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Review

Comprehensive Evaluation and Development of Irish Compost and Digestate Standards for Heavy Metals, Stability and Phytotoxicity

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Abstract: Recent EU circular economy, bioeconomy policies and the New Green Deal promote the recycling of organic wastes into soil improvers and fertilisers, thereby reducing the use of mineral fertilisers. This has renewed interest in the use of compost and digestate as fertilisers. At the same time, the Russian invasion of Ukraine has strengthened the demand for sustainable domestic fertilisers to guarantee the security of supply. It is now more important than ever that quality standards in Ireland are fit for the purpose of aiding the sustainable local production of fertilisers. Quality standards for compost and digestate ensure and protect the environment. This study collated the results of the analysis of Irish compost and digestate samples and made comparisons of the Irish data to databases, reports and standards from other countries, including the EU Fertiliser Products Regulation 2019/1009. This paper, therefore, provides comprehensive information on heavy metal, stability and phytotoxicity standards from a number of European and other countries. In addition, it includes actual data on these parameters from Ireland and a few European countries. From this collation and comparison process, we propose to update the heavy metals and stability limits in the Irish compost standard (IS 441) and heavy metals and stability limits in a new digestate standard (whole, liquid and fibre). Our methodology and collated data can be used as templates for countries, especially in Europe, which have not developed their own standards. Having an updated compost quality standard supports the development of a circular economy while still respecting the precautionary principle of avoiding pollution when compost and digestate are used on the soil.

Keywords: biowaste compost; green waste compost; digestate; heavy metals; stability; oxygen uptake rate; residual biogas potential; European Fertiliser Products Regulation 2019; phytotoxicity

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1. Introduction

'Ireland's Waste Policy—A Waste Action Plan for a Circular Economy' [1] aims to promote the segregation of food waste as outlined in the Household Food Waste Regulations (European Union (Household Food Waste and Bio-Waste) Regulations 2013, Statutory Instrument (S.I.) 71 of 2013 and Amendment Regulations S.I. 251 of 2013) and the Commercial Food Waste Regulations (Waste Management (Food Waste) Regulations 2009 S.I. 508 of 2009). The successful implementation of the regulations will be enhanced by end-of-waste criteria (depending on the feedstocks treated at a facility/installation, not all operators may pursue end-of-waste status for their treated outputs as they may be able to avail of an exclusion from the need from waste authorisation provided by Section 3.1 (g) of the Waste Management Act 1996, as amended) being available for compost and digestate. The end-of-waste status would drive the need for high-quality feedstocks to produce a compost/digestate, which meets end-of-waste criteria and does not have any impact on the environment through heavy metal input and stability of the material applied to the soil.

On a European level, under the Waste Framework Directive (Directive (EU) 2018/851 of the European Parliament and of the Council of 30 May 2018 amending Directive 2008/98/EC on waste), the separate collection of biowaste (food and garden materials) will become mandatory by December 2023. Recent EU circular economy, bioeconomy policies, and the Green Deal promote the recycling of nutrients from organic wastes into products that can be used as soil improvers and fertilisers, thereby reducing the use of mineral fertilisers. This has renewed interest in the use of compost and digestate. The EU Farm to Fork Strategy aims to look at how we produce food sustainably and reduce food waste.

In Ireland, there currently are no national end-of-waste criteria for compost and digestate derived from source-separated materials. Environmental Protection Agency (EPA) licences and local authority waste facility permits granted to composting and anaerobic digestion (AD) plants include a quality standard as part of the licence/permit conditions. However, the parameters and limit values vary considerably in older licenses/permits. The newer compost plant licences/permits contain parameters and limit values that have been adopted from the national compost Standard (IS 441) (IS 441 specifies quality requirements for compost produced from source segregated, separately collected, biodegradable materials including biodegradable municipal waste), but these are also referenced licences/permits for AD plants, an activity that IS 441 was not developed for. Some parameters, such as stability limit values, are not suitable reference values for AD plant-derived digestate.

All Irish plant permits and licences were reviewed by this study, and it was determined that there are five different types of standards being used when issuing licences/permits. There are also seven plants that have no quality standard in place. Factors which affect the final quality of compost and digestate include feedstock composition, contamination in feedstocks, process management and the end quality standard to achieve. Due to the different standards being applied, there is varying quality of compost and digestate produced, which, in turn, means there are different impacts from heavy metals, plastic and glass fragments on the soil. Overall, the system needs a uniform set of quality standards both for compost and digestate, which would replace the existing multiple standards being applied. The results of this study could be used to develop standards for the compost and digestate. In a few European countries where there are no quality standards for compost and digestate, our study could be helpful in providing guidance in developing their own standards.

It is widely recognised that end-product market development is a key element in the development of the composting and anaerobic digestion industry, and this is enhanced by quality standards being available for its products. An Irish market report prepared by rx3 [2] provided details of composting and AD plants and generally gave a positive outlook.

As part of this project, an extensive survey of composting and AD plants in Ireland (excluding wastewater treatment plants) was conducted to understand the production and use of compost and digestate derived from source-separate materials (source-separate materials are feedstocks collected separately by waste collectors. A brown bin is co-mingled food and garden waste. Garden materials are grass, tree prunings and hedge clipping). In 2018, 123 kt of digestate and 84 kt of compost were generated, as shown in Figure 1.

The primary outlet for digestate generated from source-separated materials is grassland (72%). This reflects the fact that there is a longer application window for grassland use compared to tillage, where the land application is restricted to periods in the spring and autumn. The primary outlet for compost derived from brown bin material is tillage. There is a much smaller amount of compost used in grassland, which is a notable contrast to digestate use. However, there are a number of higher-value markets developing in garden centres and landscaping, including as a peat substitute. The primary market for garden material compost is for landscaping and dilution and replacement of peat products. Landscaping is the primary market for compost derived from sewage sludge.

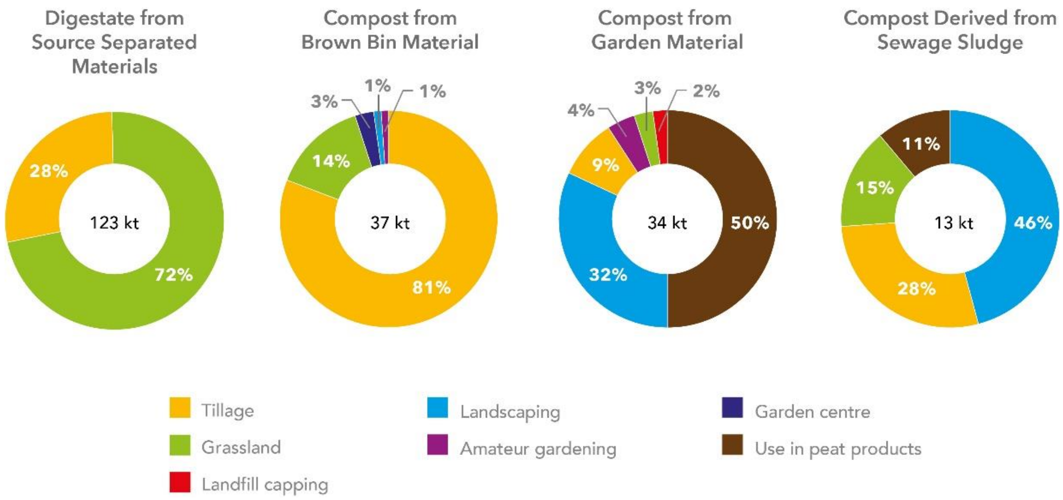

Figure 1. Digestate and compost production in Ireland in 2018.

It was not possible to examine all the parameters in quality standards in this publication, and instead, we have only focused on heavy metals, stability and maturity. Testing for heavy metals in quality standards is necessary to evaluate and monitor the potential for soil and water pollution and to reduce regulator and user concerns related to risks associated with compost and digestate application [3]. Stability is an important parameter in quality standards because unstable compost consumes nitrogen and oxygen in significant quantities to support biological activity and generates heat, water vapour and carbon dioxide. Continued decomposition when these unstable composts are added to soil or growth media may have negative impacts on plant growth due to reduced oxygen in the soil root zone, reduced available N or the presence of phytotoxicity compounds [4]. Stable compost also generates little CO_2 and can lead to carbon sequestration when applied to the soil, in contrast to fresh organic matter and unstable compost [5].

Objective

The study objectives were the following:

- To compare IS 441 and standards in plant licences/permits and quality data to standards for compost and digestate from other countries with respect to heavy metals (in this, heavy metals are defined as chemical elements that have the potential to cause toxicity to humans, flora and/or fauna, depending on concentration, bio-availability and bio-accumulation), stability and maturity with a view to updating the current national compost standard IS 441 and develop a new digestate standard for Ireland.
- To investigate the changes over the last decade of heavy metals and other parameters (e.g., stability) in Ireland and how they compared with data available from other European countries.

The findings from the study could also be used as a template by other countries to develop their own quality standards.

2. Material and Methods

2.1. Collation of the Irish Compost and Digestate Databases

Compost and AD plants were asked to provide their quality data for the years 2009 to 2018. The data provided was collated into a new database and is referred to in this study as the 2019 database, as that was the year it was collated. The references throughout this study to the 2008 database are from an earlier report [5]. The new database consolidated in this study was categorised into the following classes based on the feedstock used to produce the compost and digestate:

- Source-separated green waste compost (SSGW) included 171 samples from five compost facilities.
- Source-separated biowaste compost (SSBW) included 184 samples from seven compost facilities.
- Sewage sludge compost (SSC) included 86 samples from three facilities.
- Source-separated digestate included 6 samples from six facilities.

In circumstances where the Irish database did not have information (e.g., data on arsenic and hexavalent chromium), we tested a limited number of compost and digestate samples for these parameters.

2.2. Comparison of Irish Data to Other Databases and Standards

The new Irish database was compared to other country's databases where data is available. The standards developed in this study were compared with the quality standards from other countries and the EU Fertiliser Products Regulation.

This was followed by a technical appraisal of compost and digestate quality standards, relevant published reports and peer-reviewed papers in journals.

2.3. Structure/Type/Number of Standards

Different standards of composts and digestates apply in countries across Europe. For example, the quality criteria for digestate and guidelines applied in Germany are designated by RAL-GZ 245, which differentiates between solid and liquid digestate. In Germany, there are different standards for biowaste compost and sewage sludge compost. In the UK, there are different quality specifications for digestates and compost.

This approach was considered in this study to see if there is merit in using different standards. In 2008, the JRC published a report on end-of-waste that included a case study on compost. The findings of that report were used to assist in developing limits in the recommended compost standard by Prasad and Foster [6]. In this study, we focused on the information in the more recent JRC report [7] and the recent report on how Member States practice end-of-waste [8].

3. Results and Discussion

3.1. Heavy Metals

As mentioned earlier, tests for heavy metals are necessary for quality standards to evaluate and monitor the potential for soil and water pollution and to reduce user concerns related to health risks associated with compost and digestate application [3]. Testing may also be relevant for end-use management, especially in agriculture, as several heavy metals (e.g., copper and zinc) are also trace elements needed by plants.

Table 1 shows the heavy metal limits in various compost standards from across Europe and the world. Generally, standards have limits for cadmium, chromium, copper, mercury, nickel, lead and zinc. Germany is the only country that has a limit for thallium of 1 mg/kg. It is a metal which can be a residue of insecticides/electronic industry. Arsenic values vary from 40 mg/kg for France and Finland to 20 mg/kg.

Table 2 shows the heavy metal limits in various digestate standards from other countries. Some of the main differences in limit value for compost are that copper and zinc limits are less strict.

Table 3 shows a comparison of the limit values for heavy metals in the EU Fertiliser Products Regulation, standards and Irish databases of compost and digestate quality results. From reviewing the data in this study in Table 3, we recommend the limit value for heavy metals in compost and digestate in Ireland.

Table 1. Heavy metal (mg/kg dry matter) in compost standards from other countries collated by the authors.

Country	**BE**		**AT**		**BG**		**DE**			**GR**		**HU**	**IT**	**NL**	**PT**		**SI**		**SE**		**UK**			**NO**			**CH**		**ES**		**UAE**	**CA**		**USA**
Class		**A *Organic Agri***	**A+**	**B Non-*Agri***												**1**	**2**	**3**	**1**	**2**			**0**	**1**	**2**	**3**		**Class A**	**Class B**	**Class C**		**Category A**	**Category B**	
Cd	2	1	1	3	2	1.7	1.5	1.5	1.5	1.5	1.5	<3	2	1.5	<1	0.7	1.5	5	1.5	3	1	1.5	0	0.8	2	5	1	1	2	3	3	3	20	39
Cr	70	70	70	250	100	60	100	100	100	300	300	<250	100		<50	100	150	400	100	250	100	100	50	70	100	150		70	250	300	100	120		1200
Cr VI										2	2			0.5																				
Cu	150	150	70	500	250 label threshold >100 *	200 label threshold >100 *	100	100	100	900	900	<400	300	230	<90	100	200	600	100	500	600	200	50	150	650	1000	100	70	300	400	150	400	--	1500
Hg	1	0.7	0	3	1	0.5	1	1	1	1	1	<2.5	1	1.5	<0.3	0.7	1.5	5	1	3	1	1	0	0.6	3	5	1	0	1.5	2.5	1.5	0.8	5	17
Ni	30	60	25	100	80	40	50	50	50	80	80	<100	50	100	<20	50	100	200	50	100	50	50	20	30	50	80	30	25	90	100	50	62	180	420
Pb	150	120	45	200	180	130	150	150	150	150	150	<300	100	140	<100	100	150	500	120	200	100	200	40	60	80	200	120	45	150	200	120	150	500	300
Zn	400	500	200	1800	800 labelling threshold >400	600 labelling threshold >400	400	400	400	4000	400	<1200	---	500	<290	200	500	1500	400	1800	800	400	150	400	800	1500	400	200	500	1000	350	700	1850	2800

* Labelling threshold >100. If labelling threshold for copper or zinc is exceeded, the content must be stated on the label of the end product.

Table 2. Evaluation of standards for heavy metals (mg/kg dry matter) in digestate from other countries collated by the authors.

Country	**BE**		**BG**	**CZ**		**EE**	**Fr**	**FI**			**DE**		**GR**	**HU**						**UK**							**SI**		**SE**		**NO**			**CH**		**ES**		**USA**
Class															**Less than 1**	**1 to 1.9**	**2 to 2.9**	**3 to 3.9**	**4 to 4.9**	**5 to 5.9**	**6 to 6.9**	**7 to 7.9**	**8 to 8.9**	**9 or More**					**0**	**1**	**2**	**3**		**Class A**	**Class B**	**Class C**	
Cd	2	2	1.7	2	2	1	2	2	2	2	2	2	3	2	0.1	0.2	0.4	0.5	1	0.7	0.8	1	1.1	1	3	2	3	1	0	0.8	2	5		1	2	3	20
Cr	100	100	60	100	#	60	100	300	100	100	100	100	250	100	8	1	24	32	40	48	56	64	72	80	100	100	250	100	50	70	100	150	1	70	250	300	-
Cu	800			100, (150 *) (250 **)	100, (150 *) (250 **)	200	2	600	100	100	plausibility values apply must not be exceeded		400	100	16	32	48	64	80	96	112	128	144	160	200	200	500	600	50	150	650	1000		70	300	400	750
Hg	1	250 labelling threshold >100	200 labelling threshold >100	1	1	0	300	1	1	1	1	1	3	1	0.1	0.2	0.2	0.3	0	0.5	0.6	0.6	0.7	1	1	1	3	1	0	0.6	3	5	1	0	2	3	8.5
Ni	50	1	0.5	50	50	40	1	100	50	50	50	80	100	50	4	8	12	16	20	24	28	32	36	40	50	50	100	50	20	30	50	80	1	25	90	100	210
Pb	150	80	40	100	100	130		100	150	150	150	150	300	100	16	32	48	64	80	96	112	128	144	160	120	120	200	100	40	60	80	200	30	45	150	200	150
Zn	- - -	180	130	300 (600 *) (1200 **)	300 (600 *) (1200 **)	600	120	1500	400	400	plausibility values apply must not be exceeded		1200	---	32	64	96	128	160	192	224	256	288	320	400 *	400	1800	800	150	400	800	1500	400	200	500	1000	1400

* Labelling threshold >100. If labelling threshold for copper or zinc is exceeded, the content must be stated on the label of the end product. ** Organic and farmyard fertilisers—dry matter content exceeding 13%.

Table 3. Comparison of heavy metals (mg/kg dry matter) in regulations, standards and databases.

Parameter	**EU Fertiliser Products Regulation 2019**		**JRC Study EoW Biodegradable Waste 2014**	**ECN QAS for Compost/Digestate 2018**	**IS 441 2011/Prasad and Foster, 2008**	**Flemish Material Decree—Vlarema/Vito Study**	**Flemish Material Decree—Vlarema 2012**	**Ireland Green Compost 2019**	**Ireland Biowaste Compost 2019**	**Ireland Sewage Sludge Compost 2019**	**Ireland Digestate 2019**	**Recommended Standard Compost and Digestate**
	Product Function Category 1 Fertiliser	**Product Function Category 3 Soil Improver**				**Safety Limits Based on Dynamic Model**	**Compost Applications**	**90th Percentile**				
Cadmium	1.5	2	1.5	1.3	1.3	6	2	1.00	0.90	0.97	0.63	1.5
Hexavalent Chromium	2	2	-	-	N/A	-	-	1	<1	-	<1	2
Total Chromium			100	60	92	150	70	59.87	32.94	43.00	14.21	100
Mercury	1	1	1	0.45	0.4	1	1	0.20	0.31	0.36	0.12	1
Nickel	50	50	50	40	56	100	30	25.46	29.45	29.50	25.45	50
Lead	120	120	120	130	149	300	150	58.70	110.00	85.17	6.57	150
Inorganic Arsenic	40	40	-	-	N/A	-	-	-	-	-	-	-
Total Arsenic	-	-	-	-	N/A	20	20	13.3	5.62	-	1.36	20
Biuret	Must not be present	N/A	-	-	N/A	-	-	-	-	-	-	-
Copper	300	300	200	300	149	800	150	52.30	138.84	117.80	89.79	300
Zinc	800	800	600	600	397	-	400	186.00	311.68	347.38	452.32	800

JRC = Joint Research Centre; ECN = European Compost Network.

Since the previous report [6], the key significant publications have been the JRC Report on Biodegradable Waste in 2014 [7] and the EU Fertiliser Products Regulation 2019.

Acceptable levels of cadmium, copper, mercury, nickel, lead and zinc in composts in the EU countries and, to a great extent, the rest of Europe (e.g., Norway) are very similar, with a few exceptions. Many countries in the EU have different limit values depending on the feedstock and use—agricultural and non-agricultural. For instance, limit values for cadmium are much higher for non-agricultural use, 3 mg/kg to 5 mg/kg for Spain and Portugal, going to a low of 1 to 0.7 mg/kg, respectively, for general use. Another example applies to copper, which goes up from 100 mg/kg for general use to 900 mg/kg for non-agricultural use in Germany. Non-European countries, especially the USA and Canada and, to a lesser extent, the United Arab Emirates, have higher limit values. In a few cases, labelling is only required if it goes above a level, e.g., zinc above 400 mg/kg in Bulgaria. Only a few countries, such as Belgium, Czech, France, Germany, Spain and the USA, have arsenic limit values.

3.1.1. The Cadmium, Copper, Mercury, Nickel, Lead and Zinc Levels

It is interesting to compare the heavy metal standards for compost with that of digestate. This is not always feasible as, in some cases, Germany has a number of standards for composts (e.g., agricultural use, non-agricultural use, use for organic farming), and the standard varies with different feedstocks (e.g., sewage sludge). Nonetheless, because digestate is almost always used for agricultural use, the heavy metal standards for digestate can be compared with compost standards for agricultural use or standards for undefined usage. The heavy metal standard limits for digestate are generally much stricter than for compost, especially for copper and zinc. Examples of this are the digestate standards of Belgium and the USA. On the other hand, the standards for digestate are exactly the same as for compost for countries such as Finland, Spain and Germany (except cadmium). The UK has different standards for different fractions, with the finer fractions having stricter standards.

3.1.2. Comparison of Heavy Metals in Compost Databases with Other Countries

Databases of heavy metals in The Netherlands and Germany were obtained. The Netherlands database is based on 1000 samples from 50 plants in 2017. The German database is based on 3536 samples from 556 plants in 2018. A total of 53% of plants were just treated as green waste. The remaining plants were treated as biowaste. Table 4 shows a comparison of the databases from The Netherlands, Germany and Ireland.

Table 4. Comparsion of databases from The Netherlands, Germany and Ireland collated by the authors (The Netherlands data—BVOR, Germany data—BGK).

Parameter	Biowaste Compost—The Netherlands	Green Compost—The Netherlands	Germany's Compost	SSGW 2008	SSBW 2008	SSGW 2019	SSBW 2019	SSC 2019
	90th Percentile		95th Percentile	90th Percentile				
				mg/kg dm				
Cadmium	0.43	0.6	0.85	0.96	0.77	1.0	0.9	0.97
Chromium	26	21.9	41.9	57	64.9	59.9	32.9	43.0
Copper	49	29	66.1	81.7	100	52.3	138.8	117.8
Mercury	0.11	0.12	0.2	0.15	0.3	0.2	0.3	0.4
Nickel	13	11	27.9	37.7	39.0	25.5	29.5	29.5
Lead	54	46.1	56	113.7	100	58.7	110	85.2
Zinc	205	154	242	253.3	266	186	311.7	347.4
Arsenic	4.5	5.9	n/a	9.5	6.7	-	5.6	-

Table 4 compares the 90th percentile of the Irish biowaste/green compost to The Netherlands' (90th percentile) and Germany's (95th percentile) databases and shows the following trends:

- Irish compost has a higher content of each of the heavy metals compared with The Netherland's data;
- Irish compost is more like German compost, except for copper/zinc and lead, which were higher in Irish biowaste compost;
- The metal levels were well below the limit values for the JRC End-of-Waste Criteria Report and the EU Fertiliser Products Regulation.

The VITO Study [9], "Towards risk-based draft limit values for the use of secondary raw materials as fertilizer or soil conditioner", describes a dynamic model calculating the maximum allowable concentrations of pollutants in the soil conditioner/fertiliser on the basis of the maximum permitted enrichment of the upper soil layer over a period of 100 years, taking into account all possible input-output fluxes and soil processes (Table 3).

The parameters are used now in the Flemish legislation for sustainable recycling of biowaste (VLAREMA), and the corresponding limit values for safe use are stricter than these scientifically derived limit values and are also fully in line with the existing internationally accepted limit values for safe application, such as the ECN-QAS, the JRC study on end-of-waste criteria for compost and digestate [7] and the EU Fertilising Products Regulation.

Strict input feedstock requirements have been designated as a main driver to pursue high-quality end products in various compost quality assurance schemes across Europe (e.g., BGK). This allows the set of parameters being monitored to be kept to those deemed essential, excluding those parameters unlikely to be present in separately collected biowaste.

The trend in recent standards in other countries (the JRC study and the EU Fertiliser Products Regulation) is to have the same heavy metal content for compost and digestate.

The 2008 database for compost was compared to the new 2019 database collected for this study. It showed there have been no major changes in the quality of compost being produced by plants.

We recommend the following:

- The limited dataset for digestate suggests that the heavy metal limits previously developed for compost can be adopted for digestate;
- Alignment of the copper, zinc, lead, mercury and cadmium limits with the EU Fertiliser Products Regulation;
- Round up the lead limit from 149 mg/kg to 150 mg/kg;
- Round down the nickel limit from 56 mg/kg to 50 mg/kg;
- Alignment with the JRC Study of the total chromium limit from 92 mg/kg to 100 mg/kg;
- Belgium, Czech Republic, France and Germany have a limit for total arsenic that is either 20 mg/kg or 40 mg/kg. The data we have for total arsenic (Table 3) shows that a limit of 20 mg/kg is achievable. We recommend that total arsenic with a limit of 20 mg/kg is included in the Irish standards;
- France, Germany and Italy and the EU Fertiliser Products Regulation have a limit for hexavalent chromium. From the limited amount of Irish data, we recommend hexavalent chromium with a limit of 2 mg/kg be included in the Irish standard.

3.2. Stability

Stability in Compost

Of all the stability parameters in use for compost, scientists seem to have the greatest confidence in those methods that assess microbial respiration, as evidenced by oxygen uptake or carbon dioxide evolution. There are several ways to measure respiration, such as Oxygen Uptake Rate (OUR), Specific Oxygen Uptake Rate (SOUR), carbon dioxide, Solvita™ (Woods End Laboratories LLC, Augusta, USA) and self-heating test [10].

This section examines methods used for monitoring the biological stability of compost and digestate. In addition, a link between the limit value and compost applications was examined. In this study, we took into account a detailed review of stability carried out by WRAP [11].

Stability is the potential level of biological activity in compost [6]. It is an important parameter in quality standards because unstable compost consumes nitrogen and oxygen in significant quantities to support biological activity and generates heat, water vapour and carbon dioxide. Stable compost consumes little nitrogen or oxygen and generates little heat and carbon dioxide. If stored improperly or unaerated, unstable compost can become anaerobic, giving rise to methane, nitrous oxides and ammonia that create an odour and air pollution nuisance. Continued decomposition when unstable composts are added to soil or growth media may have negative impacts on plant growth due to reduced oxygen in the soil root zone, reduced available nitrogen, or the presence of phytotoxicity compounds [12].

The authors in a previous report [6] recommended a stability test method for compost using the Oxygen Uptake Rate (OUR, EN 16087-1 2011) with a limit of 13 mmol O_2/kg/OM/h. OUR is a European-wide method and, in our assessment, will lead to a standard method instead of a plethora of stability methods based on respiration.

3.3. Stability Database from Belgium and The Netherlands

Table 5 shows that the average temperature and OUR in green and VFG compost from Belgium were similar. These values indicate that the compost is very stable.

Table 5. Compost stability data in 2015 from Belgium (Vlaco).

Green Compost						
	Average	**Median**	**StDev**	**25th Percentile**	**75th Percentile**	**95th Percentile**
Self-heating Test Class of Stability	V	V	-	V	V	V
Temperature °C	24.9	23.7	5.4	21.7	26.1	33.0
Oxygen Uptake Rate mmol O_2/kg OM/h	5.3	3.7	3.5	2.5	5.3	9.2
Biowaste Compost (Known as VFG Vegetable, Fruit and Garden)						
	Average	Median	StDev	25th Percentile	75th Percentile	95th Percentile
Self-heating Test Class of Stability	V	V	-	V	V	V
Temperature °C	25.8	24.3	6.5	22.1	27.1	40.0
Oxygen Uptake Rate mmol O_2/kg OM/h	5.5	4.1	5.7	2.5	5.9	16.1

The OUR data (Table 6) from The Netherlands shows that the average OUR value for biowaste compost is 21 mmol O_2/kg o.s./hr and 12 mmolO_2/kg o.s./hr for green waste compost. The data are very relevant as the way biowaste is processed in compost tunnels in The Netherlands is similar to the processing in Ireland.

Table 6. OUR stability data in 2017 from The Netherlands (BVOR).

Parameter	**Average Household Biowaste Compost**	**90th Percentile Biowaste Compost**	**Average Green Waste Compost**	**90th Percentile Green Compost**
OUR mmol O_2/kg o.s./hr	21	27	12	19

Database based on 1000 samples from 50 plants.

3.4. Evaluation of Standards for the Measurement of Compost Stability in Other Countries

Several countries (Australia, Austria, Estonia, Norway (no requirement to do testing. Only product requirements ("to be stable") without any description of how to document that), Sweden (Sweden has no requirements for stability, but it should be in declaration of content using the self-heating test), Czech Republic, France, Hungary, Greece, UAE and Portugal) currently have no requirements, legal or voluntary, for a standard for compost stability. The countries which have no compost standards are Cyprus, Romania and Lithuania.

Table 7 shows the two stability methods most widely used for compost stability testing, the Oxygen Uptake Rate and the self-heating test in countries which have standards.

Table 7. Stability methods in compost standards collated by the authors.

Country	Standard Name/Reference	Stability Method	Limit Value
Belgium	Standards for green compost	Self-heating test	<40 °C (IV or V)
		Oxygen Uptake Rate	<15 mmol/kg VS/h
	Standards for VFG (food) compost	Self-heating test	<40 °C (IV or V)
		Oxygen Uptake Rate	<15 mmol/kg VS/h
Ireland	IS 441 and in EPA waste licences	Oxygen Uptake Rate	13 mmol O_2/kg organic solids/h
Finland		CO_2—production	<6 mg CO_2/g VS/day
Germany	RAL GZ 251 for compost	Self-heating test	Fresh = II Mature = IV Substrate = V
Germany	RAL-GZ 258 for sewage sludge compost	Self-heating test	Fresh = II, III Mature = IV, V
The Netherlands	Keurcompost	Oxygen Uptake Rate	No limit specified
Slovenia	Decree on recovery of biowaste and the use of compost/digestate (*Official Gazette of the RS*, Nos. 99/13, 56/15 and 56/18)	AT4	<15 mmolO_2/g DM
United Kingdom	PAS 100	CO_2 microbial respiration rate	<16 mg CO_2/g organic matter/day
USA	EPA	-	
	State requirement	Varies by state	
	US Compost Council STA	-	
	USCC STA—Consumer Use Program Acceptable Ranges	CO_2 evolution	Less than 4 mg CO_2-C per g OM per day
	USCC STA—Consumer Use Program Preferable Ranges		Less than 2 mg CO_2-C per g OM per day
Canada	Guidelines of the Canadian Council of Ministers of the Environment (CCME) are "taken back" to the province/territory to be adopted/adjusted. A total of 7 out of 10 provinces and all three territories have adopted the CCME, with British Columbia/Ontario/Quebec having adjusted them.	Maturity/ stability of compost. Cured for 21 days and one of the following: • Respiration rate if less than, or equal to, 400 milligrams of oxygen per kilogram of volatile solids (or organic matter) per hour. • The carbon dioxide evolution rate is less than or equal to 4 milligrams of carbon in the form of carbon dioxide per gram of organic matter per day. • The temperature rise of the compost above ambient temperature is less than 8 °C.	
Italy	Humic and fulvic acids		7% dry weight
EU Fertiliser Products Regulation		Self-heating test and OUR	III and 25 mmol/kg
JRC Study		Self-heating test and OUR	III and 25 mmol/kg
ECN QAS		Self-heating test and OUR	Declaration

3.5. Recommended Method for the Measurement of Compost Stability

We would recommend that the OUR test be continued for compost in Ireland. In recent years, it has garnered support as it is now a CEN method. It is accepted as a stability method in the Joint Research Centre study, the new Fertiliser Products Regulation and the Irish voluntary compost standard IS 441.

3.6. Limit Value for Compost Stability for Field Application

The only European countries that make a link between compost end use and stability are the BGK quality assurance scheme in Germany and Luxembourg. The link is with fresh compost used in agriculture, mature compost in field horticulture and very mature compost used in growing media. Some research work that relates to the use and benefits of using moderately stable (active) compost for field application has been reported [13–17]. A study in Luxemburg [18] compared fresh (stability undefined) and mature compost (stability undefined) and inorganic fertiliser in a field trial over 15 years with an arable rotation of cereals, oilseed rape and maize. No significant differences between fresh and mature compost were observed.

A researcher [18], with some trial work, discussed research publications on compost application timings and the level of stability in the self-heating test. The majority of evidence found on the use of fresh (or immature) composts is from Germany, where agricultural and field horticultural trials have generally shown agronomic benefits on crop yield and soil properties when less mature composts have been used. The German method of applying fresh compost in the autumn has been considered unlikely to cause significant leaching during the cold winter months, with nitrogen becoming available to crops the following spring as the temperature increases [19]. In a few cases, short-term nitrogen lock-up has been experienced when using fresh or mature compost. Those studies have recommended applying the compost well in advance to avoid detrimental effects on crop yield, such as in the autumn before a spring sown crop, or to apply additional inorganic nitrogen fertiliser to compensate for any locked-up nitrogen. It is interesting to note that the studies, whilst stating lock-up is a demonstrable concern, the authors suggest in-field solutions rather than using more mature compost in the first place.

The stability standard for the OUR used in the Irish standard IS 441 currently stands at 13 mmolO_2/kg organic solids/h, but if one looks at how the standard was developed more than a decade ago, it was based on the premise that the compost would be used mostly as a component growing media (peat dilution) and was based mostly on green waste. The authors of this study recommend that the limit be increased to 15 mmolO_2/kg organic solids/h for compost used in growing media. This would align the limit value of 15 mmolO_2/kg organic solids/h in the advanced growing media with industry in The Netherlands and the ECN guidelines Specification for the Use of Quality Compost in Growing Media [20].

For field application in agriculture and horticulture, this value (13 mmol O_2/kg organic solids/h) is a rather low value based on the summary of the research presented about German research and the USA's recommendations (Table 8) [21].

Table 8. Proposed relationship of self-heating class to best use of compost [21].

Class of Stability Based on Self-Heating Test	Compost Can Be Best Used for
V	Potting mixes, seedling starter
IV	General purpose gardening, greenhouse cultivation
III	Grapes, fruit, apples
II	Field cultivation, e.g., corn, tomatoes, broccoli, greenhouse hotbeds
I	Compost, raw feedstock, mushroom compost

On the basis of the above, we should now increase this figure to 25 mmolO_2/kg organic solids/h in Ireland for the use of compost in field applications (Table 9). This would be in line with the self-heating stability test III standards in Germany. This would also be in line with Woods End Laboratory in the USA's recommendation of using limits II and III for field application [21] (see Table 8).

Table 9. Recommended stability method and limit value for compost application in Ireland.

Compost Application	Method and Limit
Growing media	OUR with a limit of 15 mmolO_2/kg organic solids/h
Other applications—field/landscaping	OUR with a limit of 25 mmolO_2/kg organic solids/h

3.7. Digestate Stability

Stability testing helps ensure that digestate is fit for purpose and does not pollute soil and water resources. A reasonable question one may ask is why there is a need for a stability standard for digestate. One reason is the fact that it is included in both the new EU Fertiliser Products Regulation and the JRC End-of-Waste Criteria Report as a stability standard for digestate. The second reason is that minimum stability should avoid unwanted emissions, including strong odours during transport and storage and prevent materials from entering the market without proper treatment.

3.8. Stability Database in Belgium

Table 10 shows that about half of the samples (50%) comply with the limit value for OUR (<25 mmol/kg VS/h) for a solid fraction at 20 °C. If the same limit value would apply at 30 °C, only 33% of the samples comply. About 45% of the samples comply with the limit value for OUR (<25 mmol) for dried digestate at 20 °C. If the same limit value would apply at 30 °C, only 15% of the samples comply. Lower temperature gives lower OUR values as the method is very temperature-dependent. The methods used to monitor the stability of digestate used in Europe are Residual Biogas Potential (RBP) organic acids (Volatile Fatty Acids) (RAL GZ 245) [22], CO_2 and recently, Oxygen Uptake Rate (OUR) (Table 11). Most of the stability standards proposed for AD digestate (mostly for whole digestate) are based on RBP (UK) or Organic Acids (Germany), although recently, the JRC End-of-Waste Report and the EU Fertiliser Products Regulation have included the OUR method and given limit values.

Table 10. Stability database of digestate in Belgium [23].

Product	Residual Biogas Potential	OUR	OUR
	Litre/Biogas/g VS	mmol/kg VS/ h at 20 °C	mmol/kg VS/h at 30 °C
Dried digestate (without manure)	0.16	22	35.2
Solid fraction digestate (without manure)	0.05	9.0	16.2
Solid fraction digestate (with manure)	0.07	16.0	28.8

3.9. Evaluation of Standards for Stability in Digestate in Other Countries

Fifteen EU countries currently have no requirements legal or voluntary for a standard for digestate stability. Table 11 outlines the countries in Europe and in other countries around the world that have standards. The countries with no standard for stability as part of their overall standard are Austria, Estonia, Czech Republic, France, Hungary, Greece, Poland, Portugal, Sweden, Norway and Switzerland. The countries that have no digestate standards at all are Cyprus, Romania, Lithuania, Italy and The Netherlands.

3.10. Stability in Digestate in Ireland

Digestate stability can be measured by the RBP test or by OUR. The use of OUR for digestate is relatively new, as the method was originally developed for compost. Six plants in Ireland tested digestate samples for RBP and OUR. The results were widespread of data from low to high. The data showed that the plants met the RBP limit of 0.25 l biogas g-1 VS. However, three samples did not meet the OUR limit of 50 mmol O_2/kg organic solid/h. This is limited data, and more sampling is required. The correlation between the two methods was very good (R^2 = 0.8006) (Figure 2).

Table 11. Stability methods in digestate standards collated by the authors.

Country	Standard Reference	Stability Method	Limit Value
Belgium	Flemish Decree (VLAREMA)	Oxygen Uptake Rate	<50 mmol/kg VS/h
Finland	Decree of the Ministry of Agriculture and Forestry on Fertiliser Products (24/2011, amendments up to 7/2013)	CO_2 production: microbiological activity.	
Germany	RAL GZ 245—biowaste	Organic acids	≤1500 mg/L FM
	RAL-GZ 246 for digestate made of renewable energy crops and manure it is	Organic acids	≤1500 mg/L FM
UK	PAS 110	Residual biogas potential	<0.45 L biogas/g of volatile solids
Slovenia	Category 1—threshold for digestate containing less than 20% dry matter	Volatile fatty acids	<300 mg/L
Slovenia	Category 1—threshold for digestate containing more than 20% dry matter	Volatile fatty acids	<100 mg/L
Slovenia	Category 2—threshold for digestate containing more than 20% dry matter	Volatile fatty acids	<300 mg/L
America	American Biogas Council Digestate Testing Programme	Must be measured using VFA or CO_2 respiration. No limits set	
EU Fertiliser Products Regulation (for solid and liquid digestate)		Residual biogas potential OUR	0.25 L biogas/g volatile solids 25 mmol/kg VS/h
JRC end-of-waste criteria for biodegradable waste subjected to biological treatment (compost and digestate)		Residual biogas potential OUR Organic acids	0.25 L biogas/g volatile solids 50 mmol/kg/VS/h 1500 mg/L

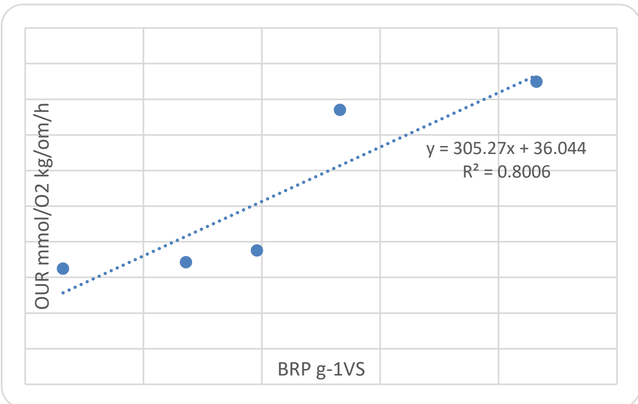

Figure 2. Relationship between BRP and OUR in Irish digestate samples (n = 5).

3.11. Residual Biogas Potential (RBP)

The RBP test is designed to measure the stability of digestate samples under anaerobic conditions. Stability is assessed by the measurement of the total quantity of biogas produced by the digestate sample during a specified period of time, which is an indicator of its residual biodegradability. However, these two tests (RBP and VFA) are designed more to test for the efficiency of the biogas process rather than for its suitability for use on soil. RBP's available data on digestate stability potential is not designed to look at the suitability of the digestate for use on soil, whereas compost stability methods are.

Identifying which tests of stability and maturity are appropriate is essential to assure digestate valorisation and their sustainable market, especially in light of the EU's policy on circular economy, bioeconomy and the new Fertiliser Products Regulation. A suitable stability test will assure their safe and direct agricultural use after digestion as a useful organic fertiliser (as defined in the EU Fertiliser Products Regulation). If it is biologically stable, it will not be a significant source of emission of methane, ammonia and nitrous oxide.

As stated, both these tests, RBP and VFA, are more relevant to process management and to ascertain whether an effective digestion process has been completed rather than the use of these materials as fertiliser products used in agricultural soils as envisaged by the new EU Fertiliser Products Regulation. The RBP test normally takes 28 days to complete, and prices quoted at the time of compiling this report vary a lot between laboratories.

3.12. Respiration Methods

A small number of comparative studies carried out showed a good correlation between RBP and respirometric tests [11]. The five Irish samples tested also showed a good correlation. According to WRAP, it may also be worth reconsidering the use of aerobic respiration measurements, as their literature review confirmed that these can show a good correlation with the RBP or BMP of the digestate.

Cossu and Raga [24] compared the 4-day cumulative oxygen consumption (respiratory index, AT4) with the 21-day biogas potential on excavated samples taken from three sanitary landfills. The correlation between the results (R^2) was 0.80 [25]. The study looked at the correlation of oxygen uptake to biogas potential for different substrates. These were first dried and then tested for a range of parameters, including oxygen demand (20 h) and biogas potential, using a serum bottle method [25]. The results showed a significant linear regression between these two parameters ($R^2 = 0.73$). However, the OUR test is simpler and cheaper than AT4, and, therefore, there has not been much incentive to look at the AT4 test for digestate. However, a good correlation was found between OUR and AT4 in stabilised biowaste derived from mixed waste organic fines [26].

3.13. Oxygen Uptake Rate

The small number of comparative studies carried out has indicated a good correlation between biogas potential tests and respirometric tests on digestate [11]. The OUR method was validated by CEN for compost. It has not been validated by CEN for digestate analysis. In Belgium, CMA has adapted the method for digestate testing. With the data from Belgium and the limited testing of Irish digestate for this study, it shows that only 50% of Belgian and none of the Irish samples met the EU Fertiliser Products Regulation limit of 25 mmol O_2/ kg VS/h. The OUR method for digestate needs to be validated and a more widespread analysis conducted to gain knowledge on how more plants can achieve the OUR limits. There are a number of materials that are applied on land, and Table 12 below shows their typical OUR value, which for many is above 25. In our view and in consultation with colleagues in Belgium, 25 mmol O_2/kg OM/h is low. We recommend a value of 50 mmol O_2/kg OM/h as in the JRC 2014 study [7].

Table 12. Comparison of OUR of different organic materials (pers communication Wim Vanden Auweele (2019)).

Product	OUR mmol O_2/kg VS/h *	Reference
Cattle manure	52.38	ILVO
Solid fraction cattle slurry	65.52	ILVO
Composted cattle manure	14.94	ILVO
Processed chicken manure	108	ILVO
Biothermal dried chicken manure and biowaste	126–180	VLACO, Belgium
Green compost	3.6–9	VLACO, Belgium
Solid fraction digestate	21.6–45	VLACO, Belgium
Dried digestate	27–63	VLACO, Belgium
Post-composted solid fraction digestate and substrate	4.3–12.78	Arbor, Biorefine
Post-composted solid fraction digestate and substrate	23.58	Arbor, Biorefine

* Results were converted to 30 °C. ILVO = Flanders Research Institute for Agriculture, Fisheries and Food. VLACO = trade body in Flanders.

3.14. Conclusions and Recommendations on Method for Digestate Stability

Based on the results of this work, as summarised above, the following conclusions can be drawn:

- The RBP test is a satisfactory method for demonstrating that an effective digestion process has taken place, and the test gives repeatable results;
- The value of 0.25 L biogas g^{-1} VS appears appropriate and achievable, as shown in data from Belgium and Ireland;
- There is limited evidence of using VFA concentration as a product stability criterion except as an initial test to indicate if an RBP test should be done;
- The small number of comparative studies carried out has indicated the correlation between the RBP test and respirometric test on digestate. This strengthens the case for the OUR test method.

We recommend that the plants' first preference should be to use the OUR test to measure the biological stability of the whole digestate and separated digestate fibre. This recommendation is based on the evaluation above and reflects the importance of the final use of digestate. However, the RBP test should also be an option if plants want to use it. The RBP is very expensive and takes a long time (28 days) in comparison with OUR. The tests are recommended for digestate in the EU Fertiliser Products Regulation and JRC End-of-Waste Criteria Report. We recommend that when more analysis is conducted on digestate with the methods and a review of the standard is completed, consideration should be given to just requiring the OUR test method for the measurement of digestate stability.

3.15. Limit Value for Digestate Stability Method

The EU Fertiliser Products Regulation has a limit of 25 mmol O_2/kg OM/h, and the JRC study recommended 50 mmol O_2/kg OM/h. In our view and in consultation with colleagues in Belgium, 25 mmol O_2/kg OM/h is low. We recommend a value of 50 mmol O_2/kg OM/h as in the JRC 2014 study [7]. The limit for the RBP value should be 0.25 l biogas/g of volatile solids as in the JRC 2014 study and EU Fertiliser Products Regulation.

3.16. Maturity

3.16.1. Compost

Compost maturity refers to the degree of decomposition of phytotoxic organic substances produced during the active composting stage. Maturity is a measure of the compost's readiness for use. It can be assessed by seed response germinated in a petri dish. These methods have been used for a long time [27], but a lack of standardisation made comparison of results from various sources difficult. A European standard for maturity has been developed (EN 16086-2, 2011) and has been widely used, particularly when compost is used for plants grown in containers.

Compost maturity is now beginning to be more recognised as a significant parameter to evaluate composts. The reason is that immature and poorly stabilised composts pose known problems during storage, marketing and use. In storage, immature composts may become anaerobic, which often leads to odours and/or the development of toxic compounds, as well as bags swelling and bursting. Immature composts may heat up on pallets during shipment. Continued active decomposition when these composts are added to soil or growing media may have negative impacts on plant growth due to the presence of phytotoxic compounds, reduced available nitrogen, or reduced oxygen in the soil-root zone. The European method for testing for phytotoxicity (EN 16086-2, 2011) is simple, rapid and relatively cheap. Seeds are placed with the compost in a square petri dish, and three days later, the number of germinated seeds is counted, and root length is measured and compared to the control.

3.16.2. Digestate

The use of digestate (including digestate fibre and liquor) needs to be tested for phytotoxic compounds if used as biofertiliser for sensitive crops and use in a growing media. A phytotoxicity test on the whole digestate is recommended. This was recommended in a draft standard prepared by the Irish Bioenergy Association [28]. Researchers from the Waterford Institute of Technology [29] used the phytotoxicity test with 11 digestates using a round petri dish and found it satisfactory. They did not use the CEN method, which uses a square petri dish where the seed is sown directly into the substrate or in soil but instead, they used an extract. The CEN method uses an extract only where it is not feasible to plant seed directly into the material, for example, coarse perlite or coarse pumice. Researchers in Finland [30] found the cress germination test on a square petri dish to be both sensitive enough to detect variation in the quality of digestate and simple enough to serve as a feasible test in quality monitoring requiring rapid throughput times. Accordingly, MTT Agrifood Research Finland, who tested the CEN phytotoxicity test for digestate, recommends this method for digestate testing and quality monitoring of organic fertiliser products. They state that “it is a promising assay for routine testing, because of its simplicity, sensitivity and turnaround time and is relative low cost”. The CEN phytotoxicity test was modified by Israeli researchers [31] for use in mineral soil, and they tested its veracity by testing the phytotoxicity of liquid olive waste. This modification could be used as a blueprint for the development of this test for digestate, both whole and liquid fractions. The advantage of the Israeli modification of the test is that it takes into consideration soil type and rate of application to the soil. Figure 3 shows the setup of the cress test.

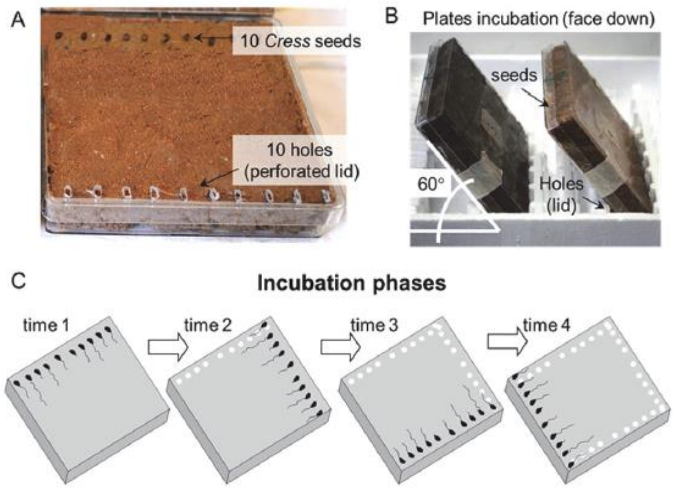

Figure 3. Illustration of cress test set up [31]. (**A**–**C**) are steps in the process. In Step (**C**), the dish is rotated in phases 1,2,3 and 4.

A germination test is used in Austria, Bulgaria and Switzerland when compost is used by hobby gardeners. Bulgaria also has this test when digestate is used in hobby gardening. In the UK, as well as germination tests, it has a plant growth test with tomatoes to determine if there are any abnormalities. The germination test will ensure that no phytotoxicity problems arise as a result of the use of digestate and compost. The CEN method was developed for compost; this method needs to be adapted and validated for digestate. Once this work has been done, we recommend it is used for digestate.

We recommend that the CEN germination test is used for testing compost (and digestate when validated) in the horticultural sector, especially when used as a component of growing media or where plants are grown in containers, where rates of compost/digestate application are very high, e.g., in preparation of topsoil. The limit would be a Munoo-Liisa Vitality index (MLV) of 80%.

The EU Fertiliser Products Regulation and the 2014 JRC research report [7] did not include a germination test in their recommendations.

4. Discussion

The proposed standards in this studyhave been developed with regard to important research publications (e.g., JRC on end-of-waste), EU Fertiliser Products Regulation, research on standards, quality standards in other countries and compost/digestate results of heavy metals and stability found in Irish samples.

The establishment of quality standards for compost and digestate offers environmental and economic benefits as this improves the certainty of when a waste becomes a product in conjunction with when it achieves end-of-waste status, promotes the production of high-quality compost/digestate and facilitates its use by avoiding unnecessary regulatory burden [32].

The 2008 End-of-Waste Criteria Report states that there should be minimum compost product quality requirements for ensuring the usefulness of compost and for achieving the desired levels of human, plant, soil and animal health protection [32]

Table 13 compares the Irish database to the recommended standards in this report and the EU Fertiliser Products Regulation. The main differences in the recommended standard developed in this report are outlined in Table 13.

Table 13. Comparison of the Irish data to the recommended compost and digestate quality standard in this study and the EU Fertiliser Products Regulation (EFR).

	Irish data Compost SSBW 2019—90th Percentile	Irish Data Compost SSGW 2019—90th Percentile	Irish Data Digestate 2019—90th Percentile	Does the Irish Data Meet the Limits for the Recommended Standards?	Does the Irish Data Meet the Limits for the European Fertiliser Regulation?
Mercury (mg/kg DM)	0.31	0.2	0.12	Yes	Yes
Cadmium (mg/kg DM)	0.90	1.00	0.63	Yes	Yes
Nickel (mg/kg DM)	29.45	25.46	25.45	Yes	Yes
Chromium—total (mg/kg DM)	32.94	59.87	14.21	Yes	Yes No limit in EFR
Copper (mg/kg DM)	138.84	52.30	89.79	Yes	Yes
Zinc (mg/kg DM)	311.68	186.00	452.32	Yes	Yes
Lead (mg/kg DM)	110.0	58.70	6.57	Yes	Yes
Inorganic arsenic (mg/kg DM)	-	-	-	Not a parameter	No data
Total arsenic (mg/kg DM)	5.62	13.1 (1 sample)	1.36 (1 sample)	Yes	Not a parameter
Hexavalent chromium (mg/kg DM)	<1	1	<1	Yes	Yes
Germination test %	100 (2008 data)	94 (2008 data)	No data	Yes for compost. No data for digestate	Not a parameter
Oxygen Uptake Rate (mmol O_2/kg Organic solid/h)	2008 data showed 6 samples ranging from 8.8 to 15.5		32.4 to 84.9 (6 samples)	Compost—yes, 50% of Digestate samples meet the limit	Compost—yes, no digestate samples meet the limit in EFR
Biogas residual potential(l biogas/g)	n/a	n/a	−0.034 to 0.166 (7 samples)	Yes	Yes

Table 14 shows that the heavy metals limits developed in this research project are similar to the 2014 End-of-Waste Criteria Report [7] and the EU Fertiliser Products Regulation parameters and limit values.

Table 14. Difference between recommended heavy metals standards and EU Fertiliser Products Regulation and comparison to the Joint Research Centre's (JRC) report on end-of-waste criteria for biodegradable waste subjected to biological treatment (compost and digestate).

Parameter	Recommended Compost Standard	Recommended Digestate Standard: Whole, Separated Fibre or Liquor	JRC 2014 End-of-Waste Criteria for Biodegradable Waste Subjected to Biological Treatment (Compost and Digestate)	EU Fertiliser Products Regulation (EFR)
Mercury (mg/kg DM)	1		1	1
Cadmium (mg/kg DM)	2		1.5	1.5 for PFC 1 and 2 for PFC 3
Nickel (mg/kg DM)	50		50	50
Chromium—total (mg/kg DM)	100		100	-
Copper (mg/kg DM)	300		200	300
Zinc (mg/kg DM)	800		600	800
Lead (mg/kg DM)	150		120	120
Total arsenic (mg/kg DM)	2		-	2
Hexavalent chromium (mg/kg DM)	2		-	2

For lead, the EU Fertiliser Products Regulation is stricter. The VITO Study [9] describes a model calculating the maximum allowable concentrations of pollutants in the soil on the basis of the maximum permitted enrichment of the upper soil layer over a period of 100 years. The study showed that a 300 mg/kg limit for lead is acceptable. The Irish data shows that biowaste compost is close to the EU Fertiliser Products Regulation limit. The limit is the same as in IS 441, in Germany and Belgium and in other classes in Portugal, Spain and Canada.

The EU Fertiliser Products Regulation has a limit value of 40 mg/kg for inorganic arsenic. However, inorganic arsenic is not routinely measured. Instead, we have included total arsenic, which, in theory, contains inorganic arsenic. We have set the limits strictly by default, and it will be low for inorganic arsenic.

The parameters and limits in the report and legislation were risk-assessed. Using the assumption that the variation of the recommended standards in Table 13 varies very little, it will protect human, plant, soil and animal health.

5. Conclusions

The objectives of this study were to examine heavy metals, stability and phytotoxicity elements, which could be used to update IS 441 and aid the development of these elements in a new national digestate standard (Table 15).

The proposed limits for heavy metals, stability and phytotoxicity that can be used in IS 441/new digestate standard have been designed so that it is mutually supportive in both helping to develop high-value markets for compost and digestate products while protecting human, plant, soil and animal health.

We conducted an update of heavy metals, stability and phytotoxicity elements in the compost standard IS 441 and proposed limits of heavy metals, stability and phytotoxicity in a new digestate standard. This was done by the following:

- Collated and analysed laboratory data on compost and digestate quality in Ireland since 2008;
- Compared the Irish data to other databases and standards to update the quality standard for compost and proposed a quality standard for digestate (whole, liquid and fibre);
- Reviewed important publications and regulations.

This paper provides a wealth of information on compost and digestate standards regarding heavy metals, stability and phytotoxicity of a great number of European and other countries, as well as actual data on some of these parameters of a lesser number of countries.

Table 15. Proposed heavy metal and stability standards for compost and digestate from source-separated waste materials.

	Compost	**Digestate: Whole, Separated Fibre or Liquor**
	Heavy Metals	
Mercury (mg/kg DM)	1	1
Cadmium (mg/kg DM)	1.5	1.5
Nickel (mg/kg DM)	50	50
Chromium (mg/kg DM)	100	100
Copper (mg/kg DM)	300	300
Zinc (mg/kg DM)	800	800
Lead (mg/kg DM)	150	150
Total Arsenic (mg/kg DM)	20	20
Hexavalent Chromium (mg/kg DM)	2	2
	Stability and Maturity	
Oxygen Uptake Rate * (mmol O_2/kg Organic solid/h)	15: Growing Media 25: Field Application	50
Biogas Residual Potential * (l biogas/g)	-	0.25
Germination Test For Use in Growing Media Munoo—Liisa Vitality index (MLV	80%	80%

* Digestate is sampled using OUR or Biogas Residual Potential.

Thus, this report also gives other countries in Europe and elsewhere that at present do not have compost standards a pathway/template on how to develop national compost and digestate standards based on standards of other countries, EU end-of-waste criteria and the EU New Fertiliser Products Regulation. In doing this exercise, they could also take into consideration any data they may already have and which may be particular to their country. This, of course, applies only to parameters of heavy metal, stability and maturity.

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Abbreviations

AD	Anaerobic digestion
BGK	Bundesgütegemeinschaft Kompost (Compost and Digestate Quality Assurance Organisation)
CEN	European Committee for Standardization
CMC	Component material category
DM	Dry matter
ECN	European Compost Network
EPA	Environmental Protection Agency
EU	European Union
FM	Fresh matter
FPR	Fertilising Products Regulation
IrBEA	Irish Bioenergy Association
IS	Irish standard
JRC	Joint Research Centre
MLV	Munoo-Liisa vitality index
NSAI	National Standards Authority of Ireland
OUR	Oxygen Uptake Rate
QAS	Quality assurance scheme
RAL	German National Committee for Delivery and Quality Assurance
RBP	Residual biogas potential
SEPA	Scottish Environment Protection Agency
SSBW	Source-separated biowaste
SSC	Sewage sludge compost
SSGW	Source-separated green waste
VFA	Volatile fatty acid
VFG	Vegetable, fruit and garden waste
VS	Volatile solids
VLAREMA	Vlaams Reglement voor duurzaam beheer van Materialenkringlopen en Afvalstoffen (Flemish Regulation on Sustainable Materials Management and Waste)
WFD	Waste Framework Directive
WRAP	Waste and Resources Action Programme

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