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Considering Grouped or Individual Non-Methane Volatile Organic Compound Emissions in Life Cycle Assessment of Composting Using Three Life Cycle Impact Assessment Methods

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Abstract: Composting is a waste management practice that converts organic waste into a product that can be used safely and beneficially as a bio-fertiliser and soil amendment. Non-methane volatile organic compounds (NMVOCs) from composting are known to cause damage to human health and the environment. The impact of waste management on the environment and workers is recognised as a growing environmental and public health concern. Measurements of NMVOCs emitted during composting have been carried out only in a few studies. NMVOC emissions are typically reported as a group rather than as species or speciation profiles. Recognising the need to investigate the issues associated with NMVOCs, the objective of this study is to estimate variation in life cycle assessment (LCA) results when NMVOCs are considered individual emissions compared to grouped emissions and to compare midpoint and endpoint life cycle impact assessment (LCIA) methods. In general, the ReCiPe 2016 LCIA method estimated the highest impact from the composting process in comparison to IMPACT World+ and EF 3.0 for the impact categories of ozone formation, stratospheric ozone depletion, and particulate matter formation. For ReCiPe 2016 and IMPACT World+, the NMVOC emissions were not linked to human toxicity characterisation factors, meaning that the contribution from NMVOC towards human health risks in and around composting facilities could be underestimated. Using individual NMVOCs helps to additionally estimate the impacts of composting on freshwater ecotoxicity and human carcinogenic and non-carcinogenic toxicity potential. If ecotoxicity or toxicity issues are indicated, then LCA should be accompanied by suitable risk assessment measures for the respective life cycle stage.

Keywords: ReCiPe; IMPACT World+; environmental footprint; human toxicity; ozone depletion

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1. Introduction

Life cycle assessment (LCA) of solid waste management systems is complicated due to the inherent system dynamics and the availability of data [1]. Composting is a waste management practice that converts organic waste into a product that can be used safely and beneficially as a bio-fertiliser and soil amendment. Microbial activity in the composting process results in the degradation of organic matter into volatile compounds. Most studies focus on greenhouse gas (GHG) emissions, especially methane (CH_4) and nitrous oxide (N_2O). Other emissions include malodorous gases in the form of ammonia (NH_3), sulphur compounds, and volatile organic compounds (VOCs). Odours from composting plants are mainly associated with the emissions of NH_3 and terpenes, alcohols, ketones, sulphur compounds, amines, etc. Apart from ammonia, the others are often grouped together as VOCs [2,3]. CH_4 is treated separately from the other VOCs (which are then referred to as non-methane VOCs or NMVOCs). NMVOCs are mostly of biogenic origin and are mainly produced during the intensive composting phase [4]. The most important parameters affecting the rate of NMVOC emissions were aeration time and moisture content in the composted material. In general, a higher aeration rate had a strong effect on increasing NMVOC emissions, while the effect of moisture content depended on the individual VOC [5].

The impact of waste management on the environment and workers is recognised as a growing environmental and public health concern [6]. NMVOC emissions are an important issue, as emissions have been observed up to 800 m away from the composting facilities [7]. NMVOCs are known to cause damage to human health and the environment. Most industrial composting facilities are equipped with a state-of-the-art exhaust gas treatment system, which significantly reduces NMVOC emissions. Inside the composting facility, processes are generally automated, but during maintenance operations, workers may have to work in waste processing areas where there is an increased risk of exposure to NMVOCs. Biofilters are used in industrial composting facilities because of their ability to treat low concentrations of various pollutants, their cost-effectiveness, their ease of operation, and the absence of secondary contaminated waste streams [8]. In a biofilter, a contaminated/odorous gas stream passes through a biologically enriched layer of a filter material such as soil, wood chips, or mixed materials, followed by biodegradation of the adsorbed pollutants [9].

Measurements of NMVOCs emitted during composting have been carried out only in a few studies, mainly due to the measurement/monitoring costs involved [10,11]. NMVOCs have been reported either as grouped NMVOCs emitted [12], as concentrations of different functional groups of NMVOCs, or as individual VOC concentrations [10,13,14]. Among the studies that investigated NMVOCs individually, only a few discussed the human health aspects of these emissions [15,16].

A major limitation of using grouped NMVOCs is that only some environmental impacts, e.g., ozone formation potential (OFP), are considered, but others are not, e.g., ecotoxicity and human toxicity potential, in most life cycle impact assessment (LCIA) methods.

The inclusion of NMVOC emissions can be seen in the majority of studies focussing on the environmental aspects of composting (Table S3). A wide range of impact categories were investigated by LCA studies, most of which included climate change, acidification, eutrophication, ozone formation, and ozone depletion. However, human toxicity was only investigated in a few studies [17,18]. Even when human toxicity was assessed, NMVOCs from the composting process only contributed to this impact category in studies using the CML LCIA methodology [19]. For other commonly used impact assessment methods, such as ReCiPe 2016 and IMPACT World+, NMVOC emissions only affect the ozone formation potential. However, in Environmental Footprint (EF) 3.0, grouped NMVOC emissions affected additional impact categories. Therefore, depending on the chosen LCIA method, the magnitude of the environmental impact caused by NMVOCs may be misestimated. Furthermore, most LCA studies only considered NMVOCs as grouped emissions and not as individual emissions (Tables S3 and S4). When characterising the human health impacts of anthropogenic NMVOC emissions, two impact categories are relevant, namely the direct damages caused by single NMVOCs towards humans and ecotoxicity and the indirect damages caused by NMVOCs towards ozone formation [20]. The difficulty in choosing an LCIA method can be attributed to the scientific complexity of the models related to the different impact categories and the similarity between LCIA methods with identical impact categories that mask the variation in scientific models behind each category [21]. In fact, different LCIA methods may partially include some of the same impact categories, but they do not use the same scientific models. For example, ReCiPe 2016 calculates the impacts of ozone-causing substances using human ozone formation potential, whereas EF 3.0 uses photochemical ozone creation potential.

To enable a comprehensive assessment of relevant impact categories, NMVOC emission inventories need to be disaggregated at the substance level. NMVOC emissions are typically reported as a group rather than as species or speciation profiles, which are distributions of individual substances that make up NMVOC emissions from a given source. The occurrence and magnitude of individual substance emissions can vary considerably between the emission sources. Recognising the need to investigate the issues associated with NMVOCs in the composting process, the objective of this study is (1) to estimate variation in LCA results when NMVOCs are considered individual emissions compared to grouped emissions; (2) to investigate the influence of different LCIA methodologies on individual NMVOC emissions; and (3) to compare the endpoint methods ReCiPe and IMPACT World+.

2. Results

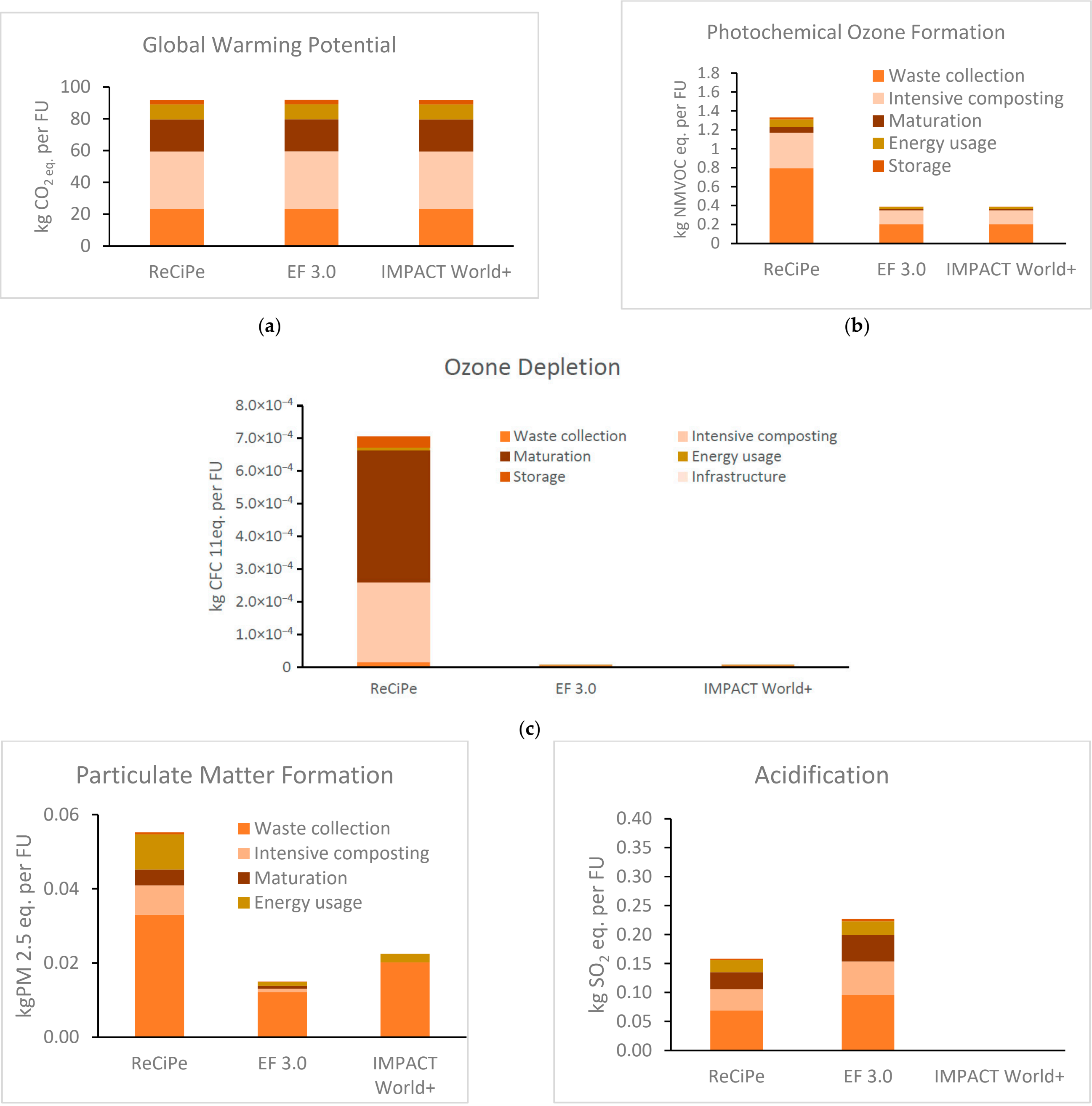
2.1. Influence of LCIA Method Selection on Overall Composting Emissions

The results from the LCA can be broadly divided into two sections: the first section consists of emissions released during biowaste composting, and the second one looks at the comparison of grouped and individual NMVOCs.

Additionally, environmental impacts associated with direct composting emissions were compared using three LCIA methodologies at the midpoint level and two at the endpoint level. For the impact categories of ozone creation, acidification potential, and particulate matter formation, unit conversion factors were applied to ensure comparability. There was an evident difference between the chosen LCIA approaches for all impact categories except for climate change (Figure 1). All three LCIA methods had nearly the same result for climate change; there was a slightly higher GWP of 0.17% for EF 3.0. This was due to a higher characterisation factor (CF) of 36.8 compared to 36 (for ReCiPe and IMPACT+) for fossil methane originating from background processes. For climate change, nearly 60% of total composting emissions were directly linked to intense composting and maturation, while 25% of emissions were due to the transportation of biowaste, and the remaining was due to energy used for the composting process.

ReCiPe 2016 showed the highest ozone formation potential; the respective impacts of EF 3.0 and IMPACT World+ were 76% lower. The biggest contributors to ozone formation were emissions directly connected to transportation, followed by emissions directly associated with composting. ReCiPe 2016 yielded a much larger estimate for ozone depletion than the other two LCIA methods because it considered dinitrogen monoxide in the impact category, whereas the other two LCIA methods neglected it. The largest contributor to particulate matter emissions was input material transportation, and the net impact was 82% and 62% lower for EF 3.0 and IMPACT World+, respectively, compared to ReCiPe 2016. Overall, ReCiPe 2016 higher particulate matter formation and ozone depletion can be attributed to the wider spectrum of emissions considered. EF 3.0 was estimated to have a 27% larger impact on acidification potential compared to ReCiPe 2016, but IMPACT World+ had a much lesser impact compared to other LCIA approaches.

Human health-related endpoint impact categories with a common unit of disability-adjusted life years (DALYs) were compared between ReCiPe 2016 and IMPACT World+ (Figure 2). When looking at the impact categories affected by direct composting emissions, climate change and the creation of fine particulate matter had the greatest endpoint impact on human health. In comparison to other endpoint impact categories, the contribution of ozone formation and ozone depletion was small. In contrast to ReCiPe 2016, the net effects of composting on human health when employing IMPACT World+ were about 22 times lower.



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

(**c**)

(**d**) (**e**)

Figure 1. Impact of composting on midpoint-level impact categories (**a**) ozone formation, (**b**) climate change, (**c**) ozone depletion, (**d**) particulate matter formation, and (**e**) terrestrial acidification assessed using the ReCiPe 2016, EF 3.0, and IMPACT World+ LCIA methodologies.

Figure 2. Selected midpoint impact categories (disability-adjusted life years) for ReCiPe 2016 and IMPACT World+.

2.2. *Influence of LCIA Method Selection on Overall Composting Emissions*

The magnitude of the impacts arising from individual NMVOC emissions in the respective impact categories varied depending on the substance coverage as well as the CFs used by the LCIA methods (Tables S1 and S2). The percentage change in overall composting impacts was determined in order to compare the effects of composting using either grouped or individual NMVOC emissions. Grouped NMVOC emissions were considered to be the default, and the changes from using individual emissions were calculated for the affected impact categories. A percentage reduction in overall impacts from considering NMVOC emissions as individuals would imply that there is an underestimation in impacts from using individual emissions. From the three impact categories compared, ozone formation and human carcinogenic toxicity had the most evident difference when considering the NMVOC emissions individually (Figure 3). There was a strong decrease of nearly 33% and 44% in ozone formation for both EF 3.0 and IMPACT World+, respectively. Only a minor reduction in overall ozone formation was seen when estimating impacts as individual emissions using ReCiPe 2016. For the impact categories of freshwater ecotoxicity, there was little difference between using individual versus grouped emissions for all three LCIA methods. For human non-carcinogenic toxicity, EF 3.0 showed a considerable variation of over 80% between individual and aggregated NMVOC, but RECIPE and IMPACT World+ showed only a minimal difference.

For the impact category ozone formation, the share of grouped NMVOC emissions contributed 79.8% and individual NMVOCs 1.1% when World Impact+ was used, while 10.7% of grouped NMVOC contributed and 8.7% of individual NMVOC emissions when ReCiPe2016 was used (Table 1). Looking at the share of NMVOCs in the total composting emissions, the grouped NMVOCs had a higher share compared to the individual NMVOCs. This was clearly seen for the impact category of ozone formation, where grouped NMVOCs had a share of 10, 33, and 80%, respectively, for ReCiPe 2016, EF 3.0, and IMPACT World+. The grouped NMVOCs had a significantly lower share of 9, 0.6, and 1.1% for the selected LCIA methodologies, respectively. The impact category freshwater ecotoxicity covered grouped NMVOC only for EF 3.0, but the individual NMVOCs were covered by all 3 selected impact assessment methods. Similarly, using EF 3.0, the grouped NMVOC emissions made up almost 84% of the total emissions, compared to 8.4% for the individual NMVOC.

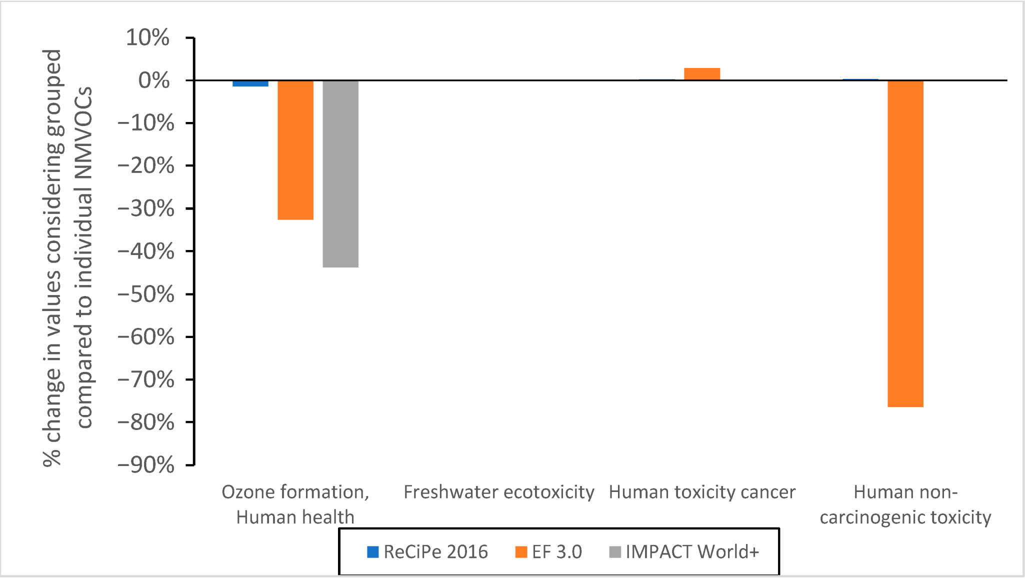


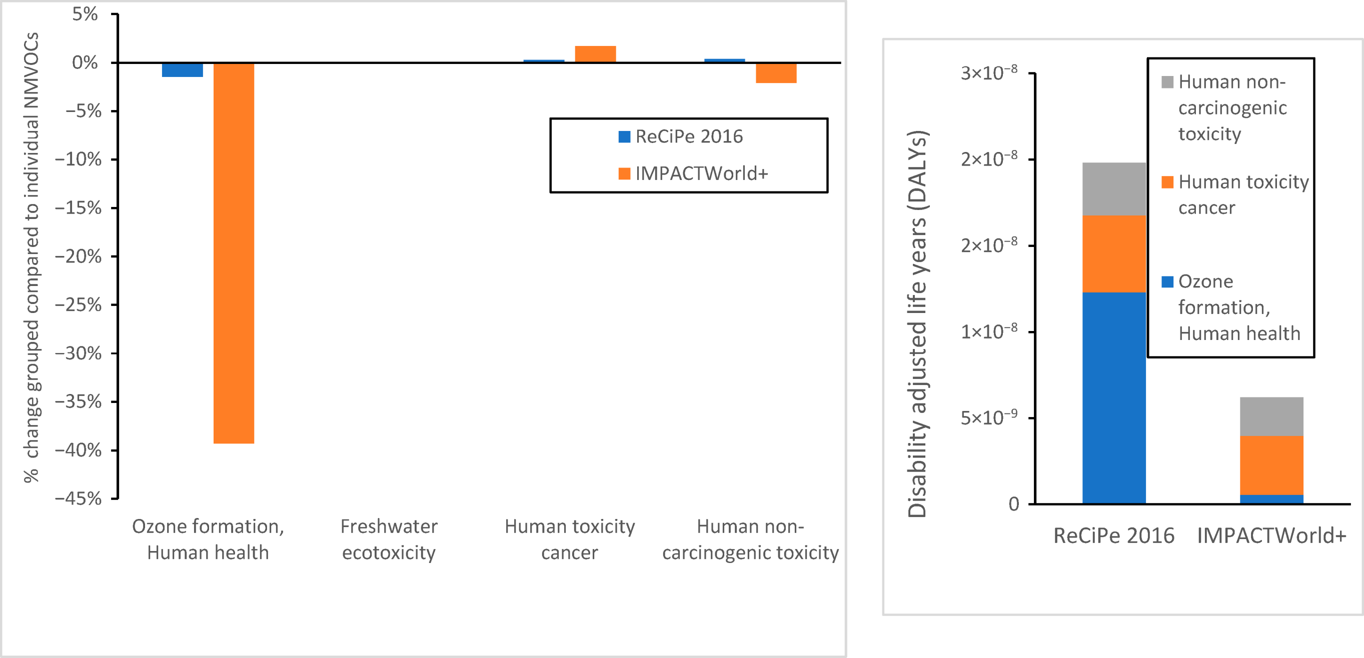
Figure 3. Contribution by each of the selected endpoint impact categories towards DALY (disability-adjusted life years) for ReCiPe 2016 and IMPACT World+ LCIA methods.

Table 1. Environmental impacts for composting for the impact categories affected by NMVOCs, the share of NMVOC emissions from the total impact when evaluating using grouped and individual emissions are also given.

		ReCiPe 2016 (H)		**EF 3.0**		**IMPACT World+**	
Ozone formation	Total composting emissions	kg NOx	1.5×10^{-1}	kg $NMVOC_{eq}$	2.6×10^{-1}	kg $NMVOC_{eq}$	1.1×10^{-1}
	Grouped NMVOC	kg NOx	1.6×10^{-1}	kg $NMVOC_{eq}$	8.8×10^{-1}	kg $NMVOC_{eq}$	8.8×10^{-1}
	% share of total		10.2%		33.2%		79.8%
	Individual NMVOC	kg NOx	1.4×10^{-1}	kg $NMVOC_{eq}$	1.6×10^{-1}	kg $NMVOC_{eq}$	1.2×10^{-1}
	% share of total		8.7%		0.6%		1.1%
Freshwater ecotoxicity	Total composting emissions	kg 1,4-Diclorobenzene (DCB)	2.3	kg CTUe	-1.0×10^{4}	kg CTUe	1.6×10^{5}
	Grouped NMVOC		×	kg CTUe	7.6×10^{-1}		×
	% share of total		×		0.0%		×
	Individual NMVOC	kg 1,4-DCB	6.6×10^{-7}	kg CTUe	2.0×10^{-3}	kg CTUe	5.5×10^{-14}
	% share of total		0.0%		0.0%		0.0%
Human toxicity, carcinogens	Total composting emissions	kg 1,4-DCB	4.8×10^{-1}	kg CTUh	8.1×10^{-9}	kg CTUh	5.9×10^{-7}
	Grouped NMVOC		×	kg CTUh	×		×
	% share of total		×		×		×
	Individual NMVOC	kg 1,4-DCB	1.4×10^{-3}	kg CTUh	2.4×10^{-10}	kg CTUh	3.0×10^{-10}
	% share of total		0.3%		2.9%		0.1%
Human toxicity, non-carcinogens	Total composting emissions	kg 1,4-DCB	3.5	kg CTUh	6.4×10^{-9}	kg CTUh	-1.3×10^{-6}
	Grouped NMVOC		×	kg CTUh	5.4×10^{-9}		×
	% share of total		×		84.8%		×
	Individual NMVOC	kg 1,4-DCB	1.3×10^{-2}	kg CTUh	5.4×10^{-10}	kg CTUh	8.3×10^{-10}
	% share of total		0.4%		8.5%		−0.1%

2.3. Endpoint Impact Categories: Considering Individual NMVOC vs. Grouped NMVOC

Evaluation at the endpoint level aided in determining the overall health effects of ozone formation and human toxicity. Results for endpoint impacts were similar to midpoint-level assessments when comparing the effect of composting using individual and grouped NMVOC emissions. The highest variation was seen for ozone formation assessed using IMPACT WORLD+, which implied an underestimation of the ozone formation impact (Figure 4a). ReCiPe 2016 showed 69% higher impacts compared to IMPACT World+. Individual NMVOC emissions accounted for roughly 13% of the impacts on ozone formation for ReCiPe 2016, compared to 35% for IMPACT World+. NMVOCs' effects on human toxicity were negligible, accounting for less than 1% of all harm to human health. Looking at the impact of only the individual emissions (Figure 4b), the human health impact is 70% lower for IMPACT World+ compared to ReCiPe.



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

Figure 4. (**a**) Comparison between grouped and individual NMVOC emissions used for assessing composting impacts for the endpoint impact categories of ozone formation, freshwater ecotoxicity, and human carcinogenic and non-carcinogenic toxicity. (**b**) Comparison of the human health impact calculated by individual NMVOC with ReCiPe and Impact World+.

3. Discussion

3.1. LCIA Method Comparison

During composting, N_2O and CH_4 emissions are the major contributors to climate change; hence, the characterisation factors (CFs) used for both of these emissions strongly influence the end results. Since all three LCIA methods were based on the IPCC's fifth assessment report [22], the CF used for biogenic methane emissions was the same for all three approaches at 34 kg $CO_{2eq.}$ However, the underlaying methodology behind the CFs is constantly evolving, and hence, a variation in results from using the newer methodology can be seen. EF 3.1, a revised version of EF 3.0, has a 20% lower CF for biogenic CH_4, i.e., 27 kg CO_{2eq} [23]. The lower CF for CH_4 in the later version of EF can be attributed to the 2021 IPCC report used compared to the 2013 version of the IPCC report used in EF 3.0 as well as ReCiPe 2016 and IMPACT World+. Hence, using the latest version of EF could result in estimating lower emissions from composting. The EF 3.1 was not investigated further in this study as the implementation of the method in the LCA software had data gaps with respect to relevant compounds.

For the impact category of ozone formation, EF 3.0 and IMPACT World+ use the same CFs (1 kg $NMVOC_{eq}$/kg substance) for NO_x, NO, NO_2, and grouped NMVOC, whereas for ReCiPe 2016, NO_x and NO emissions have a CF that is 5.5 and 8.5 times higher, respectively, compared to the grouped NMVOC. NO_x being a main emission from the transportation process as well as from the biofilter after intensive composting, its being assigned a lower CF resulted in an underestimation of the impact of composting. Although VOCs and NO_x are needed for ozone formation, the role played by each of the emissions varies depending on the geographical and meteorological conditions [24].

To characterise the impact of photochemical ozone formation on human health, the LOTOSEUROS model was used by EF 3.0 and IMPACT WORLD+ [25], whereas the ReCiPe 2016 method used the global source-receptor model TM5-FASST [26]. The underlying variation in the characterisation model used results in different CFs of NO_x and grouped NMVOC.

The ozone formation potential can contribute to human health and terrestrial ecosystems. Only human health was considered in this comparison because EF 3.0 and IMPACT WORLD+ consider only the human health-related impacts of ozone formation [27]. ReCiPe 2016 assesses the impact of ozone on terrestrial ecosystems as well, which is important in understanding the role of ozone and how its oxidative properties damage the photosynthetic organelles, leading to discolouration of the leaves followed by the withering of the plant.

Chlorofluorocarbons (CFCs) have been the major contributors to ozone depletion in past decades, and strict regulations have reduced their use [28]. However, N_2O emissions also contribute significantly to ozone depletion [29]. During the composting of biowaste, N_2O is formed directly from biowaste decomposition and indirectly due to the breakdown of NH_3 in the biofilter [30]. Hence, the exclusion of N_2O emissions in the estimation of stratospheric ozone depletion would compromise the benefit of using LCA, as an important quantifiable substance would be left out [31]. In the ReCiPe 2016 method, N_2O is considered for ozone depletion, whereas for EF 3.0 and IMPACT WORLD+, N_2O is not taken into account [32]. Although the CF for N_2O is substantially lower than that of other ozone depletion-causing substances, in this study, the overall ozone depletion increased by more than 90% when ReCiPe 2016 was used.

All three LCIA methods in this study use different versions of a stratospheric ozone depletion model developed by the World Meteorological Organisation (WMO). Even though EF 3.0 and IMPACT World+ are also based on WMO (Table 1), the reason for excluding N_2O for ozone depletion is not clear [33].

Two of the most common substances causing acidification in terrestrial ecosystems, NH_3 and NO_x, were direct emissions from the composting process. Focussing on acidification potential, CFs for NH_3 and NO_x for the IMPACT World+ method were the lowest among the three LCIAs. CFs for ReCiPe 2016 and IMPACT World+ are based on changes in acid deposition following changes in air emissions of NO_x and NH_3 and were calculated with the GEOS-Chem model [34]. Even though ReCiPe 2016 and IMPACT World+ were based on the same characterisation model, the acidification impact was estimated at a much higher spatial resolution of $2° \times 2.5°$ (latitude × longitude) for IMPACT World+ as compared to ReCiPe 2016 [27]. Hence, the results for acidification when using IMPACT World+ must be interpreted considering the spatial resolution. For EF 3.0, the acidifying potency of a substance was modelled as the accumulated exceedance above the critical load in terrestrial and freshwater ecosystems to which acidifying substances deposit [35,36].

Particulate matter is classified as primary when it is emitted directly and secondary when it originates from the atmospheric oxidation of primary gases such as nitrogen oxides and ammonia into ammonium nitrates [37]. In terms of substance coverage, ReCiPe 2016 and EF 3.0 had CFs for NH_3 and nitrogen oxides, which were the main composting emissions that contributed to particulate matter formation. IMPACT World+ did not consider the contribution of NH_3 emissions towards particulate matter (PM) formation. NH_3 was a substantial contributor to the fine particulate matter ($PM_{2.5}$) fraction in Europe, where it caused almost 50% of all $PM_{2.5}$ [38]. Hence, excluding NH_3 would result in an underestimation of $PM_{2.5}$, which was seen in the case using IMPACT World+. In general, the CFs for NO_x were almost 11 and 15 times higher for ReCiPe 2016 compared to IMPACT World+ and EF 3.0, respectively. CFs for IMPACT World+ were modelled using factors derived from [37,39]. However, for ReCiPe 2016, the change in ambient concentration of $PM_{2.5}$ after the emission of a precursor, i.e., NH_3, NO_x, SO_2, and primary $PM_{2.5}$, was estimated using the TM5-FASST model [26]. For EF 3.0, the method recommended by UNEP was used, and PM was estimated using disease incidences.

3.2. Midpoint Impact Categories: Considering Individual NMVOC vs. Grouped NMVOC

The main difference in considering NMVOC as individual emissions was the broader range of impact categories affected. Grouped NMVOC emissions contribute to ozone formation in all considered LCIA methods. Only EF 3.0 considers their impact on freshwater ecotoxicity and non-carcinogenic human toxicity [40]. Looking at the impact category of ozone formation, the formation of ozone at the ground level of the atmosphere was caused by NO_x and NMVOCs in the presence of sunlight. Ozone is a health hazard to humans because it can inflame the airways and damage the lungs [41]. Hence, considering individual NMVOC emissions could aid in better quantification of the ozone formation potential. Between the LCIA methods, the ReCiPe 2016 method had a lower difference between individual and grouped NMVOCs compared to EF 3.0 and IMPACT World+. This is attributed mainly to the substance coverage. Looking at the overall substance coverage for the impact category of ozone formation, ReCiPe 2016 had the highest coverage with 134 substances, compared to 65 in EF 3.0 and 104 in IMPACT World+. When looking at the individual NMVOC emissions used to calculate the ozone formation, the ReCiPe 2016 method covered nine ozone-forming substances compared to EF 3.0 and IMPACT World+, which covered only five and four substances, respectively. ReCiPe 2016 covered alpha and beta-pinene in addition to the other LCIA methods. Alpha and beta-pinene are important contributors to ozone formation [42], hence their omission from EF 3.0 and IMPACT World+ results in the underestimation of the ozone formation potential.

Additionally, the CFs for the individual emissions varied between ReCiPe 2016, EF 3.0, and IMPACT World+. The CFs for EF 3.0 and IMPACT World+ were almost 11% lower for decane and up to 139% higher for styrene in comparison to ReCiPe 2016. In a similar comparison between the older versions of the three methodologies, for ozone formation, substance coverage was the major differentiating factor, followed by CFs, and, to a certain extent, the errors in the software used also played a minor role [43]. Across multiple studies, limonene was found to occur in one of the highest concentrations during the composting of biowastes [10]. Similar to other NMVOCs, limonene also contributes to ozone formation through photochemical reactions [44]. However, only the ReCiPe 2016 method accounts for the ozone formation impacts of limonene. The inclusion of limonene, along with its high concentration and significant characterisation factor, contributed to the elevated impacts observed when individually assessing NMVOC emissions using ReCiPe 2016.

Looking at the impact category of freshwater ecotoxicity, all substances except dimethyl disulphide were covered by all three LCIA methods. Hence, the CFs used by the respective methods were the reason for the variation in the NMVOC emissions between the LCIA methods. The CF for pyridine was the highest for all three LCIA methods compared to other substances, which is mainly because of the high ecotoxicity and human toxicity potential of pyridine [45]. Similar to ozone formation, ReCiPe 2016 had the highest impact when estimating the individual NMVOC emissions for freshwater ecotoxicity as well. The additional coverage of pinene and xylene substances was the reason for ReCiPe 2016 having the highest impact on ozone formation. In comparison to EF 3.0 and IMPACT World+, ReCiPe 2016 had higher ecotoxicity CFs for all substances except for alpha-/beta-pinene and limonene. The differences mainly originate from discrepancies in approaches to characterisation modelling [43]. The ReCiPe 2016 method is based on the USES-LCA 2.0 model, whereas the USEtox model is used for EF 3.0 and IMPACT World+ [46]. Looking at the human toxicity impact categories, human carcinogenic and non-carcinogenic toxicity, the substance coverage was the same for all LCIA methods. The NMVOC substances classified as having carcinogenic and non-carcinogenic toxicity were styrene, pyridine, and toluene. The CF for pyridine and toluene in RECIPE 2016 was almost 24% and 100%, respectively, higher in comparison to EF 3.0 and IMPACT World+. However, for styrene, ReCiPe 2016 had a comparatively lower CF. Even though the inclusion of individual NMVOC emissions only increased the total human toxicity potential from composting by less than 1%, using only grouped NMVOC emissions completely excluded the impact on human toxicity by all the LCIA methods. Though dimethyl disulphide affected the impact categories of freshwater ecotoxicity and non-carcinogenic human toxicity and was covered in EF 3.0, CFs for the air emissions of the substance were not covered by the software programme.

There are currently multiple limitations in the substance coverage of LCIA methodologies. For example, the USEtox model, which has one of the largest databases of CFs for the assessment of toxicity effects in LCA studies, includes only a few hundred substances relevant to human toxicity, whereas the European Inventory of Existing Commercial Chemical Substances lists more than 100,000 substances identified by industry as potentially of commercial use. Therefore, the development of generic CFs may require frequent updates, i.e., as new CFs for individual NMVOCs are generated, there is a significant risk that they will overlook the effects of substances with a significant contribution to human toxicity and lead to biassed impact scores. In USEtox, CFs for human toxicity span 12 orders of magnitude [47]. Therefore, the distributions of individual NMVOC emissions have a strong influence on the human toxicity impact scores. As toxic emissions are highly source-specific, significant biases are more likely to occur when averaging over significant source contributors. Therefore, although a few attempts have been made in the past [48], the use of generic CFs differentiated by sector for human toxicity assessment is not advocated.

3.3. Endpoint Impact Categories: Considering Individual NMVOC vs. Grouped NMVOC

The availability of characterisation factors (CFs) for endpoint-level assessment was limited to ReCiPe 2016 and IMPACT World+; hence, EF 3.0 was excluded from the following analysis. The consistency in substance coverage for individual NMVOCs between midpoint and endpoint assessments across the compared LCIA methods remained the same as for the midpoint assessment. Analysis of DALYs attributed to individual NMVOC emissions revealed higher impacts estimated by ReCiPe 2016 compared to IMPACT World+, consistent with findings at the midpoint level. This disparity could be largely attributed to the broader substance coverage provided by ReCiPe 2016.

The observed lower impacts on DALYs from ozone formation caused by individual NMVOCs compared to those from human toxicity are in line with previous findings by [20]. Spatial variability in NMVOC emissions warranted consideration, as substantial variations across countries may amplify damages in certain regions. Photolytic processes influencing ozone formation, contingent upon factors such as time horizon, weather conditions, and geographical area, necessitated a comprehensive assessment encompassing both CFs for individual emissions and spatial/temporal factors.

Diverse methodologies exist for assessing the reactivity of NMVOCs, underscoring the complexity inherent in such evaluations. Additionally, consistent consideration of indoor emissions via dedicated CFs is emphasised in the literature [49]. To enhance the accuracy of human health impact assessments related to NMVOCs, periodic updates to CFs reflecting advancements in LCIA methodologies, along with spatial differentiation accounting for population density in recipient regions, are warranted [20].

4. Materials and Methods

4.1. Investigated Composting Systems

In Germany, kitchen and garden waste is usually disposed of in the same organic bins and collected weekly by municipal refuse vehicles in urban areas. The containers are emptied weekly in densely populated areas and at biweekly intervals in less populated areas [50]. At the same time, public green-cut waste from parks and roadsides and larger amounts of private garden waste are delivered separately to the composting facility. An average transport distance of 21.9 km was assumed for the transportation of biowastes during the collection and delivery to the composting facility [51]. Upon arrival at the plant, the input material goes through the pre-processing steps of magnetic separation, screening, and crushing. The pre-treated waste is mixed together to achieve a textural consistency for an ideal composting process, which requires a moisture content in the 45–65% range [52]. A default mixing ratio of 70% of biowaste and 30% of green-cut by weight was assumed in the modelled system.

The technology used for the composting process affects the emissions during decomposition and also the final compost products [53]. Enclosed composting (EC), partially enclosed composting (PEC), and open composting (OC) are the most commonly used industrial composting technologies [54].

PEC uses intensive decomposition that is assumed to take place in an enclosed environment, with the exhaust gases treated using a biofilter. The input material is laid in windrows. For intensive composting, the material is turned in weekly, with an average composting time of three weeks [55]. After the intensive composting stage, the product is referred to as fresh compost and still contains degradable organic matter and can be further matured. The maturation stage takes place in an open environment over a period of 10 weeks. The turning frequency is every two weeks and is carried out with diesel-powered turning vehicles. The product obtained is classified as mature compost (MSC) with a decomposition degree of 4 or 5 and can be used in horticulture [56]. Similarly, MSC can be used as a growing media compound, replacing peat and fertiliser.

4.2. Goal and Scope

The goal of this study was to compare LCIA results due to NMVOC emissions. NMVOCs were assessed as grouped and individual emissions using three life cycle impact assessment (LCIA) methods, namely EF3.0, RECIPE, and IMPACT World+. The variation in LCA results of the composting system from those LCIA methods was investigated at the midpoint and endpoint impact levels, as well as the influence of single scores on grouped and individual NMVOCs.

4.3. Life-Cycle Inventory

Emissions occur at different stages of the composting process. However, the intensity of these emissions varies depending on the composition of the input material and the process parameters at each stage. To estimate emissions of CH_4, N_2O, and NH_3 from the composting process, country-specific emission factors related to the input material (biowaste and green-cut waste) and the type of composting process were used. The emission factors for emissions occurring at each composting stage were taken from UBA [23]. In addition, there were emissions from the operational activities during the composting process, which were mainly caused by upstream emissions from the energy production processes. With the exception of NO_x, all emissions occurred directly from the composting process. NOx emissions occur in the biofilter during the breakdown of NH_3 [30]. The CO_2 emissions arising from composting were considered biogenic.

4.4. Life Cycle Impact Assessment

Environmental impacts are calculated as the product sum of emissions multiplied by their respective characterisation factor (CF). A CF denotes an elementary flow's quantity-based contribution to a specific impact category. The CFs are estimated using scientifically competent models of the environmental mechanism that depict the cause-and-effect chain of elementary flows contributing to an impact category (Table 2).

Table 2. Underlaying models were used for CF estimation for the impact categories considered for the comparison between the LCIA methods.

	ReCiPe 2016	**EF 3.0**	**IMPACT World+**
Climate change	IPCC AR5 [23]	IPCC AR5 [23]	IPCC AR5 [23]
Acidification potential	GEOS-Chem [57]	[35,36]	GEOS-Chem [33]
Ozone depletion potential	WMO 2011 [57]	WMO 2014 [33]	WMO 2014 [33]
Ozone formation potential	TM5-FASST [26]	LOTOSEUROS [25]	LOTOSEUROS [25]
Particulate matter formation	TM5-FASST [26]	UNEP recommendations	[37,39]

ReCiPe 2016 (H), EF 3.0, and IMPACT World+ are compared in order to identify variations in environmental impacts caused by NMVOCs [27,32,40]. The impact categories for the study elaborated in Table 1 were selected as the emissions of CH_4, N_2O, NH_3, NO_x, and NMVOC from foreground activities during the various stages of composting had a direct impact on these impact categories. The comparison between grouped and individual emissions was also considered as the impact categories that were impacted by individual NMVOC emissions, including ozone production, freshwater ecotoxicity, and the ability to create carcinogens and non-carcinogens in humans (Table 3).

Table 3. Impact categories in the ReCiPe 2016, EF 3.0, and IMPACT World+ LCIA methods affected by NMVOC emissions.

	ReCiPe 2016	**EF 3.0**	**IMPACT World+**
Ozone formation	kg NOx eq.	kg NMVOC eq.	kg NMVOC eq.
Freshwater ecotoxicity	kg 1,4-DCB	kg CTUe	kg CTUe
Human toxicity, carcinogens	kg 1,4-DCB	kg CTUh	kg CTUh
Human toxicity, non-carcinogens	kg 1,4-DCB	kg CTUh	kg CTUh

ReCiPe 2016, EF 3.0, and IMPACT World+ LCIA were used to analyse the composting system at the midpoint level. Impact categories influenced by NMVOCs encompassed the ozone formation potential (OFP), human toxicity potential (HTP), and freshwater ecotoxicity (FETP). This study is carried out using embedded features of OpenLCA v.1.10.3, which was used to model the system. Ecoinvent 3.9 provided the datasets for the background processes [58]. An endpoint-level comparison of the human health-related impact, which was assessed using disability-adjusted life years (DALYs), was conducted to determine the total impact on human health.

4.5. Analysis of NMVOC Emissions

Data on the various NMVOC emissions during the composting of municipal solid waste were gathered from scientific literature [13,14,59]. For quantifying the individual NMVOC emissions, emission factors estimated by [10] were chosen from an extensive list of studies that focussed on individual NMVOC emissions from composting (Tables S4 and S5). The composition of NMVOCs depends on the input material and composting time; the list of individual NMVOCs used in this study is shown in Table 4. The selection of the NMVOCs was based on the studies covering NMVOCs during composting (Table S5). The similarity in the waste being composted and the composting procedure were used as selection criteria for the 10 NMVOCs investigated in this study.

Table 4. List of individual NMVOC emissions.

NMVOC Emissions	
Styrene	Dimethyl disulfide
2-Pentanone	Pyridine
Alpha-pinene	Toluene
Beta-pinene	Xylene
Limonene	Decane

A three-step approach developed by [60] to analyse the LCIA methods in the context of decision-making was used in this study (Figure S1). The first step involves the evaluation of the scope and detail of the characterisation models using the respective LCIA methods. In the second step, the elementary flows covered by each method were determined, and the CFs associated with the flows were identified. Depending on the coverage of elementary flows in the LCIA methods, the third step involved identifying the significance of the potential impact of the elementary flows.

In this study, the above approach was adapted to understand how the LCIA methods evaluate the impacts of individual NMVOC emissions. In the first step, the impact categories affected by individual NMVOC emissions were identified, and the respective cause-and-effect chains were analysed. In the second step, the elementary flows of individual NMVOC emissions and the coverage by the respective LCIA methods were identified (Tables S1 and S2). Following the identification of the NMVOC elementary flows that were included or neglected by the respective LCIA methods, the characterisation factors connected to the LCIA methodologies' elementary flows were listed, and the overview can be found in Tables S1 and S2.

Since the impact category for ozone formation comprises different reference units for each LCIA method, an approach proposed by [61] was used to derive common reference units (Equation (1)). A study comparing different LCIA methods by [43] used the same approach.

$$\mathrm{ISj} = \mathrm{ISi} \times \mathrm{UCFi} \rightarrow \mathrm{j} \tag{1}$$

where ISj is the impact score expressed in a unit of a new reference substance for a given impact category, ISi is the impact score in old units for that impact category, and unit conversion factors (UCFi → j) is the method- and impact category-specific unit conversion factor, defined as the reciprocal of a characterisation factor for the new reference substance (Equation (2)).

$$\mathrm{UCFi} \rightarrow \mathrm{j} = 1/\mathrm{Cfi} \tag{2}$$

where CFi is the characterisation factor for the new reference substance, expressed in original units i. For the comparison between the LCIA methods, the results for the impact categories were converted into a common reference unit using UCFs (Tables S1 and S2).

ReCiPe 2016 and the other LCIA methods employed in this study had different reference units for ozone formation. ReCiPe 2016 calculated effects based on the human ozone formation potential (HOFP), while EF 3.0 and IMPACT World+ took the photochemical ozone creation potential (POCP) into account [26]. While both HOFP and POFP relate to the formation of ozone, they approach the concept from different perspectives. HOFP focuses on emissions caused, considering the specific mixture and concentrations of pollutants released and their role in ozone formation. POCP, on the other hand, examines the intrinsic reactivity of individual substances and their ability to undergo photochemical reactions that lead to ozone formation [32]. Hence, to make the LCIA methods comparable, POCP is derived from HOFP for ReCiPe using Equation (3) defined by [32].

$$\mathrm{POCP_x} = \frac{\mathrm{POCP_{NMVOC}}}{\mathrm{HOFP_{NMVOC}}} \times \mathrm{HOFP_x} \tag{3}$$

The reduction in emissions utilising biofilters was also evaluated using a disaggregated technique for the analysis of both individual and aggregated NMVOC emissions (Table S6). When looking at grouped NMVOC emissions, a high removal efficiency of up to 97% was found [12], although the removal efficiencies for individual NMVOC differed. For the most commonly occurring compound, e.g., toluene, a removal efficiency of up to 82% was reported, and for alpha-pinene, it was less than 64% [62]. Since more than 100 VOCs were emitted during the composting process, selecting an appropriate biofilter system targeting all the compounds still remains limited [63].

5. Conclusions

This study helps in the decision-making process of an LCA practitioner who has performed an inventory analysis and needs to decide which LCIA methodology to use in order to assess composting processes. Furthermore, the consequences of estimating NMVOC emissions as grouped and individual emissions are also assessed. Substance coverage and the characterisation factors used for the emissions were the differentiating factors between the LCIA methods. This study also shows that after conversion to a common metric, discrepancies in impact scores between ReCiPe 2016, EF 3.0, and IMPACT World+ can be large for certain impact categories. In general, the ReCiPe 2016 LCIA method estimated the highest impact from the composting process in comparison to IMPACT World+ and EF 3.0 for the impact categories of ozone formation, stratospheric ozone depletion, and particulate matter formation. Hence, it can be deduced that the characterisation model used for ReCiPe 2016 had higher CFs for composting-related emissions. In the assessment of climate change-related impacts, all three LCIA methods had nearly the same estimation of impacts.

For ReCiPe 2016 and IMPACT World+, the NMVOC emissions were not linked to human toxicity characterisation factors, meaning that the contribution from NMVOC towards human health impacts was underrepresented in the calculated impact. As a consequence, the human health risks related to NMVOC emissions in and around composting facilities could be underestimated. Using individual instead of grouped NMVOCs could overcome this underrepresentation to a certain extent, as ReCiPe 2016 and IMPACT World+ methods contain CFs for individual NMVOCs for human toxicity and freshwater ecotoxicity. In general, using individual NMVOCs helps to additionally estimate the impacts of composting on freshwater ecotoxicity and human carcinogenic and non-carcinogenic toxicity potential. In general, LCA is a powerful environmental assessment tool; however, the ecotoxicity and toxicity-related impact categories carry a considerable level of uncertainty. Therefore, if ecotoxicity or toxicity issues are indicated, then LCA should be accompanied by suitable risk assessment measures for the respective life cycle stage.

In this study, only the characterisation step was in focus. However, the normalisation phase, with its differences in normalisation references between the methodologies as well as the weighting step, is an extra potential source of difference. Despite the presence of emission classes categorised by low and high population densities and indoor impacts, the CFs available in LCIA methods for these classes remained largely the same. Thus, this highlights an area for potential refinement and development in future assessments to better differentiate between the emission classes.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/recycling9030035/s1. Figure S1: Overview of the three-step approach to evaluate LCIA methods developed by Bach und Finkbeiner (2017); Table S1: Characterisation factor used for by the LCIA methods for individual NMVOCs for the impact categories ozone formation and freshwater ecotoxicity, Table S2: Characterisation factor used for by the LCIA methods for individual NMVOCs for the impact categories ozone formation and freshwater eco, Table S3: List of LCA studies investigating VOC emissions from composting processes toxicity, Table S4: List of LCA studies investigating individual NMVOC emissions arising from composting. The individual VOC numbers are elaborated in Table S5, Table S5: List of NMVOC emissions arising from composting of MSW. Table S6: Amount of NMVOC compounds before and after biofiltration (kg/t compost produced).

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