occurred [31]. Therefore, long-term trials and field experiments, despite the fact that they are time and money consuming, should be performed before an agricultural use of organic products as they are the best indicators of organic matter utilization and sustainability and permit to define optimum application rates while minimizing negative environmental impacts.

The data currently available in literature are often rare or superficial. Therefore, there is a crucial need to bring more data on digestates composition in order to compare their characteristics to quality standards and thus to assure their safe use in agriculture.

Characterization of Solid Digestates Treatability Through an Aerobic Post-Treatment

As discussed in the previous section, digestates characteristics are for the moment not much known. Potential toxicity or sanitization issues could lead to the necessity of digestates post-treatment. Composting is an adequate option to improve digestates quality. The suitability of substrates for composting depends on several characteristics. The considered waste shall present a sufficient biodegradability but also physical characteristics compatible with an aerobic treatment. Biodegradability is defined by two complementary ideas: the waste ability to be biodegraded and the kinetics of biodegradation.

Biodegradable Potential

Several indicators used previously to estimate stability can be also discussed to describe biodegradability. Respirometric measure allows the quantification of aerobic biodegradability and this residual biodegradable potential is indicative of a feasible biological treatment of organic residues by composting. In addition to a sufficient amount of organic biodegradable matter, physico-chemical conditions must be favourable to biodegradation. As previously discussed, biological degradation depends essentially on the use of carbon and nitrogen by micro-organisms. Carbon and nitrogen constitute energy sources for micro-organisms growth and diversification [23, 70]. If the amount of nitrogen is limiting, microbial populations' growth will stagnate and thus biodegradation will be delayed. On the other hand, excess nitrogen beyond the microbial requirement can lead to nitrogen losses as ammonia. Indeed, C/N ratio characterizes the nutritive potential of an organic waste for micro-organisms development. Igoni et al. [71] suggested a C/N equal to 30 to optimize anaerobic biodegradation as they mentioned that bacteria in digestion process use up carbon 30–35 times faster than the rate at which they convert nitrogen. C/N value of 30 has also been reported as the most favourable situation for a rapid composting [27, 64]. Nevertheless, C/N ratios lower than this "ideal" value have been often reported for compostable raw wastes [63]. Moreover, indicators based on total amounts of carbon and nitrogen do not consider fractions of carbon and nitrogen available for micro-organisms biodegradation. Substrates with comparable C/N values may thus present very different levels of biodegradability.

Other chemical or biochemical parameters are also used to assess a biodegradable potential of organic wastes. The initial pH of wastes, determined on aqueous extracts, is for instance estimated suitable for composting if it is within the range 6–8 [35]. As previously discussed, organic matter content and chemical oxygen demand can be used to estimate organic load of wastes in terms of biodegradability. However, organic matter content and chemical oxygen demand may overestimate the effective biodegradability as their measures quantify also non biodegradable compounds [72]. Biochemical fractions determined by the Van Soest protocol are also used to estimate biodegradability. Lignin and cellulose content are often use to assess anaerobic biodegradability [23, 24] and Buffière et al. [22] showed that the sum of lignin and cellulose correctly correlated with food wastes anaerobic biodegradability. Chandler also used the lignin content to calculate a biodegradable fraction of organic wastes in anaerobic conditions (Chandler (1980) cited in [21]). Several authors deem that the biodegradable fraction of a waste is unchanged under anaerobic or aerobic conditions [73, 74]. Indeed, a linear relationship between the lignin content and biodegradability was also found in aerobic conditions [75].

Table 7 Initial chemical characteristics of compostable wastes

Nature of wastes	C/N	pH	VS (%DM)	Reference
Urban sludge	6–11	–	–	[64]
Agricultural wastes	15–25	–	–	
Green wastes	11–41	–	–	
MSW	20–30	–	–	
Sludge + straw	–	5.9	–	
Urban wastes	–	5.0	–	
Paper industry sludge	–	7.3	–	
Biowastes	17–42	–	47–74	[76]
MSW	25–65	–	68–73	
Green wastes	23	–	54	
Household wastes	27	8.5	76	[77]
Separated pig solids	12	–	72	
Food wastes	13	–	91	
Pig slaughterhouse sludge	8–12	7–9	82	
Green algae	8	8	53	

Table 7 presents characteristics of different fresh organic wastes intended to be composted [64, 76, 77]. These chemical characteristics vary widely according to the nature of the wastes illustrating that acceptable initial conditions for composting materials are quite large.

Biodegradation Rates

Respirometric tests can evaluate the biodegradation rates of an aerobic degradation of organic matter. Oxygen consumption and carbon dioxide production can be used to follow the respirometric activity. Oxygen consumption measurement is rather preferred. Indeed anoxic zones can produce CO_2 and lead to misrepresentations of respirometry [78]. Several respirometric indices exist (AT_4 or DRI

Table 8 Biological characterization of compostable wastes (based on [80])

Nature of wastes	Total oxygen consumed (gO_2/kgDM)	Maximal OUR (mgO_2/h/kgDM)
Green wastes	218	1.7
Urban sludge	91–172	0.8–3.2
Slaughterhouse sludge	481	2.8
Grape marc	442	2.6
MSW	326–727	2.9–3.5
Separated pig solids	400	5.8

for instance, see Table 5) depending on experimental conditions. These indices are measured on small quantities of dried and ground waste and thus do not take into account the physical structure of organic solid wastes. Consequently, Tremier et al. [79] developed a specific respirometric apparatus consisting in a hermetically closed reactor filled with about 10 L of solid wastes and placed under controlled conditions. This respirometric device allows the assessment of the maximal biodegradable potential of physically unmodified samples. Table 8 gives examples of total oxygen consumed and oxygen uptake rate (OUR) measured during respirometric tests of various organic compostable wastes [80]. The different amounts of oxygen consumed allow the determination of biodegradability levels according to the biodegradable potential in wastes. MSW, separated pig solids or grape marc appear to be highly biodegradable while green wastes or urban sludge that have already been biologically treated are less biodegradable. Monitoring oxygen consumption during biodegradation allows the fractionation of organic matter according to their biodegradation rates [79, 81]. Following OUR and modeling biodegradation kinetics allow the measure of the easily biodegradable fraction, the slowly biodegradable fraction and the inert fraction of organic matter. Indeed, respirometric methods lead to a qualitative and quantitative characterization of the different parts of organic matter according to their degradation rate.

Physical Parameters

Among parameters affecting biodegradation ability and kinetics, physical parameters are the most important. In particular particle size affects the biological transformation rates of the waste. A decreasing particle size leads to an increase in hydrolysis rate of slowly biodegradable fraction as the total surface area accessible to micro-organisms increases [71, 82]. Aerobic biological activity depends strongly on the maintenance of favourable conditions for micro-organisms growth. Substrate porosity determines the quantity of oxygen available for microbial flora. Porosity impacts consequently micro-organisms growth and thus indirectly the biodegradation rate [83]. Porosity linked with permeability influences the air flow inside the substrate matrix and thus the aeration of the waste [84]. Porosity and permeability are determining factors in the preservation of optimum conditions for aerobic biodegradation. During an aerobic treatment by composting, the range of optimum air porosity varies according to authors: higher than 30% [85], 32–36% [86], higher than 35% [87], 30–36% [88] or 30–65% [89].

Conclusions

The characterization of organic residues treatability by composting is based on biological, chemical but also physical characteristics. Several indicators applied previously to characterize the direct agricultural use of digestates can also describe their potential biodegradability for a further biological treatment. Indeed respirometry, carbon and nitrogen content or chemical oxygen demand illustrate the residual potential of biodegradable matter and its ability to be degraded by micro-organisms. Additional physical parameters complete the assessment of an aerobic treatability as physical environment in wastes also impact on biodegradation. Appropriate particle size, porosity and permeability will thus insure favorable conditions for aerobic biodegradation.

Conclusion

Identifying the relevant characteristics of digestates is essential to assure their full valorization and their sustainable market. A complete characterization of digestates will assure their safe and direct agricultural use after digestion as useful by-products and will also optimize their aerobic post-treatment if necessary. A series of analytical parameters have been presented and discussed. Each one can be valuable in a specific viewpoint but also presents limits in its use and interpretation. Soil amendment quality, fertilizing effect and innocuousness are complex notions influenced by several interacting factors. Thus, no single parameter can be used to estimate quality of organic substrates coming from different sources [90]. Depending on the objective of the characterization, several parameters will thus be needed to assess digestate quality as agricultural conditioner or their aerobic treatability. This review also highlighted that available data on digestates characterization were scarce at the time. There is an actual need to characterize digestates biological, biochemical and physical properties in order to state on their potential for an agricultural use. In this respect, the second part of this two part paper will bring results on several solid digestates properties coming from different organic substrates. Based on the relevant choice of indicators discussed in this review, a characterization of 6 digestates will be established to assess their quality. This will constitute a preliminary step in digestates study in order to assure their agricultural valorization.

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