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Suitability of Biowaste and Green Waste Composts for Organic Farming in Germany and the Resulting Utilization Potentials

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Abstract: In this study, the suitability of biowaste and green waste composts in organic farming is presented based on quality assurance data of approximately 21,000 compost analyses from 2015 to 2020. The evaluation of compost suitability was based on both the legal regulations of the EU 2021/1165 and the requirements of the two largest German organic farming associations Bioland and Naturland. In 2020, 70.1% of the composts agreed with the above-mentioned regulations, 21.6% exceeded the limits for heavy metals and 7.3% exceeded the limits for foreign matter. The negative influence of the single elements regarding the suitability of composts for organic agriculture declined in the order Zn > Pb > Cd > Ni > Cu. In the bio-waste composts, the impurity content subsequently decreased by more than 50% from 2015 to 2020. In 2019 and 2020, approximately 2.5 million Mg fresh mass (FM) of the analyzed composts were suitable for organic farming. With an average compost application of 5 Mg FM per hectare (ha) and year, about 500,000 ha of arable land could have been supplied in 2020.

Keywords: organic farming; compost quality; compost potentials; compost impurities; suitability of compost

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1. Introduction

1.1. Status of Organic Farming and Projected Development in Germany

Organic farming has shown dynamic growth in many countries over the past decades, with the result that the agricultural area under organic management worldwide rose from about 11 million ha to nearly 75 million ha between 1999 and 2020 [1]. In Germany, the agricultural area (AA) managed at least in accordance with the mandatory requirements of the EU Regulation on "Authorizing certain products and substances for use in organic production and establishing their lists" (Regulation EU 2021/1165 of 15 July 2021, with regard to biowaste compost: Annex 2) has grown since 1980 from less than 0.5% to 10.8% in 2021, which corresponds to an AA of almost 1.8 million ha [2]. Approximately 36% of this area is managed according to the above-mentioned legal guidelines for organic farming and approximately 64% according to the stricter private-law guidelines of the nine organic farming associations based in Germany. Among these, the internationally active organic farming associations Bioland, Demeter and Naturland are the best known and cover about 77% of the farming area of the nine organic farming associations in Germany [3].

Furthermore, there are now ambitious political targets for the further development of organic farming in Germany. In addition to the many ecological advantages of this form of farming [4], demand for organic products is also based on strong consumer demand for organically produced food in Germany, which led to an increase in sales of food produced according to the above-mentioned standards of around 20% in 2020 compared to 2019 [3].

Well-known retail chains in Germany, some of which operate internationally, have in the meantime introduced a wide range of organically produced food or work together with Bioland, Demeter and Naturland in fixed marketing cooperations.

Accordingly, since 2022, the Federal Ministry of Agriculture and Food (BMEL) has set the new target of achieving 30% of organically farmed AA in Germany by 2030 as part of the "Future Strategy for Organic Agriculture". This corresponds to almost a tripling of organically farmed areas within 10 years [5].

For successful implementation of such growth scenarios, a wide range of structural support and accompanying measures are required. In particular, there are many discussions in Germany about further promoting the marketing of organic food, e.g., by integrating it into public catering facilities. However, it is equally important to support the production bases and organize them in a sustainable way.

Therefore, one focus in this study is the return of plant nutrients to organic farming, which are exported with the products sold from the farms. Contrary to what is still often claimed, the nutrient cycles in organic farming are not closed at the farm level. Numerous studies, both at the level of individual farms and in the balancing of organic agricultural areas of entire German states, show high negative nutrient balances for N, P and K in area balances in most cases, if no nutrient recycling takes place via approved external fertilizers in organic farming [6–10]. This is particularly the case for arable and market fruit farms and vegetable farms with no or low livestock numbers.

According to initial calculations, quality-assured composts produced from the separate collection of organic residues could make a significant contribution to the above-mentioned required nutrient recycling [11].

Furthermore, it would be possible to achieve soil-improving effects across a broad spectrum with compost fertilization, as well as to significantly support humus supply or humus build-up and thus also (temporary) C-sequestration through the supply of stabilized organic matter [12–15]. Consequently, organic fertilization in general, and in this case especially the application of composts as an essential instrument to support soil fertility, contribute significantly to increasing the climate resilience of soils and to reducing the environmental impact of land management systems under an organic farming approach [4,12–17].

1.2. Status of Composting in the EU and in Germany as Well as the Relevance of Compost Products for Organic Farming

The Green Deal [18] presented by the EU Commission in 2019 is intended to implement the strategic targets of the UN's Agenda 2030 and the Paris Climate Agreement (2015). Within this framework, the new Circular Economy Action Plan [19] was created, which calls for producer responsibility and an intensification of recycling. Based on the Waste Framework Directive [20], the recycling targets of municipal solid waste (MSW) shall be increased from a minimum of 55% (by 2025) to up to 65% (by 2035).

In the EU, approximately 60 million Mg of biowaste (of which 38 million Mg from MSW) was collected separately in 2020. This is around 17% of MSW. Of this, just under 60% was composted and 40% was treated in anaerobic digestion plants. A total of 17.6 million Mg of composts was produced, most of which was utilized in agriculture. Currently, about 3100 composting plants and 1600 anaerobic digestion plants for separately collected biowaste (from municipal and non-municipal sources) are operating in the EU [21].

To achieve the EU recycling targets, it is necessary that 35% of MSW is recycled by composting and anaerobic digestion based on the proportion of biowaste of around 40% in MSW. Therefore, around 40 Mio Mg/a of biowaste has to be separately collected and treated in addition to the actually separate collected biowaste to meet the 2035 target [21]. By 31 December 2023, EU member states are required to collect biowaste separately or recycle it at the source.

Composts with the quality label RAL-GZ 251 in Germany according to the quality assurance system of the Federal Compost Quality Association (Bundesgütegemeinschaft

Kompost e.V. (BGK)) are produced nationwide in an annual quantity of approximately 3.5 million Mg [22]. In addition to this, approximately 500,000 Mg of biowaste and green waste composts from the quality assurance of the regional Bavarian Compost Producers Association and from the nationwide quality assurance system (QLA) of the Association of German Agricultural Analytic and Research Institutes (Verband Deutscher Landwirtschaftlicher Untersuchungs- und Forschungsanstalten (VDLUFA)) should be added, totaling up to approximately 4 million Mg of quality-assured composts that are produced in Germany.

In principle, composts from waste management in the framework of the circular economy (biowaste and other organic waste, green waste) are permissible in organic agriculture according to the Regulation EU 2021/1165 if they originate from a separate collection system recognized in the respective EU member state and if defined heavy metal limit values are complied with. According to the guidelines of Bioland and Naturland, green waste composts have also been usable for some time and biowaste composts since 2015 in the association's farms, as long as their quality complies with the specifications of a comprehensive catalogue of requirements ([23], see Section 2) and a defined quality assurance is carried out. These association guidelines also define, for example, the maximum permissible foreign matter content in the composts, which is not the case under the Regulation EU 2021/1165, or the procedure for analyzing and releasing the compost batches for plant cultivation use.

In relation to the aforementioned contexts, the question arises as to whether and to what extent the quality-assured biowaste and green waste composts produced throughout Germany comply with these legal and private-law requirements. This is linked to the question of what quantity and nutrient potentials could actually be made available to organic farming with these composts beyond the initial rough calculations mentioned above.

However, these questions are even more relevant against the background that since the approval by the above-mentioned organic farming associations in 2015, only relatively small quantities of these composts have actually been used in organic farming. Thus, according to the data of the BGK, in 2020, i.e., six years after the approval of biowaste composts in the above-mentioned organic farming associations, the quantity of biowaste and green waste composts quality-assured according to RAL GZ 251 was only approximately 180,000 Mg nationwide, which corresponds to just about 5% of the RAL quality-assured compost quantity. Some relevant representatives of organic farming have also occasionally argued that the proportion of suitable composts for organic farming is not very high anyway, i.e., specifically estimated at a maximum of 30% of the above-mentioned total compost quantity.

1.3. Objectives and Significance of the Study

Based on these facts, our objective at first was to analyze how high the proportion of compost suitable for organic farming actually is according to the listed guidelines and what quantity and nutrient potentials can be derived from this for this form of cultivation in Germany. In addition, causes of compost unsuitability for organic farming and whether certain "sensitive" parameters can be identified in this respect were investigated. From the results of these investigations, conclusions were drawn regarding the possibilities for optimizing compost quality. This relates both to the operation of the composting plants themselves and to the upstream system of separate collection of organic residues and waste. This work is performed within the framework of the R & D project "ProBio" (see Acknowledgements) and shown in the present publication.

According to the above statements, the novelty of this research work is, on the one hand, to provide an exact quantification of the previously unknown suitability of biowaste and green waste composts for organic farming and the resulting volume potentials of suitable composts in Germany. On the other hand, the results allow an exact and quantified estimation of the factors and parameters, which were unknown so far and which have prevented up to now the suitability of the composts for organic farming, using which approaches for further optimization of the compost qualities can be derived.

2. Materials and Methods

2.1. Standards to Be Complied with According to Legal or Private Law Regulations Regarding the Quality Assurance of Biowaste/Green Waste Composts for Organic Farming and Test Scheme

The permissibility of the use of biowaste and green waste composts in crop production is fundamentally regulated by the Closed Substance Cycle Waste Management Act in Germany (Kreislaufwirtschaftsgesetz) and the Fertilizing Act (Düngegesetz) with the two central subordinate legal provisions, i.e., the Biowaste Ordinance (BioAbfV [24]) and the Fertilizer Ordinance (DüMV [25]). These legal requirements must also be observed by all agricultural enterprises, irrespective of the form of management they use. Accordingly, these requirements are also directly integrated as "co-applicable legal regulations" into the BGK's quality and testing regulations under private law for the quality assurance of compost according to RAL-GZ 251.

For the use of biowaste and green waste composts specifically in organic farming, there are legally binding regulations for all organic farms (Regulation (EU) 2018/848 of 30 May 2018 "on organic production and labelling of organic products" and Regulation EU 2021/1165, Annex 2). With regard to the use of compost, however, many organic farmers and most organic farming associations do not consider these to be sufficient. One of the main points of criticism is that the EU Organic Farming Ordinance ("EU-ÖkoV") does not include any specifications regarding maximum permissible foreign matter content. Therefore, in 2013/14, the two largest organic farming associations Bioland and Naturland, in cooperation with the BGK, developed a comprehensive testing system for biowaste and green waste composts [23], which has since been adopted by other organic farming associations in Germany and parts of the official advisory services of the federal states, as well as accordingly in many cases in EU organic agriculture in Germany.

As a result, the Bioland-/Naturland-standards for the use of compost in organic farming in Germany have now largely established themselves as a nationally applied, albeit unofficial, testing standard [23]. Within the framework of a contractual agreement between Bioland, Naturland and the BGK, the latter carries out a test of the corresponding private-law requirements of the two organic farming associations as part of the quality assurance of composts. For the composting plants that submit to this additional testing, the BGK indicates the suitability of the respective analyzed compost batches for organic farming on the test certificates.

In Figure 1, an overview of the BGK quality assurance process according to the legal requirements and the standards of Bioland and Naturland is given. Table 1 shows the parameters analyzed in the process with reference to the regulations that define these parameters and the test intervals.

Due to the described nationwide recognition of this procedure, the above-mentioned testing standard was applied for this investigation and used as the basis for determining the suitability of biowaste and green waste composts for organic farming. We did not consider a test based solely on the quality requirements of the EU Regulations to be sufficient, which only stipulates separate collection according to a recognized system of the respective member state, as well as heavy metal limit values.

In contrast, Annex 2 of the new EU Regulation 2021/1165 was applied with regard to the permissible input materials for composting with or without upstream anaerobic digestion (AD), and not the stricter specifications of Bioland or Naturland, which go beyond this. In our opinion, the reason for this is that the composts are suitable if the additional quality parameters of the Bioland/Naturland directive are used for testing (Table 1). They include criteria that must be taken into account for organic farming, as the example of foreign matter shows. This is completely independent of whether we are talking about organic farms that are only subject to the EU Regulation or association farms.

On the other hand, the additional requirements of Bioland/Naturland regarding the permissible input materials for composting are not necessarily relevant from a professional point of view. However, they are rather assessed as association-specific special regulations, which are therefore not generally to be taken into account for all organic agricultural enterprises.

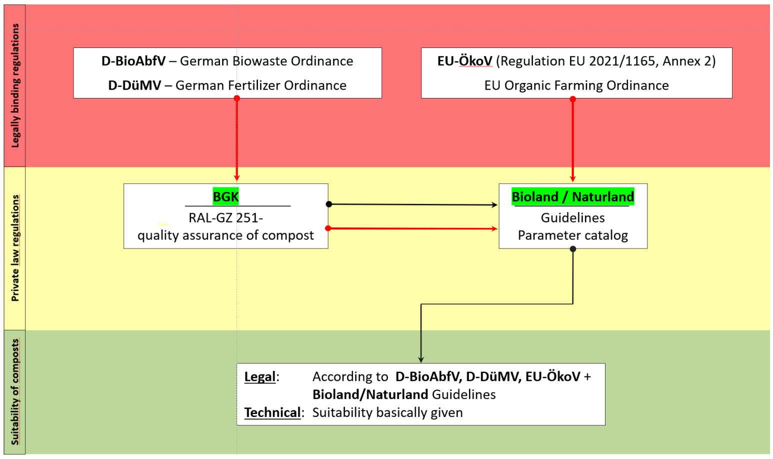

Figure 1. Quality assurance scheme in the determination of suitability of biowaste and green waste composts for use in organic farming in Germany. → Applicable legal requirements automatically flow into the private sector guidelines as "co-applicable legal regulations". / → Examination of composts according to listed regulations.

Table 1. Parameter catalog of legal (EU-ÖkoV) and private law regulations (directives of Bioland/Naturland) as well as their relevant guideline/limit values for the use of biowaste and green waste composts in organic farming in Germany (1).

Parameter	Set of Regulations	Analysis Interval	Guideline Values (1)	Unit
1—Salmonella	RAL-GZ 251 Compost of BGK; Bioland/Naturland-Guidelines (3/2020) (6)	Parameter 1–3 Analysis in each batch	n.d. (2)	Salmonell./50 g FM
2—Plant compatibility (3)			≥90%	Relative yield compared to control
3—Degree of rotting (4)			II–V	I–V (4)
4—Pb	EU Organic Farming Regulation (Regulation (EC) 2021/1165, Annex 2); Bioland-/Naturland-Guidelines (3/2020) (6)	Parameter 4–11 Analysis in each batch	≤45	mg/kg DM
5—Zn			≤200	
6—Cr total			≤70	
7—Cr VI			n.d. (2)	
8—Cu			≤70	
9—Ni			≤25	
10—Hg			≤0.40	
11—Cd			≤0.70	
12—Seeds (5)	Bioland-/Naturland-Guidelines (3/2020) (6)	Parameter 12–14 Analysis in each batch	0.0	number/l FM
13—Foreign matter (content grav.) (7)			≤0.30	% DM
14—Foreign matter (surface index) (8)			≤10	cm^2/l FM
15—As		Parameter 15–18 Analysis every 3 years	≤20	mg/kg DM
16—Tl			≤0.50	mg/kg DM
17—PAH			≤6.0	mg/kg DM
18—Dioxins + dl-PCB			≤20.0	ng WHO-TEQ/kg DM
19—PFC		Parameter 19 + 20 Once for classification	≤0.05	mg/kg DM
20—Thiabendazol			5.0 (9)	mg/kg DM

All analyses according to the BGK-handbook of analyzing methods (2021) [26]. (1) EU-ÖkoV (Regulation (EC) 2021/1165, Annex 2), Bioland/Naturland guidelines (2014/2020), BGK RAL-GZ 251 compost (BGK—Bundesgütegemeinschaft Kompost (Federal Compost Quality Association)). Regulations of BioAbfV (German

Biowaste Ordinance, 2022) and DüMV (German Fertilizer Ordinance, 2017) are not listed here, as the guideline values from the organic farming regulations place higher requirements on the composts than the German statutory regulations. (2) n.d. = not determinable. (3) With an amendment of a 25 Vol.% compost. (4) Degree of rotting according to self-heating test, temperature-dependent stages I to V (II/III fresh compost, IV/V mature compost). (5) Seeds = germinable seeds and plant parts capable of sprouting. (6) EU-ÖkoV only applies to biowaste composts, Bioland/Naturland guidelines apply to biowaste and green waste composts. (7) Gravimetrically measured foreign matter content (all foreign matter (e.g., glass, hard plastics, metals) $\geq$ 2 mm (till 2020) respective $\geq$ 1 mm (since 2021), dry weight). (8) Surface index: standardized area measurement of foreign matter, usually light film plastics and composites with a high surface area are recorded, which only account for a small proportion in the gravimetric measurement, but are particularly conspicuous visually. (9) Not a guideline value, but merely an orientation value derived from food law.

2.2. Data Basis, Parameter Catalog, and Procedure for Evaluation

The calculations were generally based on the population of all composts or the different types of compost (biowaste and green waste composts) from the RAL-251 quality assurance of the BGK, which accounts for about 85–90% of the total quality-assured composts in Germany. Depending on the year of evaluation, between 3272 (2015) and 3841 (2020) compost analyses were evaluated on the basis of the survey grid according to Table 1, which originated from 500 or 576 plants for composting or combined upstream AD and composting with an input of biowaste and green waste of between 6.4 and 7.8 million Mg p.a.

In the first step, the procedure included an evaluation of the qualities found in the various compost groups by determining the median values for all the parameters examined in the individual years and the statistical distribution of the values, whereby the 90% percentile was of particular interest. When comparing the analytical values of groups of different composts with applicable limit values, often only the median is used in order to obtain a statement on the extent to which problems with specific parameters regarding the suitability of the compost for organic farming are to be expected or not. However, this only provides an initial orientation, since no statement can be made about the spread of values, which has a significant influence on the proportion of limit value transgressions for the respective quality parameter. The addition of the 90% percentile enables a better and simple assessment of problem parameters.

In the second step, the analysis values found for each individual compost were then compared for all relevant parameters according to Table 1 with the applicable limit values of the respective parameter. This was performed using BGK's ZASLAB software. As a result, it was possible to determine the extent to which the analyzed composts complied with the specified limit values and, accordingly, which proportion of the composts was suitable for organic farming, and which was not.

With regard to the tested parameters according to Table 1, this evaluation also yielded a result on the proportion of composts exceeded the limit values in relation to the specific individual parameter and thus also give an indication on the relevance of the respective parameter with regard to compost suitability for organic farming.

3. Results

3.1. Relevant Quality Parameters and Nationwide Analysis Results Regarding the Suitability of Biowaste and Green Waste Composts for Organic Agriculture

With regard to the high scope of analysis according to the quality assurance specifications in Table 1, the first question that arises is, to what extent the parameters with limit or guideline values actually have a relevant influence on the suitability of composts for organic farming. It is shown that only 8 of these 20 parameters have a significant influence on the suitability of compost for organic farming. In other words, for these parameters, the proportion of analyzed composts with values exceeding the underlying limit or guideline values for organic farming in the population of analyzed composts (n = 3272–3841) is in the higher single-digit percentages, and in some cases, double-digit percentages. This was especially the case for the five heavy metals Zn, Pb, Cd, Ni, and Cu and for the two foreign matter parameters "gravimetric foreign matter content" and "surface index" (see Section 3.3) as well as to a much lesser extent or only partially for the hygiene parameter "germinable seeds and sprouting plant parts".

For all other parameters according to Table 1, however, their influence on the suitability of the composts for organic farming is non-existent or only very slight (0.0–1.3% composts with limit or guideline values exceeded). These include, for example, salmonella, the heavy metals Cr, Hg, Tl and As, as well as the organic pollutants PAH and dioxins + dl-PCB.

Table 2 shows the median values from the nationwide analyses of the composts for seven of the above-mentioned actually relevant parameters with regard to the suitability of the composts for organic farming, namely from the parameter group (a) foreign matter (n = 2, i.e., gravimetric foreign matter content and surface index) and (b) heavy metals (n = 5, i.e., Cd, Pb, Ni, Zn and Cu). The eighth parameter "germinable seeds and sprouting plant parts" is not shown in this table, as it was only partially relevant (see Section 3.3).

Table 2. Average foreign matter and heavy metal content of quality-assured composts compared to the requirements of organic farming in Germany in 2015–2020 (composts according to RAL-GZ 251 Compost from BGK).

Biowaste (1)/Green Waste Compost (2)		**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**Guideline-Values**	
Parameter	**Unit**							**Generally Valid (3)–(5)**	**Organic Farms (6)–(7)**
Heavy metals									
Pb	mg/kg DM	29.6	29.0	28.3	28.0	26.5	25.9	150	45
		26.3	26.0	25.7	25.7	24.3	23.6		
Cd	mg/kg DM	0.37	0.38	0.38	0.39	0.38	0.36	1.5	0.7
		0.34	0.36	0.36	0.38	0.36	0.35		
Cu	mg/kg DM	41.8	42.8	42.5	42.0	40.0	39.0	100	70
		31.0	30.7	31.5	31.7	30.0	29.3		
Ni	mg/kg DM	12.0	12.0	12.8	13.0	11.6	11.0	50	25
		11.0	11.6	11.9	12.3	11.7	11.0		
Zn	mg/kg DM	164	168	167	169	156	153	400	200
		139	140	140	142	133	132		
Foreign matter (8)									
content gravimet. (9)	% DM	0.08	0.09	0.08	0.07	0.06	0.06	0.40/0.10 (4)	0.30
		0.02	0.02	0.02	0.01	0.01	0.02		
surface index (10)	cm^2/l FM	6.24	5.00	4.80	3.70	3.00	3.00	15 (11)	10
		0.36	1.00	1.10	1.00	0.50	1.00		

Legend: Biowaste compost, Green waste compost. (1) Median n = 1856 in 2015, n = 1857 in 2016, n = 1843 in 2017, n = 1900 in 2018, n = 1874 in 2019 and n = 1899 in 2020 for foreign matter and heavy metals—according to data BGK (2016–2021). (2) Median n = 1416 in 2015, n = 1488 in 2016, n = 1518 in 2017, n = 1636 in 2018, n = 1803 in 2019 and n = 1942 in 2020 for foreign matter and heavy metals—according to data BGK (2016–2021). (3) Limit values (≤) according to BioAbfV—German Biowaste Ordinance (2022). (4) Limit values (≤) according to DüMV—German Fertilizer Ordinance (2015/2017). For foreign matter: 0.40 = glass, hard plastics, metals/0.10 = deformable plastics, total max. 0.50. (5) Limit values (≤) according to RAL-GZ 251 compost (BGK). (6) Limit values (≤) according to EU-ÖkoV—EU Organic Farming Regulation (VO (EC) 2021/1165, Annex 2). (7) Guideline values (≤) according to Bioland/Naturland guidelines (3/2020). (8) ≥ 2 mm. (9) Gravimetrically measured foreign matter content (all foreign matter (e.g., glass, hard plastics, metals) ≥ 2 mm (till 2020) respective ≥ 1 mm (since 2021), dry weight). (10) Surface index: standardized area measurement of foreign matter, usually light film plastics and composites with a high surface area are recorded, which only account for a small proportion in the gravimetric measurement, but are particularly conspicuous visually. (11) Only in RAL-GZ 251 compost (BGK).

The comparison of the measured values from 2015 to 2020 and the applicable limits or guideline values show, for the respective parameter, that the analytically determined median values are generally far below the maximum limits set by law or private law. However, it should be noted that according to Figure 2, the 90% percentile for selected heavy metals is in the range or even already above the limit values (Pb, Zn), in contrast to others (Cd) where no problems have been found. This means that even with comparatively low median values of these parameters, problems can arise with regard to compost suitability for organic farming due to the structure of the value distribution.

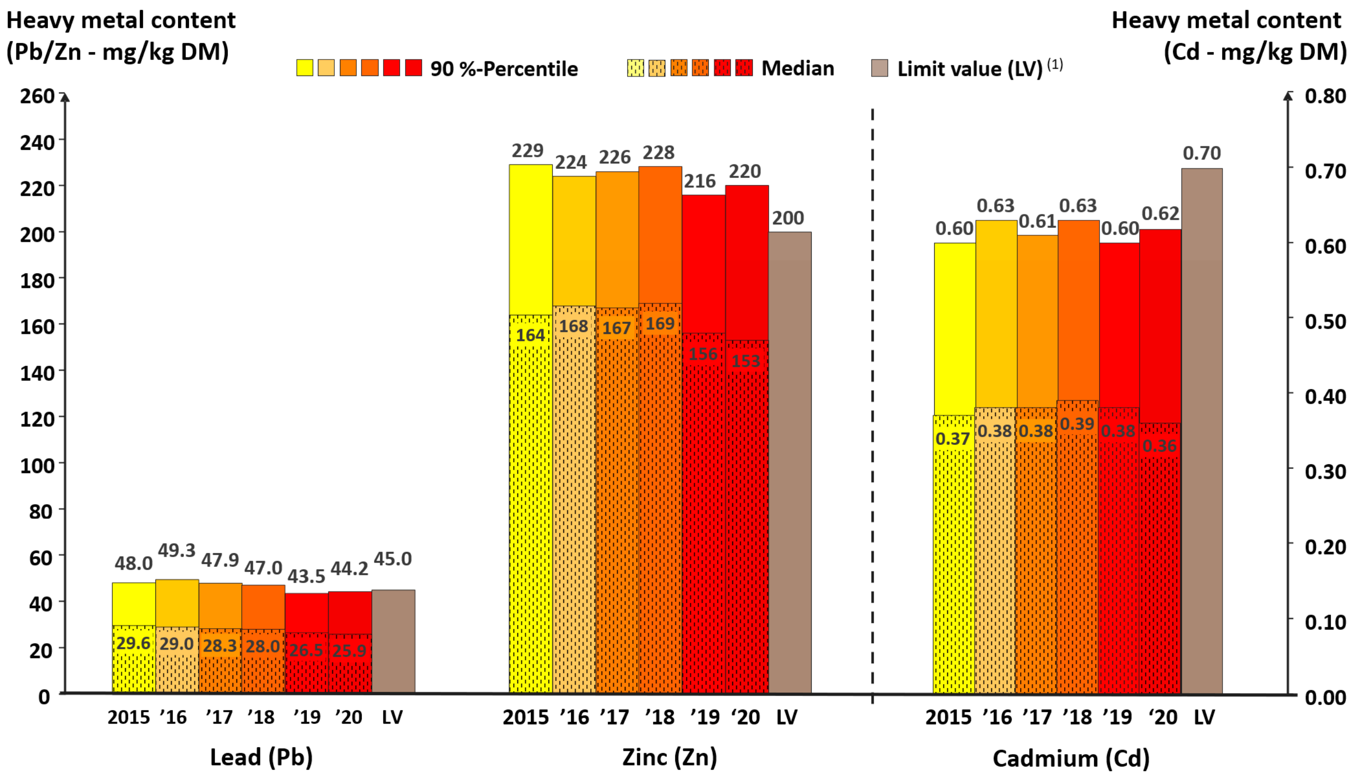

Figure 2. Sensitivity of selected parameters in the parameter group "heavy metals" regarding the suitability of quality-assured biowaste composts without upstream anaerobic digestion (composts according to RAL-GZ 251 Compost from BGK) for organic farming [(1),(2)]. [(1)] Limit values (≤) according to EU-ÖkoV—EU Organic Farming Regulation (VO (EC) 889/2008, Annex 1 resp. 2021/1165, Annex 2). [(2)] n = 1856 in 2015, n = 1857 in 2016, n = 1843 in 2017, n = 1900 in 2018, n = 1874 in 2019 and n = 1899 in 2020—according to data BGK (2016–2021).

3.2. Suitability Levels of Biowaste and Green Waste Composts for Organic Farming in Germany

In 2020, 70.1% of Germany's biowaste and green waste composts were suitable for organic farming. This assessment was based on the entire quality assurance catalogue, which results from the sum of the requirements regarding all quality parameters of the composts produced according to the guidelines of both the EU Regulation on organic production and Bioland/Naturland [23], according to Table 1.

For the permissible input materials of composting with or without upstream AD, however, only the legal requirements of the EU Regulation (EU) 2021/1165 on organic farming were taken into account and not the additional input requirements of Bioland/Naturland (for reasons see Section 2). Taking into account these additional input requirements, the suitability values of the composts for organic farming in 2018–2020 were 2.5–2.9 percentage points lower, depending on the year, than when the input catalogue of the EU Regulation on organic production alone was used as a basis.

The various types of compost showed differences in their suitability for organic farming both in 2020 and in previous years (Figure 3). In 2020, for example, 62.8% of the composts from biowaste and 77.3% of the composts from green waste were suitable for organic farming. Over the six years of evaluation from 2015 to 2020, the suitability percentage of the green waste composts was always higher than that of the biowaste composts, ranging from approximately 10% to approximately 21% depending on the year. The difference between the relative suitability levels of the two compost types decreased continuously from 2015 to 2019, but increased again in 2020 (Figure 3).

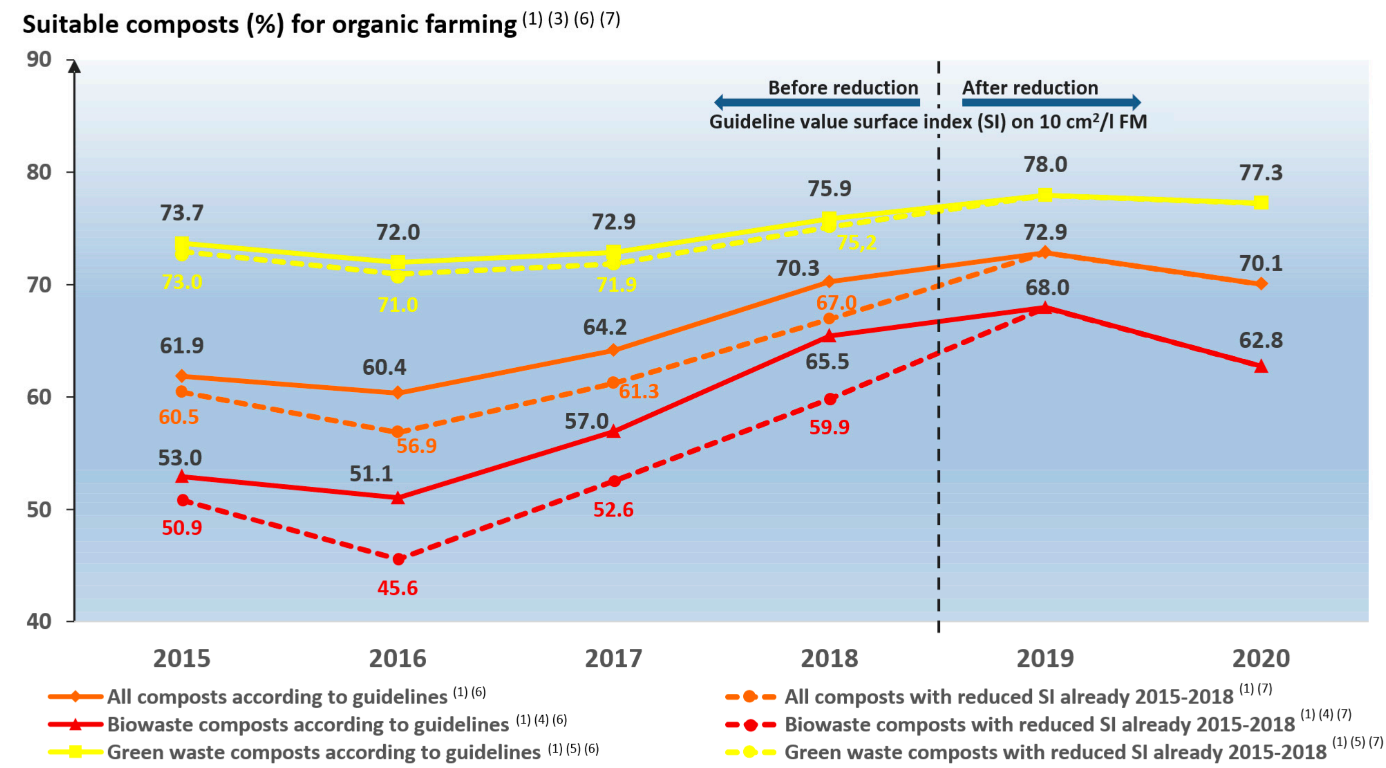

Figure 3. Proportion of biowaste and green waste composts suitable for organic farming in Germany in 2015 to 2020 (composts according to RAL-GZ 251 Compost from BGK 2015–2020) (1).(2). (1) Limit values ($\leq$) according to EU-ÖkoV—EU Organic Farming Regulation (VO (EC) 889/2008, Annex 1 resp. 2021/1165, Annex 2) and guideline values ($\leq$) according to Bioland/Naturland guidelines (5/2014 to 3/2020). (2) n = 3272 in 2015, n = 3345 in 2016, n = 3361 in 2017, n = 3536 in 2018, n = 3677 in 2019, n = 3841 in 2020, data from RAL Quality Assurance 251 (BGK, 2016–2021). (3) % of all analyzed composts according to RAL-GZ 251 Compost. (4) Biowaste composts (with and without upstream anaerobic digestion). (5) Green waste composts. (6) Incl. foreign matter (also parameter surface index (SI)). Foreign matter is not regulated according to EU-ÖkoV but to Bioland/Naturland guidelines. Composts according to Bioland/Naturland guidelines are regulated with guideline surface index (SI) $\leq$ 15 cm^2/l FM from 2015 to 2018, $\leq$ 10 cm^2/l FM from 2019 onwards. (7) Composts with theoretical approach of a reduced guideline value for surface index (SI) $\leq$ 10 cm^2/l FM also already from 2015 to 2018 (mandatory only from 2019 onwards)–s. (6)).

In general, it was observed that the suitability of both compost types for organic farming increased in the evaluation period between 2015 and 2019 and then practically stagnated for the green waste composts. This is also noteworthy in this respect, as in 2019, the guideline value of 10 cm^2/l FM for the surface index of the foreign matter content in the composts was introduced, which is significantly more stringent.

For the group of biowaste composts, however, the degree of suitability for organic farming fell noticeably again after 2020. Compared to 2018, the suitability of this compost group for organic farming was also lower in 2020, if it was assessed in accordance with the guidelines (2018 with a surface index of 15 cm^2/l FM, 2020 with 10 cm^2/l FM). However, the level of compost suitability for organic farming would also have been above the 2018 level for the total group of biowaste composts in 2020 if the stricter foreign matter standard of 10 cm^2/l FM had been applied for the surface index in both years (Figure 3), indicating an improvement with regard to the foreign matter content in the composts between 2018 and 2020. The corresponding results are documented in detail under Section 3.3.

The biowaste composts with and without upstream AD must be viewed differently. While the suitability of biowaste composts without upstream AD was initially slightly reduced during the period under consideration, significant improvement was noted from

2016 to 2018, whereas the suitability values fluctuated strongly between 2018 and 2020, indicating no clear trend (Figure 4). In contrast, the biowaste composts with upstream AD show an almost continuous improvement in suitability scores for organic farming from 2015 to 2020. The reasons for this differential development are presented under Section 3.3 and in the discussion.

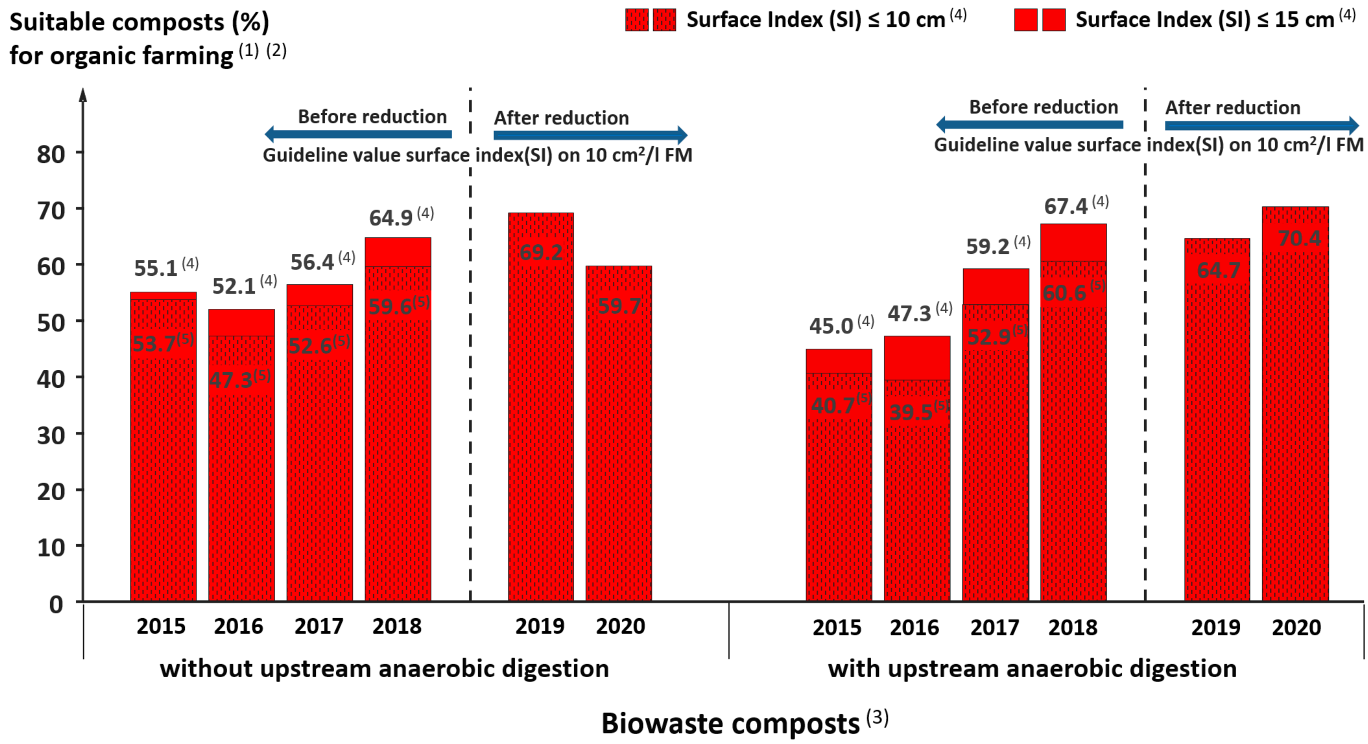

Figure 4. Differences in suitability of quality-assured biowaste composts with and without upstream anaerobic digestion according to RAL-GZ 251 Compost of the BGK with regard to their use in organic farming in Germany in 2015 to 2020 [(1)]. [(1)] Limit values ($\leq$) according to EU-ÖkoV—EU Regulations on organic farming (Regulation (EC) No. 889/2008, Annex 1 resp. 2021/1165, Annex 2; guideline values ($\leq$) according to Bioland/Naturland guidelines (5/2014 to 3/2020). [(2)] % of all analyzed composts according to RAL-GZ 251 Compost. [(3)] n = 1856 in 2015, n = 1857 in 2016, n = 1843 in 2017, n = 1900 in 2018, n = 1874 in 2019, n = 1899 in 2020, data from RAL quality assurance 251 compost (BGK, 2016–2021). [(4)] Incl. foreign matter (also parameter surface index (SI)). Foreign matter is not regulated according to EU-ÖkoV but to Bioland/Naturland guidelines. Composts according to Bioland/Naturland guidelines are regulated with guideline surface index (SI) $\leq$ 15 cm^2/l FM from 2015 to 2018, $\leq$10 cm^2/l FM from 2019 onwards. [(5)] Composts with theoretical application of a reduced guideline value for surface index (SI) $\leq$ 10 cm^2/l FM also already from 2015 to 2018 (mandatory only from 2019 onwards)—s. [(4)]).

3.3. Causes of Unsuitability of Compost for Organic Farming

As already mentioned in Section 3.1, only less than half of the quality parameters applied according to Table 1 have a significant influence on the suitability of composts for organic farming. The strongest effect can be attributed to the "parameter group heavy metals", followed by the "parameter group foreign matter" (Figure 5), and thereafter, the individual hygiene parameter "germinable seeds and sprouting plant parts".

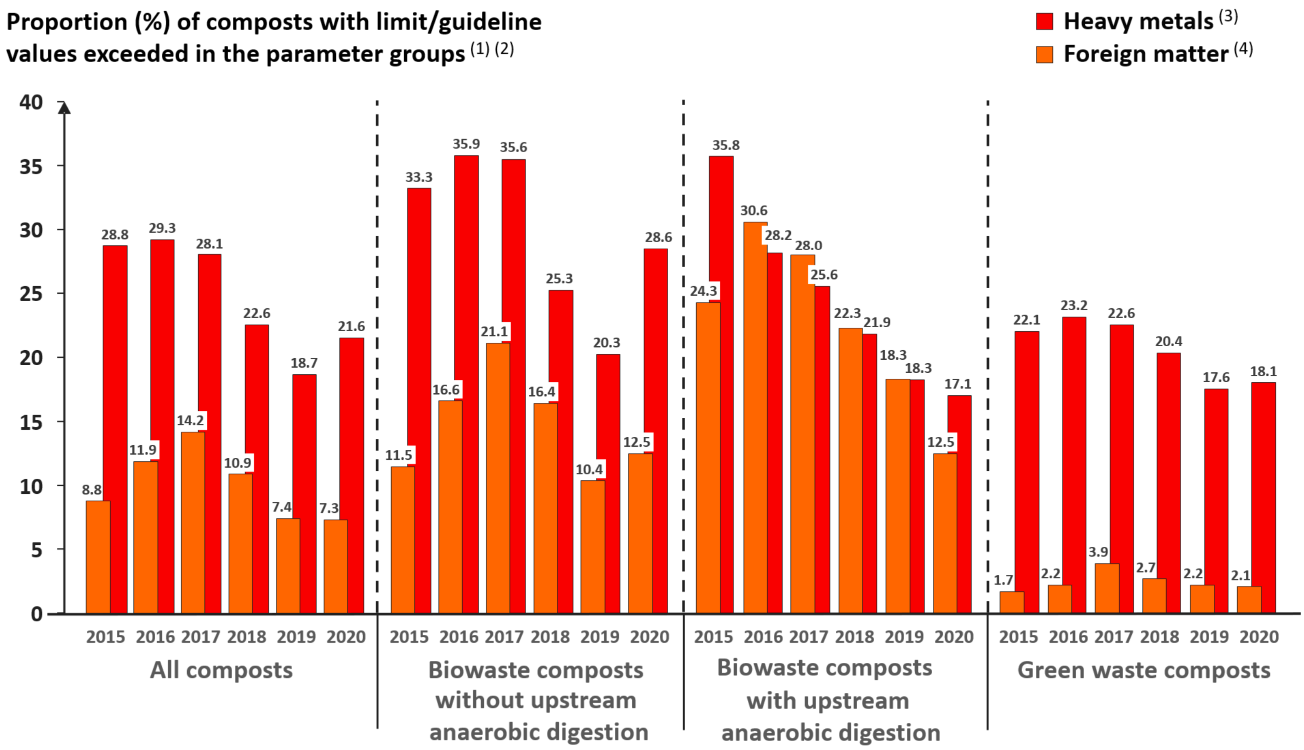

Figure 5. Influence of the parameter groups "heavy metals" and "foreign matter" on the proportion of biowaste and green waste composts not suitable for organic farming (composts according to RAL-GZ 251 Compost of BGK in Germany in 2015–2020) (1) (3) (4). (1) Limit values (≤) according to EU-ÖkoV—EU Regulations on organic farming (Regulation (EC) No. 889/2008, Annex 1 resp. 2021/1165, Annex 2; guideline values (≤) according to Bioland/Naturland guidelines (5/2014 to 3/2020). (2) Proportion of composts with limit/guideline values exceeded in the respective parameter group = Proportion of composts unsuitable for organic farming in % of all composts of the RAL quality assurance 251 compost of BGK (n = 3272 in 2015, n = 3345 in 2016, n = 3361 in 2017, n = 3536 in 2018, n = 3677 in 2019, n = 3841 in 2020 (BGK 2016–2021). (3) Parameter group heavy metals: Pb, Cd, Hg, Cr, Ni, Zn, Cu. (4) Parameter group foreign matter: (a) gravimetrically measured foreign matter content (all foreign matter, dry weight), (b) surface index (standardized area measurement of foreign matter, usually light film plastics and composites with a high surface area are recorded, which only make up a small proportion in the gravimetric measurement but are particularly conspicuous visually).

Considered across all compost types, in the individual years, limit values were exceeded by 18.7% to 29.3% of the composts analyzed for the group of seven heavy metals analyzed according to BioAbfV or Regulation (EU) 2021/1165 (Figure 5). Approximately 98% of these results are associated with the five metals Zn, Pb, Cd, Ni, and Cu, while Cr (total) and Hg play only a minor role (see below). Furthermore, the individual elements from the above-mentioned group of the five relevant heavy metals exert a very different influence with regard to suitability of composts for organic farming. The metals with the strongest negative influence on compost suitability in the entire period under consideration was Zn (10.3–15.3% limit value transgressions in all analyzed composts), followed by Pb (8.4–12.3%), Cd (6.0–8.3%), Ni (4.0–6.9%) and Cu (2.3–3.9%—Figure 6).

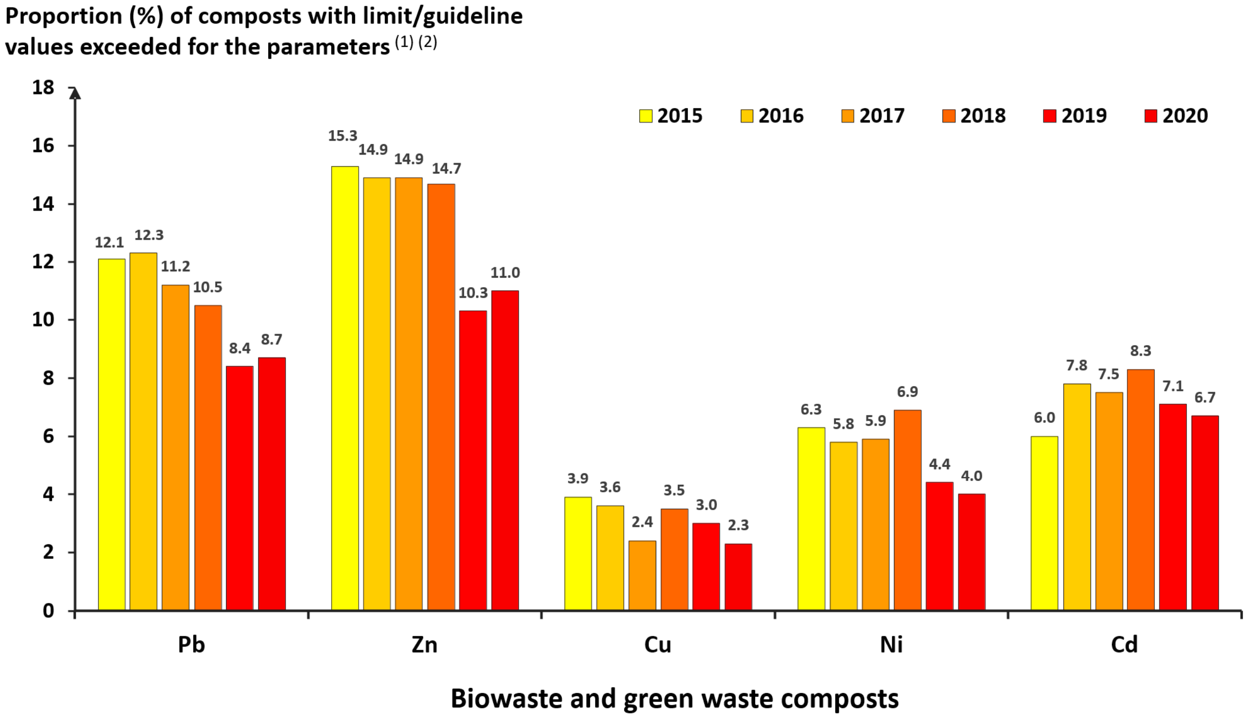

Figure 6. Proportion of quality-assured biowaste and green waste composts not suitable for organic farming due to exceedance of the heavy metal limits of the EU Organic Farming Ordinance (EU-ÖkoV) (composts according to RAL-GZ 251 Compost of BGK in Germany in 2015–2020) (1) (2). (1) Limit values (≤) according to EU-ÖkoV—EU Regulations on organic farming (Regulation (EC) No. 889/2008, Annex 1 resp. 2021/1165, Annex 2; guideline values (≤) according to Bioland/Naturland guidelines (5/2014 to 3/2020). (2) Proportion of composts with limit/guideline values exceeded for the respective parameter = Proportion of composts unsuitable for organic farming in % of all composts of the RAL quality assurance 251 compost of BGK, n = 3272 in 2015, n = 3345 in 2016, n = 3361 in 2017, n = 3536 in 2018, n = 3677 in 2019, n = 3841 in 2020 (BGK 2016–2021).

This order with regard to the negative influence of the aforementioned heavy metals on the suitability of compost for organic farming applies not only in the above overall consideration of all composts, but also to the two types of compost in the group of biowaste composts (with/without upstream AD). In green waste composts, on the other hand, the negative impacts of Zn, Pb and Cd in 2018–2020 are at a similar level (depending on the year between 6.3–10.0% limit value exceedances), followed by Ni (3.7–6.2% guideline value exceedances) and followed by Cu (0.7–1.1% limit value exceedances–not shown). The element Cu thus exerts a considerably lower influence on the compost suitability for organic farming in the green waste composts than in the biowaste composts.

In relation to the different types of compost, the negative influence of the aforementioned entire group of five heavy metals in the last three years is higher in the biowaste composts without upstream AD than in the biowaste composts with upstream AD. The latter, in turn, still shows a slightly stronger negative influence than the green waste composts in 2018, but this levelled off in 2019 and 2020 (Figure 5).

In the period under review, a decrease in the concentrations of most of the heavy metals in the composts can still be observed over time. In the group of the above-mentioned five relevant heavy metals, this is particularly evident with regard to the lead content of the biowaste composts, which fell continuously by a total of almost 13 percentage points between 2015 and 2020 (Figure 7).

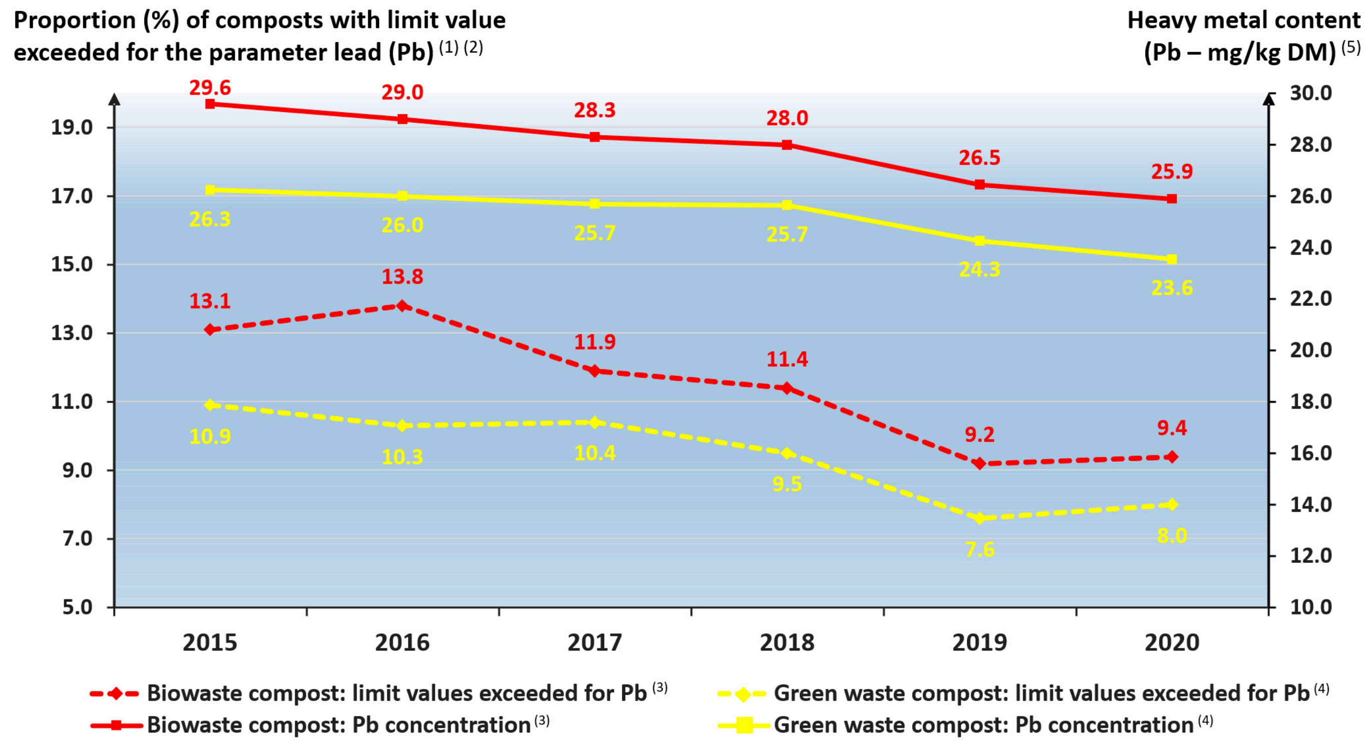

Figure 7. Comparison of the average lead (Pb) content of quality-assured biowaste and green waste composts with the proportion of limit value exceedances for lead (Pb) in relation to compost suitability in organic farming in Germany in 2015–2020 (composts according to RAL-GZ 251 Compost of BGK in Germany in 2015–2020) [(1)]. [(1)] Limit values (≤) according to EU-ÖkoV—EU Regulations on organic farming (Regulation (EC) No. 889/2008, Annex 1 resp. 2021/1165, Annex 2). [(2)] Proportion of composts with limit values exceeded for the parameter lead (Pb) = Proportion of composts unsuitable for organic farming in % of all composts of RAL Quality Assurance 251 Compost (BGK 2016–2021). [(3)] n = 1856 in 2015, n = 1857 in 2016, n = 1843 in 2017, n = 1900 in 2018, n = 1874 in 2019, n = 1899 in 2020, data from RAL quality assurance 251 compost (BGK, 2016–2021). [(4)] n = 1416 in 2015, n = 1488 in 2016, n = 1518 in 2017, n = 1636 in 2018, n = 1803 in 2019, n = 1942 in 2020, data from RAL quality assurance 251 compost (BGK, 2016–2021). [(5)] Median values.

In contrast, this correlation does not apply to Cd, neither in the biowaste nor in the green waste composts, as far as the entire observation period of this study is taken as a basis. On the other hand, after a slight increase between 2015 and 2017, the Cd values fell again, which led to a reduction in the limit value exceedances for both compost groups from 2018 onwards and thus to an improvement in the suitability of the composts for organic farming.

Differences between the Cd concentrations of biowaste and green waste composts were also observed in the sub-period 2018–2020 with regard to the 90% percentile, which, depending on the proximity of the value to the applicable limit value, already gives an initial impression of the problems to be expected, i.e., the potential level of limit value exceedances. At the 90% percentile, the values for both types of biowaste compost varied in 2018–2020 without any discernible trend between 0.60 mg Cd/kg DM and 0.64 mg Cd/kg DM, while this value for the green waste composts fell continuously between 2018 and 2020, namely from 0.70 mg Cd/kg DM to 0.65 mg Cd/kg DM to 0.60 mg Cd/kg DM (limit value: 0.70 mg Cd/kg DM). This effect found in the green waste composts between 2018 and 2020 with regard to the parameter Cd was therefore influenced both by a more favorable value distribution and by a drop in the median values.

Compared to the situation described above for the five relevant heavy metals in composts, in addition to the heavy metals Cr (total) and Hg, which are analyzed continuously in every compost sample, the metals Cr^{VI}, Tl and As, which are analyzed discontinuously or only in biowaste composts, play no or only an absolutely subordinate role with regard to the suitability of composts for organic farming at the currently valid limit values. This is independent of the year of investigation and the respective type of biowaste composts with or without upstream AD (limit value exceedances in the respective years per parameter for the two first-mentioned metals depending on the year of investigation between 0.3% and 1.2%, and for the three last-mentioned parameters between 0.0% and 0.2% of the analyzed composts).

The second strongest negative influence on the suitability of composts for organic farming, after the five heavy metals mentioned above, is exerted by the foreign matter load in these products. Considering all types of compost, in the individual years for the group of the two foreign matter parameters "gravimetrically recorded foreign matter content" (in the following "foreign matter grav.") and "surface index" (see under Section 2), guideline values were exceeded by a total of between 7.4% and 14.2% of the composts examined (Figure 5). In general, the negative influence of the parameter "surface index", which essentially represents the light foreign matter with a large surface (film composites, plastic films), is higher than the influence of the parameter "foreign matter grav.", which mainly includes glass, hard plastics and metals. The above statement applies to all study years and all compost types, albeit to varying degrees.

With regard to the individual types of compost, it can be stated that the influence of the foreign matter content on the suitability for organic farming is low for both green waste and biowaste composts. The total exceedance of the guideline values for the foreign matter content, i.e., cumulated for both the above-mentioned foreign matter parameters, is only between 1.7% and 3.9% of all analyzed green waste composts considered over the individual years of investigation. The biowaste composts without upstream AD achieved higher values between 10.4% and 21.1% and the biowaste composts with upstream AD between 12.5% and 30.6% of all analyzed compost samples exceeding the guideline values.

In the overall view of the investigation period, it can be determined that the foreign matter load based on the parameter "surface index" in the biowaste composts with and without upstream AD dropped continuously and clearly over time by more than 50% to 3.0 cm^2/l FM (Figure 8). In contrast, the values for the "surface index" for the green waste composts oscillate at a low level between 0.4 and 1.1 cm^2/l FM seen over the years without significant changes. There was also a slight drop in the median values for the "foreign matter content grav." for the biowaste composts to 0.6 wt.% DM, but only from 2019 and for 2020, while this value averaged 0.8 wt.% DM between 2015 and 2018 with a small range of variation. As in the case of the "surface index", there are no significant differences in the "foreign matter content grav." for the green waste composts (median 0.1–0.2 wt.% DM over all study years).

The exceedances of the guideline value for the hygiene parameter "germinable seeds and sprouting plant parts" vary only slightly from 2015 to 2020, between 2.7% and 3.9% of all composts examined. Significant, systematically occurring differences between the different compost types in each year of investigation are not noted and are also not expected, as this is essentially a parameter influenced by the process technology.

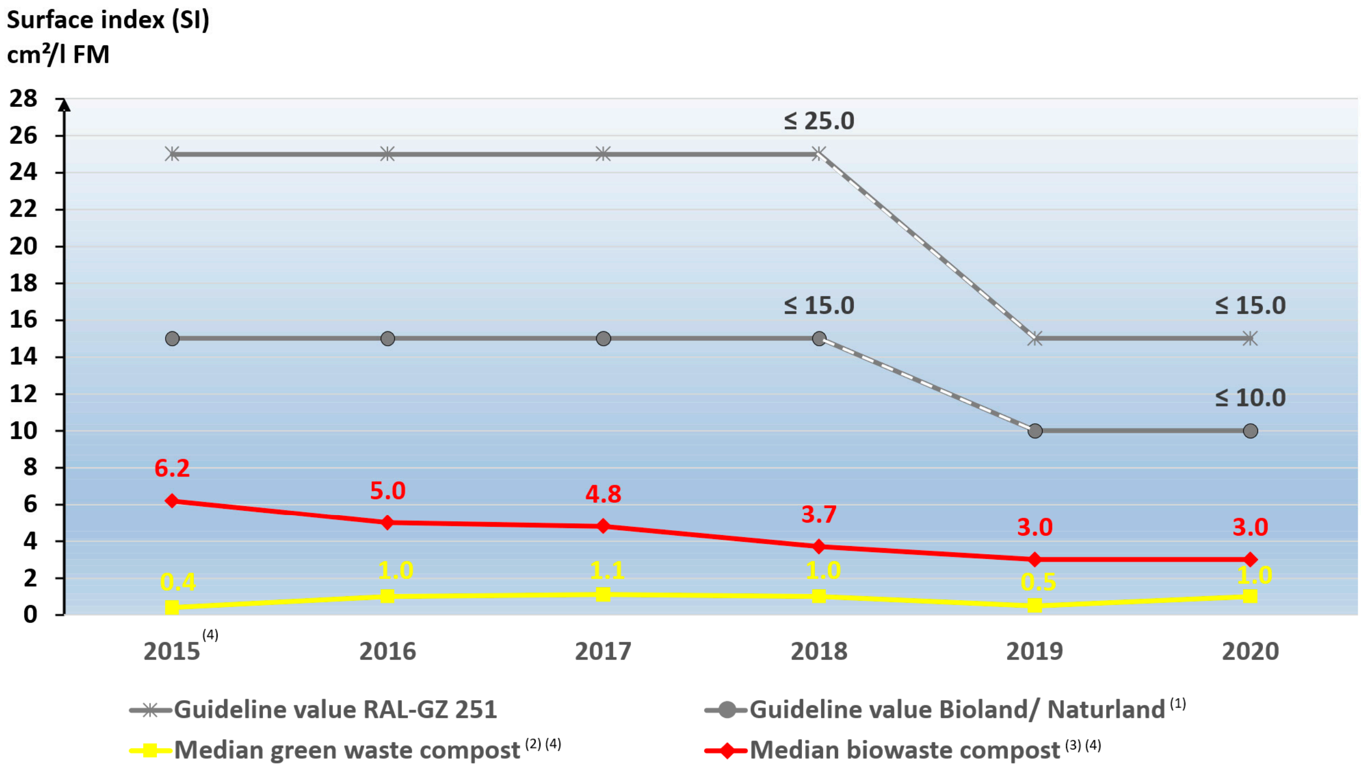

Figure 8. Average content of deformable plastic and film contaminants with high surface area (surface index—SI) of quality-assured biowaste and green waste composts in Germany in 2015–2020 (composts according to RAL-GZ 251 Compost of BGK in Germany) (1) (5). (1) Guideline values (≤) according to Bioland/Naturland guidelines (5/2014 to 3/2020). (2) n = 1138 in 2015, n = 1488 in 2016, n = 1518 in 2017, n = 1636 in 2018, n = 1803 in 2019, n = 1942 in 2020, data from RAL quality assurance 251 (BGK, 2016–2021). (3) n = 1772 in 2015, n = 1857 in 2016, n = 1843 in 2017, n = 1900 in 2018, n = 1874 in 2019, n = 1899 in 2020, data from RAL quality assurance 251 (BGK, 2016–2021). (4) n = 1138 (green waste composts) and 1772 (biowaste composts) in 2015, as not all composts were analyzed for the new "surface index" parameter in 2015. (5) Surface index: standardized area measurement of foreign matter, usually light film plastics and composites with a high surface area are recorded, which only account for a small proportion in the gravimetric measurement, but are particularly conspicuous visually.

3.4. Mass Potential of Biowaste and Green Waste Composts Suitable for Organic Farming

The mass potential of biowaste and green waste composts produced in Germany that are suitable for organic farming from the RAL quality assurance of the BGK is now around 2.5 million Mg. (Figure 9). The increase in the mass of compost suitable for organic farming between 2015 and 2019 amounts to approximately 0.7 million Mg, or just under 38% relative to the comparative basis of 2015. Since the total RAL quality-assured compost quantity also increased in the same period by approximately 18%, this result is also largely due to the described quality improvements in the period under consideration. So far, however, only about 7% of this mass potential has actually been used in organic farming.

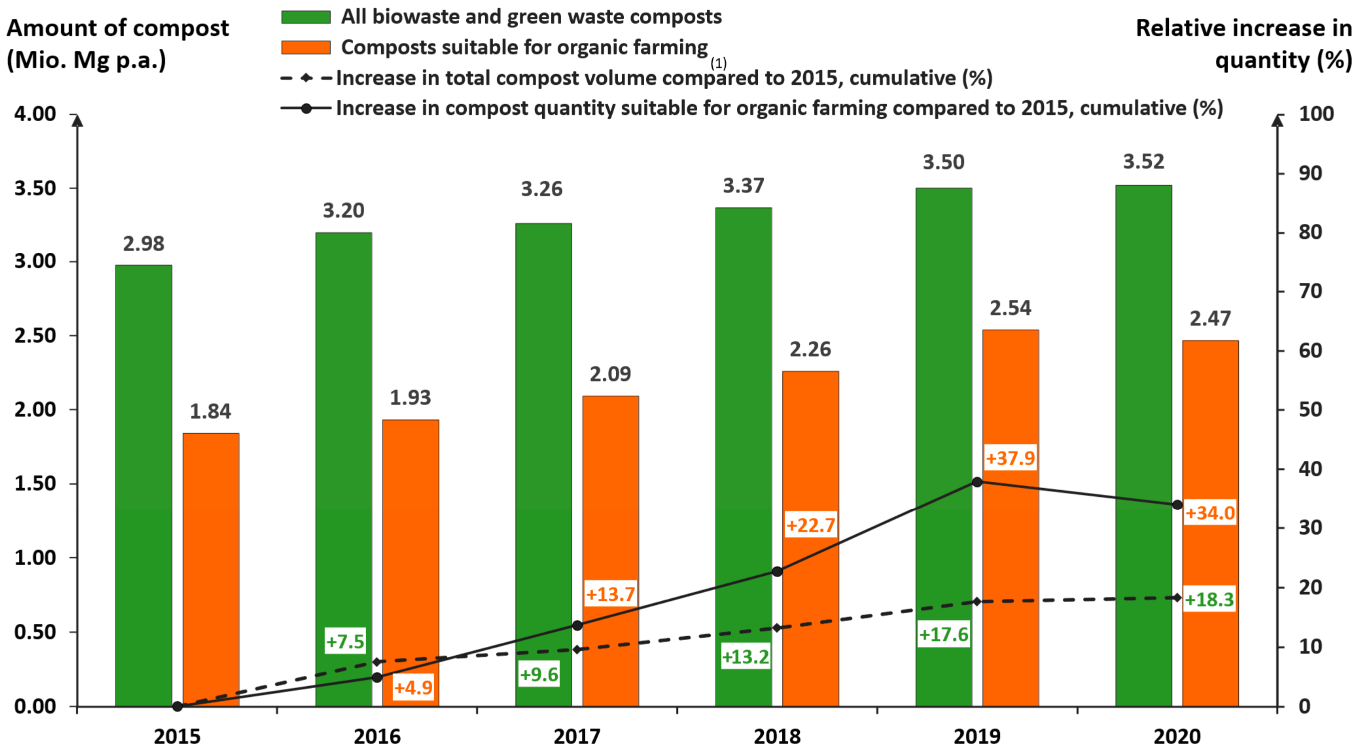

Figure 9. Development of the volume potential of quality-assured biowaste and green waste composts for organic farming in Germany in 2015–2020 (composts according to RAL-GZ 251 Compost of BGK in Germany in 2015–2020). (1) Limit values (≤) according to EU-ÖkoV—EU Regulations on organic farming (Regulation (EC) No. 889/2008, Annex 1 resp. 2021/1165, Annex 2; guideline values (≤) according to Bioland/Naturland guidelines (5/2014 to 3/2020).

With regard to the total nationwide potential of composts suitable for organic farming, biowaste and green waste composts originating from other quality assurance systems must also be taken into account, i.e., in Germany from the QLA system of the VDLUFA and the quality assurance of the Bavarian Compost Producers Association. Assured quantity data on this are not available. Based on the number of quality-assured plants and input quantities of these two quality assurance systems, it can be estimated that, in this respect, hardly more than 5–8% of the above-mentioned BGK compost quantity is additionally available that could be used in organic farming.

Finally, the quantities of green waste composts from composting plants that are not quality-assured by the private sector, which are monitored according to the regulations of the Biowaste Ordinance (BioAbfV [24]) and the Fertilizer Ordinance (DüMV [25]), must also be addressed. In this regard, too, it can be estimated—with all due caution—on the basis of input data from nationwide waste statistics (DESTATIS [27]) that up to 30% of the above-mentioned compost quantity obtained from BGK quality assurance could be represented as additional potential for organic farming.

Overall, the total pool of suitable biowaste and green waste composts for organic farming, including the green waste composts monitored according to BioAfV and probably also suitable in principle, could be more than 3.0–3.3 million Mg FM in Germany in 2020.

4. Discussion

4.1. Test System and Methodological Issues

The present evaluations show that the assessment of the suitability of biowaste and green waste composts for organic farming should not be carried out solely according to Regulation (EU) 2021/1165 within the framework of a reliable and consistent testing system, but that the extensive additional catalogue of criteria of the organic farming and

Naturland standards should also be used (Figure 1, Table 1). If this is not performed, there is the possibility that biowaste composts with, in some cases, considerable foreign matter contamination or green waste composts without specifications on maximum heavy metal contents (neither of which is regulated in the Regulation (EU) 2021/1165) would be used in organic farming for example. Moreover, without an analysis of the specific batch of compost used in organic farming, as provided for by Bioland and Naturland, it could not be excluded that composts with possibly undesirable properties enter organic farming systems.

These three examples from a series of relevant examples of a necessary "upgrade of the requirements" for "premium composts" compared to the Regulation (EU) 2021/1165, which organic farming in Germany rightly demands, make it clear that a combination of the Regulation (EU) 2021/1165 with the above-mentioned association standards is necessary with regard to a test of compost quality. This combination of the legal basis of the EU Regulation and the professionally necessary and factually sound guidelines of Bioland and Naturland expands the spectrum of monitored quality parameters for premium composts in organic farming according to the latest state of knowledge.

4.2. Suitability of Biowaste and Green Waste Composts for Organic Farming

With regard to this topic, it is necessary to show what measures are required first to produce composts that are suitable for organic farming. Referring to this, the necessity of separate collection becomes obvious just by looking at the heavy metal concentrations. For example, the heavy metal concentrations in biowaste composts from separate collection (2020) are 76% (Cr) to 97% (Ni) lower than in composts from mixed MSW (1980) in Germany. For the particularly relevant heavy metals, this is 88% lower for Pb, 90% lower for Cd, and 95% lower for Hg. In the case of composts from mixed municipal solid waste (MSW), as still produced in some EU states (example France), the values for particularly relevant heavy metals are 10-fold higher for Hg, 6-fold higher for Pb and 4.5-fold higher for Cd than those of biowaste composts from separate collection [28].

The heavy metal concentrations of composts from separately collected biowaste and green waste from other EU member states (e.g., AT, IT, FR, UK (former), SE) are in the same range as found in Germany and comply with the quality standards set in the countries. For some biowaste composts, the limits for Ni are not met; in many cases, this is due to geogenic contamination. In contrast, heavy metal concentrations of composts produced with sewage sludge and manure and from mechanical-biological treatment (MBT) plants exceed these standards. These results are based on the analysis of 14,000 samples in EU [29].

The above statements also apply to foreign matter. While composts from separately collected biowaste at least meet the 90% percentile level, composts from mixed waste collection (e.g., composts from MBT plants) do not meet the End of Waste (EOW)-limit values proposed by the EU [29].

For salmonella (hygiene parameter), the EU regulation for fertilizing products (EU 2019/1009) determines the absence in 25 g samples. This regulation applies in a large number of EU countries (national ordinances). The RAL GZ 251 of BGK has set this value stricter with no salmonella in 50 g compost.

If the separate collected biowaste is considered from which composts and digestates are produced, it can be determined on the basis of the literature, that the impurities in biowaste are significantly lower from rural areas than from urban areas. For heavy metals, the concentrations of Zn are significantly higher in rural areas; for Pb, Cu, Cr, and Ni, they are slightly higher (mean values) in rural areas, while for Cd, As, and Tl, no clear differences can be observed. The influence of the season is low compared to the settlement structure [30].

The proposal that a maximum of one-third of the biowaste and green waste composts produced in Germany are suitable for organic farming [31], which has been voiced in the past by some practitioners of organic farming and waste management, has been refuted by the present evaluation. This can be stated for the evaluation results themselves in retrospect up to 2015, even though the suitability of composts for organic farming has continued to increase since then, reaching around 70–73% in 2019/2020. This improvement in organic farming suitability from biowaste composts is significantly more than that from green waste composts, which was expected to improve for a number of measures regarding the input quality and foreign matter load in biowaste, but which has not yet been proven in terms of data [32–34].

The continuous increase in the suitability of biowaste and green waste composts for organic farming is therefore causally related to improvements in the contamination levels of biowaste composts and partly also to the reduction of the heavy metal content in the composts. This does not apply consistently to all analyzed heavy metals and also affects the different types of compost to a very different extent, as shown in Section 3.3.

It is also important to consider the different behavior of the two types of biowaste compost with and without upstream AD with regard to the limit value exceedances for organic farming for the relevant heavy metals. While the limit value exceedances for the biowaste composts without upstream AD varied at a high level between 20.3% and 28.6% of all analyzed composts between 2018 and 2020 without any discernible trend, these fell continuously for the biowaste composts with upstream AD in these three years from 21.9% to 17.1% of all analyzed composts. It is also noticeable that with regard to the individual heavy metals, the limit value exceedances, especially for Zn and Pb, are at a significantly higher level in the biowaste composts without upstream AD (Zn 14.9–21.9%, Pb 10.6–12.9% limit value exceedances) than in the biowaste composts with upstream AD (Zn 9.6–11.6%, Pb 5.3–6.9% limit value exceedances). While for Zn, among other things, a lower proportion of galvanized steel parts is assumed in the plants with upstream AD, as well as a partial transfer of Zn from the raw digestate to the liquid digestate during the separation of solid and liquid digestate before composting [32], the reasons for Pb are unclear, especially since the falling median values for Pb are found equally in both types of biowaste compost in the period under consideration.

As far as the continuous improvement of compost suitability for organic farming in the biowaste composts with upstream AD between 2015 and 2020 is concerned, in addition to the above-mentioned lower heavy metal contamination, the decreasing foreign matter content plays an even greater role. In the period under review, this effect was significantly stronger for the biowaste composts with upstream AD than for the biowaste composts without upstream AD. Thus, the guideline value exceedances for the sum of the two extraneous matter parameters “surface index” and “foreign matter content grav.” even increased to 21.1% for the biowaste composts without upstream AD in the years 2015–2017, while they fell to a range between 10.4% and 16.4% in 2018–2020 without any discernible trend. On the other hand, in the case of biowaste composts with upstream AD, there was a continuous decrease in the foreign matter-related guideline value exceedances from 30.6% in 2016 to 12.5% in 2020.

The reasons for this can be found, on the one hand, in the improvements in input quality and contamination of biowaste in recent years, which are now the result of numerous measures and campaigns by the public bodies responsible for waste disposal, the relevant associations, the quality assurance organizations and the composting plants themselves for separate collection by type [34–37]. On the other hand, the tightening of the guideline value for the surface index of 25 cm^2/l FM to 15 cm^2/l FM in 2018 within the framework of the RAL Quality Assurance Compost of the BGK, which had been highly controversial for many composting plant operators, played a significant role in this. As a result, composting plants not able to comply with these new guidelines in their products were forced to implement upstream measures (public relations work, input controls, sorting, etc.) or technical optimizations, especially in the screening and air separation areas, to improve compost quality. Failure to achieve these guideline values meant problems in quality assurance certification and include the withdrawal of the RAL quality mark compost of the BGK.

This situation particularly affected many biowaste composting plants with upstream AD due to the pre-shredding of the biowaste which also includes foreign matter. Shredding is usually applied with a view to improving the biogas yield. However, the resulting smaller particle sizes can technically only be removed with much greater effort, and in some cases, not at all. This was pointed out by both studies and internal BGK data [32,33], which caused an extensive discussion process and subsequent optimization measures at the biowaste composting plants with upstream AD. For the most part, these optimizations were carried out successfully with regard to the foreign matter content in the composts, also underlined by the present results. In some cases, however, improved foreign matter content was only achieved by finer screening of the composts, which in turn led to increased rejection of screen overflows and can be regarded as counterproductive in view of their high organic content.

The foreign matter content also characterizes the results regarding the compost suitability for organic farming in the comparison of the two compost groups biowaste and green waste composts. Both in the surface index and in the gravimetric foreign matter content (Table 2, Figure 7), the mean foreign matter content of the green waste composts in the period under consideration was only 7–33% of the mean foreign matter content of the biowaste composts. This is mainly due to technical reasons for collection and due to incorrect sorting during collection, because substances and products were dropped into the containers by mistake. Therefore, the best possible purity of the specific input materials when collecting biowaste in the biowaste bin has not yet been implemented in some cases [32,34,36,38,39].

Accordingly, the foreign matter content of the green waste composts is also responsible for only a very small proportion of the exceedances of the guideline values with regard to compost suitability for organic farming. Compared to the two types of biowaste compost with and without upstream AD, the green waste composts showed only one-fifth to less than one-tenth of foreign matter-related guideline value exceedance, depending on the year of evaluation. The tightening of the guideline value for the surface index of 15 cm^2/l FM to 10 cm^2/l FM in 2019 by Bioland and Naturland therefore also had only a minor impact on the suitability of the green waste composts for organic farming.

Comparing the data for the exceedance of the guideline values due to heavy metals in both compost groups, the heavy metal content considered across all the composts analyzed has a much stronger limiting influence on the suitability of the compost for organic farming than the foreign matter content. Of course, this applies in particular to the green waste composts, but also to the biowaste composts without upstream AD and, more recently, also to the biowaste composts with upstream AD due to the significant optimization of the foreign matter content of this compost type in 2018–2020. It should also be noted in this context that the state of affairs documented in this way is diametrically opposed to the conditions consistently expected by composting practice until a few years ago and still partially expected today [31,40].

With regard to the individual metals, it is also of interest that Cu had hardly any influence on the compost suitability for organic farming in the green waste composts due to the low Cu concentrations in contrast to other heavy metals. The significantly higher negative influence of Cu on the suitability of composts for organic farming in the group of biowaste composts, on the other hand, once again underlines the connection between higher Cu contents in the composts and stronger impacts from residential areas due to the use of Cu in various materials and products there. This is mainly caused by the input of foreign matter into the bio-bin.

Compared to this scientifically substantiated approach, the effects of the foreign matter content in composts on the acceptance of these combined soil improvers and fertilizers in organic farming are still stronger than those of the heavy metal content. In the course of the intensified discussion about microplastic contamination in the environment, the situation in this respect is expected to intensify [40,41].

In this context, it should also be noted that of the group of metals relevant to compost suitability for organic farming, the elements Zn and Cu are regulated as heavy metals according to BioAbfV and Regulation (EU) 2021/1165 for organic farming (EU-ÖkoV) and are generally considered as pollutants. The limit values in the above-mentioned EU Regulation are specified for Cu $\leq$ 70 mg/kg DM and Zn $\leq$ 200 mg/kg DM. These are significantly below the limits of the German Biowaste Ordinance (Cu $\leq$ 100 mg/kg DM, Zn $\leq$ 400 mg/kg DM, BioAbfV [24]).

At the same time, however, they are also obligatory micronutrients for plants. Zn and Cu are thus assessed differently both by a scientific approach and in agricultural practice than, for example, the heavy metals Cd, Pb and Hg, which are generally considered harmful [12]. The German Fertilizer Ordinance [25] therefore also classifies the two elements Zn and Cu as non-pollutants, but as micronutrients and allows significantly higher limits for them than the BioAbfV [24]. Since in the composts examined, about one-third of the total limit value exceedances from the group of heavy metals are caused by Zn and Cu, these correlations definitely play a considerable role on the factual side as well as on the acceptance level in organic farming. Of course, this does not change the actual regulation of biowaste composts for organic farming due to the fixed limit values of the Regulation (EU) 2021/1165 for Zn and Cu.

Since 1990, heavy metal emissions in Germany, especially of As, Cd, Hg and Pb, have fallen by between 60% and over 90%. The ban on leaded gasoline since 1997 has led to a significant reduction in emissions of lead in particular. Emissions of As, Hg and Ni are particularly caused by energy production (incineration processes), while Cd is emitted especially during metal production. Emissions of Pb, Cr, Cu and Zn are particularly caused by traffic (abrasion of tires and brakes) [42].

Emissions from industrial processes can be expected to decline further as a result of more advanced waste gas purification systems. The ban on mercury-containing products (e.g., in batteries) will further reduce Hg emissions.

Since heavy metals in biowaste and green waste are caused not only by misdirected waste but also by emissions (deposition on soils and plant surfaces, uptake by plants), it can be assumed that the heavy metal concentrations of composts and digestates will continue to decrease in the future. Further improvements in separate collection must be made to ensure that the purity of biowaste is further improved and foreign matter contents are reduced.

4.3. Volume Potential and Practical Impacts Regarding Nutrient Recycling

The potential quantities of biowaste and green waste composts for organic farming in 2020, as presented in Section 3.4, show the high relevance that this group of combined soil improvers and fertilizers from a circular economy has for organic farming in principle and especially with regard to its targeted growth. For example, the German government's "Organic Farming Strategy for the Future" (ZöL—Zukunftsstrategie ökologischer Landbau) has specified an increase in organically farmed agricultural land from just under 11% at present to 30% of the total agricultural land (LF) in Germany by 2030 [5].

This planned growth rate on the one hand and the considerable increase in livestock-free and intensive arable/market fruit and vegetable farms in organic farming in Germany on the other [43] make it even more necessary than before to support production in organic farming by supplying external nutrients in order to balance the nutrient exports with the food sold [6–10]. In the meantime, nutrient balances carried out in Germany within the framework of extended area balances in large regions or entire federal states such as Schleswig-Holstein, Hesse, Baden-Wuerttemberg and Bavaria show high negative nutrient balances of organic farming, if no nutrient recycling via fertilizers from sources external to the farm takes place. These negative nutrient balances are—for example—between -20 and -22 kg P_2O_5/ha*a for phosphate in relation to the total organic agricultural area of the mentioned federal states and can amount to up to 3500 Mg P_2O_5 p.a. in relation to phosphorus in individual federal states [9,44].

Essential elements of fertilization in organic farming are usually, at the farm level:

1. The recycling of plant nutrients and organic matter back into the soil via crop residues and plant or animal manures,
2. The integration of clover grass, catch crops and grain legumes to bind nitrogen from the air but also to make plant nutrients more available, e.g., via root exudates. The obtained above-ground biomass can be used as fodder, for fertilization purposes on other farm areas with fertilization requirements (cut and carry) or via other processes for biomass preservation (ensiling or composting), later used as fertilizer, which particularly concerns the use of clover-grass/alfalfa-grass stands.
3. Fodder/manure cooperations and, for some years, cooperations with biogas plants for NaWaRos/farmyard manure.

In addition, organic farms also purchase a number of approved fertilizers from off-farm sources, such as Dolophos, Patentkali (potash), hair meal pellets, etc. These fertilizers become increasingly important the more intensively the farm is managed (cash crops including root crops such as potatoes, sugar beets, corn and sunflowers as well as field vegetables, fine/intensive vegetable farms) and the lower the number of livestock.

The latter group of external fertilizers also includes biowaste and green waste composts, which not only allow the supply of all essential macro- and micronutrients, but (except for N and partly S) also have a high nutrient availability for the essential plant nutrients [12]. As just the above-mentioned data on nutrient balances without external fertilizer supply in organic agriculture of the listed federal states show, these composts are of very great importance for the return of plant nutrients exported from the farms with the food. Thus, on a regional level, without long transport distances and with a cost-effective combined soil amendment and fertilizer, the nutrient cycle can actually be closed on organic farms. This will become even more important with the targeted growth of organic farming compared to the state of affairs in recent years, when e.g., Kolbe already stated in 2016 that in many organic farms in Germany "the nutrient cycles are partly wide open" [8].

If we assume an average annual compost supply of 5 Mg FM/ha*a in organic arable farming, the above-mentioned quantity potential of biowaste and green waste composts in Germany could cover approximately 500,000 ha (only composts from BGK quality assurance) to over 600,000 ha (estimated total quantity of suitable composts) of organically farmed arable land annually (organic arable land in Germany in 2020 733,986 ha). The above-mentioned compost quantity is based on the compensation of the average P exports of organically managed livestock-less arable/market crop farms of medium intensity (cereal-focused, biennial clover grass, possibly grain legumes; P-export-farms: 18–22 kg P_2O_5/ha*a; average P-content composts: 3.9 kg P_2O_5/Mg FM [10,22]).

Compared to the possibilities thus demonstrated for land coverage through consistent compost use, the currently realized utilization rates of biowaste and green waste composts in organic farming are rather low, with values of about 5% of the total compost production and about 7% of the volume potential suitable for organic agriculture (see Sections 1 and 3.4). Thus, more than 2.3 million Mg of suitable composts in Germany are still not used in organic farming. This characterizes the current state of affairs, despite a slowly increasing momentum in compost utilization in organic agriculture over the last three years [15,40]. The reasons for this low level of potential utilization to date are primarily to be found in the area of a lack of information or insufficient communication from or between the organic farms and the composting plants. These causes clearly show that intensive efforts are needed to successfully and sustainably connect the different areas of organic farming and composting in the future. The first large-scale model projects exist in Hesse and Baden-Wuerttemberg [45].

4.4. Further Benefits of Biowaste and Green Waste Composts for Organic Farming

Beyond nutrient recycling, biowaste and green waste composts can contribute largely to the humus supply of soils and to the improvement of a large number of relevant parameters for soil fertility in organic farming, especially in the area of water retention and infiltration capacity, pore volume, aggregate stability and biological revitalization, which, among other things, reduces the erosion tendency of soils and strengthens their resilience to extreme weather events [12,14,46]. For example, scientific field tests under Central European climatic conditions showed a significant reduction in storage density and an increase in pore volume and usable water capacity of the fertilized soil by approximately 7 and 12%, respectively, compared to the control variant not fertilized with composts, after only 4 years of application of biowaste composts on a medium-heavy loess soil [46]. During 12 years of field trials in Central European soil/climatic environments, a significant improvement in water capacity and an increase in microbial biomass was found by compost fertilization at all five sites tested in Baden-Württemberg [12].

Phytosanitary effects of compost application have also been widely reported in scientific studies over the last 30 years [47–49]. In these studies, infestation with various phytopathogens such as Pythium ultimum or Rhizoctonia solani was significantly reduced by compost fertilization, which had a positive effect on yield and quality of the cultivated crops. An interesting recent development of compost application is the row application especially to potatoes, which showed very positive effects on the reduction of Rhizoctonia solani infestation of potatoes in multi-year R & D projects. Thus, the sclerotia population on the potato surface could be significantly reduced by up to approximately 80% and the number of deformed cones by up to approximately 50% [47]. The prerequisite was the concentrated introduction of the green waste compost into the plant row and the placement of the potatoes directly onto/into the compost (application rate 5 Mg DM/ha).

A significant advantage of the application of biowaste and green waste composts is furthermore shown with regard to the possible C sequestration with these materials. The (temporary) sequestration of C during the application of some organic fertilizers can integrate carbon into the soil and thus contribute to climate protection [12–15,50]. In scientific field trials with compost fertilization on six sites in Central European soil/climate regions over 12–14 years, significant increases in humus content in the soils and recovery rates of 38–51% of the TOC added with the composts were documented after the above-mentioned study periods [12,13]. An Austrian study over 14 years also showed GHG sequestration in the total arable system at medium to high compost applications of −262 to −388 kg CO_2-equiv./ha*a due to the C sequestration of the biowaste composts used [13]. In contrast, the exclusively minerally fertilized variants showed partly high GHG release rates between +1107 to +2307 kg CO_2-equiv./ha*a.

Even under tropical climatic conditions with correspondingly higher organic matter conversion rates, especially in the light, sandy soils of northern Thailand, an improvement in the area-related CO_2 footprint was observed in organic rice cultivation compared to conventional rice cultivation, which was also essentially attributed to C sequestration effects [16,17]. The authors also point out further advantages of organic rice cultivation in the areas of nitrogen footprint, water footprint, and lower grey water production [16].

In a review of TOC levels in the sandy soils of northern Thailand, the same authors point to the observed potential of many of these soils for further C sequestration and the strong positive yield effect that can be expected from such an increase in soil TOC levels [17].

The possible humus accumulation and thus C sequestration is one of the most significant beneficial effects in organic agriculture, as soil organic carbon (SOC) is a vital factor for soil productivity and supports the numerous ecosystem services provided by terrestrial soils quite significantly [4,51,52]. Incorrect land use and mismanagement of soils reduces soil quality, thus degrading soil ecosystem services and leading to a large ecological footprint. In contrast, increasing the levels of SOC can improve physical, chemical, and biological soil quality, which in turn leads to optimized ecosystem services and accordingly to a higher value for the society [52].

In a meta-study comparing organic and conventional farming systems in which 528 individual studies from 1990 to 2018 were evaluated, the authors found high overall benefit effects of organic farming compared to conventional farming systems. In terms of SOC, organically managed soils had an average 10% higher content and a 256 kg C/ha*a, corresponding to 938 kg CO_2-eq./ha*a higher carbon sequestration rate [53]. Taking into account the 24% lower nitrous fumes emissions, the cumulative climate protection performance of organic farming was 1082 kg CO_2-eq./ha*a in terms of area [53].

Studies in Thailand based on balances regarding product quantities furthermore show lower carbon footprint intensity in organic rice production relative to conventional rice production (−0.13 versus + 0.82 kg CO_2-eq./kg rice yield [54]) beyond the above-mentioned area-based balances. The high increase in SOC in the organic system was 1107.6 kg C/ha*a and thus about 77% higher than that in the conventional cropping system. The value of carbon sequestration ecosytem services (VCSES) calculated on the part of the authors for the organic cropping system was also nearly 80% higher than that of the conventional cropping system. In modelling the impact of climate change on SOC, rice yield and VCSES, the authors concluded that the negative impact should be lower in the organic cropping system [54].

A number of crop cultivation methods lead to a possible humus accumulation in organic farming, which includes in particular the cultivation of clover grass and catch crops, the extensive use of organic fertilizers and the reduced tillage in many farms in the meantime. As documented by the above-mentioned results from long-term fertilization trials with biowaste and green waste composts, these secondary raw material fertilizers can further support C sequestration in organic farming to a considerable extent.

With these multifunctional effects in terms of nutrient recycling, support and optimization of soil fertility, as well as in terms of the positive influence on climate resilience and climate protection, biowaste and green waste composts represent important tools for ensuring sustainable growth in organic agriculture.

5. Conclusions

The investigations show that, starting from 2015 until 2020, 61.9% to 70.1% and therefore a high percentage of the composts from separately collected biowaste and green waste are increasingly suitable for use in organic farming based on EU regulation 2021/1165 and the guidelines of the two largest organic farming associations Bioland and Naturland. The heavy metal concentrations are exceeded by 21.6% of the composts, for foreign matter by 7.3% of the composts in 2020. The negative influence of the single elements regarding the suitability of composts for organic farming declined in the order Zn > Pb > Cd > Ni > Cu. In the bio-waste composts, the impurity content subsequently decreased by more than 50% from 2015 to 2020. In 2019 and in 2020, approximately 2.5 million Mg fresh mass (FM) of the analyzed composts were suitable for organic farming. Negative nutrient balances, which according to available studies are between −20 to −22 P_2O_5/ha*a for phosphate without the use of external fertilizers, can be compensated by composts. With an average compost application of 5 Mg FM/ha*a, about 500,000 ha of arable land could have been supplied in 2020.

A further improvement of the compost quality is possible and should be strived for, especially against the background of compost utilization in organic farming. With regard to heavy metals, it is to be expected that the trend of a further reduction of heavy metal emissions will be continued by further reduction of industrial emissions and the ban of heavy metals in products (e.g., Hg and Cd). The input of foreign matter in the separate collection of biowaste must be further improved through public relations for the households and control measures. In composting plants, the process technology and the control of material flows must be controlled to make a product that is as low in foreign matter as possible; this also applies in particular to biowaste composting plants with upstream AD.

Through this continuous optimization, especially with regard to collection technology and minimization of foreign matter in the input of composting plants, further quantities of suitable composts for organic farming can be made available. Moreover, according to the latest nationwide residual household waste analysis, it is estimated that approximately 4–6 million Mg of biowaste and green waste per year are not recorded [55]. Depending on the process focus of the processing plants, around 1.5–3 million Mg of compost could be produced annually from the above-mentioned additional input quantity. Assuming an average degree of suitability for organic farming of approximately 70%, as found so far, this would mean that a further 1–2 million Mg of biowaste and green waste composts could be obtained for organic farming.

Considering all these aspects, future research questions on the one hand lie in the area of changing the qualities of biowaste through the further expansion of separate collection in order to enable further recycling of biowaste, to meet the EU-targets of recycling and to reduce the content of organic substances in residual waste. Likewise, the effects of quality-enhancing measures in the collection and treatment of biowaste are to be investigated. On the other hand and with regard to the use of composts in organic farming, it is of particular importance to enhance research on the many effects of composts in terms of fertilizing, soil improvement, phytosanitary aspects and C-sequestration. Moreover, the monetary benefits from composts need to be further investigated, both for the organic farms and also regarding the value of optimized ecosystem services.

Last but not least, the suitability of other secondary raw material fertilizers for the use in organic farming is a matter of special importance. This aspect will be further investigated as part of the continuation of the R & D-project "ProBio", especially regarding liquid digestate from AD and wood ashes.

6. Glossary with Definitions

Definition of green waste composts/biowaste composts: (with/without upstream anaerobic digestion (AD)): As a rule, separately collected garden and park waste as well as separately collected private household waste (content of organic waste bins (biowaste bin)) are used for composting on an industrial scale. Green waste compost refers to composts in which only the vegetable garden and park waste or comparable vegetable materials are processed. If, on the other hand, private household waste (contents of organic waste bins) is also used, it is referred to as biowaste compost. In addition to the composting of organic materials alone, many plants in Germany have in the meantime added an upstream anaerobic digestion (AD) stage to the process. This means that biogas can first be produced from the organic waste used for energy use and the resulting digestate can then be fed into the composting process. The product of this process is compost. Depending on whether AD is used before composting or composting alone, a distinction is made between compost with or without upstream AD.

Differentiation between limit values and guideline values: In addition to the legal regulations and the limit values for certain parameters included therein, there are also defined quality criteria for quality-assured composts from private-law regulations (guideline values). In the particular case of foreign matter content, the quality assurance of the BGK defines the visual contamination (fraction > 1 mm) in addition to the gravimetric determination of the foreign matter content. This so-called "degree of contamination" is determined by means of the visible surface of the foreign matter analyzed and is also evaluated within the scope of the quality assurance and provided with a limit value here (surface index). Since these limit values only apply within the framework of quality assurance and are not a legal requirement, these criteria are referred to below as a guideline value. This guideline value for the degree of contamination was tightened by the BGK on 1 July 2018 and is fixed now at a maximum surface index of the foreign matter > 1 mm of 15 cm^2/l for quality assurance. Since the Bioland and Naturland associations have agreed on stricter requirements for foreign matter for the use of compost in organic farming, these requirements have been tightened accordingly for the suitability of compost for use on organic/natural land and, since 1 January 2019, the maximum value for the degree of contamination has been set at a surface index of 10 cm^2/l in accordance with the association's guidelines.

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