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Assessing the potential of co-composting rose waste as a sustainable waste management strategy: Nutrient availability and disease control

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ABSTRACT

The current limited usage of rose waste makes rose cultivation far from a sustainable circular industry. Unfavorable properties of horticultural waste such as the high lignin content of stems and high polyphenol levels in both flowers and leaves makes it difficult to re-use. These traits hamper an effective composting process and so far little studies have focused on optimizing this process. The aim of this study was to investigate the potential of (co-)composting rose waste with other on-farm available green wastes (tomato and kalanchoe) or mature rose compost to obtain an improved compost with high fertilizing capacity. In a small-scale composting system the evolution of five mixtures was closely monitored in terms of their physico-chemical parameters. The *in-vitro* disease suppressive capacity of mature rose compost was assessed. All mixtures resulted in stable and mature compost after six months showing industry standard suitable macro- and micro-nutrient concentrations. The matured compost showed a C/N below 10, a strong decrease in polyphenols of ≥70% and a good fertilizing capacity with an increase in cation exchange capacity since the start of ≥100%. These results demonstrate that the ligneous character of rose waste is not preventing an effective composting process. However, an increased duration of the maturation phase might be favored for optimal results. The addition of mature compost accelerated the composting process as shown by significantly increases in OM degradation rates. For the first time a high disease suppressive capacity against several common rose pathogens was shown for mature rose compost. Overall, this study showed the potential of (co-)composting rose waste as sustainable waste management strategy to further improve the circular economy waste-based objectives of the horticultural sector.

1. Introduction

Flower cultivation is a crucial part of the Kenyan economy with a contribution of 70% of the total value of horticultural exports in 2017 (Adeleye and Esposito, 2018). Waste management within this sector has not yet received the full attention it deserves. Rose production generates large amounts of green waste through crop maintenance, rejected produce and grading (Idrovo-Novillo et al., 2018). This can average to 50 kg ha^{-1} d^{-1}. For a mid-scale rose farm of 40 ha, this equates to over 730 t y^{-1} of green waste, which makes it an interesting amount for composting. Current common practices of green waste management include incineration or landfilling, both posing negative ecological effects to the environment (Lim et al., 2016; Awasthi et al., 2020). The environmental impact of flower cultivation raised considerable concerns over the last decades, specifically within densely cultivated cut-flower-producing regions like Naivasha in Kenya (Kuiper and Gemählich, 2017). Recycling rose waste within the production cycle helps to lower the environmental impact and reduce synthetic fertilizer demand. Recycling green waste via composting has recently regained attention as promising waste management practice but more research is needed prior to large-scale implementation within flower cultivation (Case et al., 2017; Idrovo-Novillo et al., 2019; Dutta & Kumar, 2021).

Composting is defined as the controlled, incomplete aerobic degradation by microorganisms that transform organic matter (OM) into a biologically stable humus-like substrate called compost (Bernal et al., 2017; Pergola et al., 2018; Ruiz et al., 2020). Composts can be successfully applied to the soil, to (1) recover degraded soils, to (2) maintain/increase soil fertility *sensu lato*, to (3) exert plant pathogen suppression and to (4) sequester C into the soil (Bernal et al., 2017; Milinković et al., 2019).

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Rose plant material has a large potential for recycling since it has a low pH and high OM content, as well as significant concentrations of nutrients like N, K, Ca, Mg and Fe. These nutrients are mainly located in the leaves of the roses (Idrovo-Novillo et al., 2018). High moisture levels around 66%, a low C/N of approximately 21, high phenolic acids and lignin levels characteristic for roses might hamper the composting process. (Idrovo-Novillo et al., 2018). The latter might hinder both successful initiation as well as the subsequent composting process due to limited access for decomposers and complex molecular structure (Min et al., 2015; Bernal et al., 2017). Due to the prevalent usage of pesticides in the sector, the potential accumulation of pesticides residues in mature compost is a concern (Silva et al., 2019).

To improve start-up conditions and facilitate the composting process, co-composting with other types of organic wastes is often advised (Meghvansi and Varma, 2020). These organic wastes range from manure, for the addition of desired microorganisms and readily available C, to sawdust to optimize the C/N or straw which serves as structuring material (Bernal et al., 2017; Idrovo-Novillo et al., 2018; Pergola et al., 2018; Sharma et al., 2018; Ruiz et al., 2020). These co-composting materials make up a relatively large part of the total fresh weight (15–50%). This adds up quickly with the large amounts of green waste produced in the horticultural sector (Idrovo-Novillo et al., 2018; Sharma et al., 2018). These co-composting materials are valuable in themselves and rarely locally available. For this study rose waste was (co-)composted with locally available green wastes or matured compost to evaluate the potential for economically low-cost (co-)composting.

Compost can exert natural suppressiveness of soil-born plant pathogens (De Corato, 2021). The extend of suppression is largely depended on the interplay between specific diseases and the microorganism community present in the compost (Pane et al., 2013; De Corato, 2021). Composts from various origins have successfully been used to suppress diseases common in rose farming: *Fusarium, Phytophthora* and *Agrobacterium* (Cotxarrera et al., 2002; Blaya et al., 2013; De Corato et al., 2019; Milinković et al., 2019). So far no studies on potential disease suppressive capacities of rose waste composts have been conducted.

The novelty of this research was to study the potential of recycling rose waste via (co-) composting as a regional sustainable and economical viable waste management strategy. The objective was to increase the understanding of composting lignocellulosic rose waste, which will help with the implementation of composting practices within Kenyan rose production and thereby reduce its negative ecological impact. This study compared the performance of composting (1) solely rose waste (2) with the addition of different green wastes, or with (3) the addition of mature rose compost. Furthermore, (4) the effect of the leaf-to-stem ratio on the process was investigated. Finally, the ability of mature rose compost to exert plant pathogen suppression against common rose diseases was tested. Due to the similar characteristics of green wastes, limited differential effects of the additions were hypothesized. For the addition of mature compost and the alteration in leaf-to-stem ratio, it was hypothesized that OM degradation would be enhanced and thus an accelerated process was expected.

2. Materials and methods

2.1. Starting materials

Green wastes for the initial characterization of the starting materials and the mature compost were collected at Bilashaka Flowers Ltd. close to Naivasha in Kenya. These wastes are a significant waste stream at the company. The mature compost consisted mainly of rose waste (85%) mixed with tomato- and pepper plants, kalanchoe, and hay. It was >1 y old and turned at least four times during the active phase. Table 1 shows the initial characteristics of the different starting materials. Measurements were conducted in duplicate and analytical methods are explained in 2.3.

Rose waste for the composting experiment was collected from the distribution center of Bilashaka Flowers Ltd. in the Netherlands. Approximately 200 kg of rose waste was divided in flowers, stems and leaves and subsequently mixed again at fixed ratios to ensure homogeneity among treatments and replicates. Co-composting green wastes for the experiment were chosen based on on-site availability at the rose farm in Kenya. Due to logistical reasons with transportation because of the Covid-19 pandemic these wastes were collected, respectively from a tomato and kalanchoe farm, in the Netherlands. These farms cultivate genetically the same species on the same substrate as the materials previously collected the rose farm in Kenya. Mature compost was obtained from Kenya as described above. All materials were cut <5 cm prior to composting (Fig. 1).

Table 1
Physicochemical characterization and nutrient contents of the green waste starting materials on a dry weight basis: rose flowers (Rflower), rose stems (Rstem), rose leaves (Rleaf), tomato (Tom), kalanchoe (Kal) and mature compost (Com). Heavy metal contents of the starting materials can be found in table A1.

	Starting materials[a]					
	Rflower	Rstem	Rleaf	Tom	Kal	Com
Characteristic						
Moisture content (%)	86	78	75	86	94	54
pH	5.2	5.4	5.6	5.9	5.9	7.3
EC (dS m^{-1})	2.6	2.0	2.9	7.9	8.6	1.5
OM (%)	94.6	95.7	90.2	80.7	79.9	25.5
C/N	16.8	33.1	13.5	9.5	10.0	7.7
DOC[b] (mg g^{-1})	13.9	6.4	7.4	4.4	9.9	3.0
Phenols (g EGA kg^{-1})	52.5	8.6	23.4	8.0	12.2	0.1
Macro-nutrients (g kg^{-1})						
P	2.6	2.0	2.2	6.9	3.6	4.5
Na	0.1	0.8	0.1	6.1	0.7	2.9
K	22.0	16.2	25.3	38.2	55.7	13.5
Ca	3.7	4.5	18.1	30.2	40.8	20.7
Mg	2.2	1.7	3.6	10.2	7.4	5.3
Micro-nutrients (mg kg^{-1})						
Fe	66.7	50.2	193.0	146.9	142.7	12828.8
Mn	40.7	25.4	176.8	458.1	66.2	654.0
Cu	7.1	10.9	8.2	195.2	18.4	21.6
Zn	33.6	39.1	126.3	66.6	78.0	174.5

[a] mean, dry weight basis, n = 2.
[b] DOC Dissolved Organic Carbon.

2.2. Composting process

Five treatments of rose waste with various additives were prepared in triplicate, resulting in a total of 15 mixtures which were composted for 181 days. One treatment contained solely rose waste (R), for the other treatments either tomato (T), kalanchoe (K) or mature compost with different leaf-to-stem ratios (C and CL) was added to the rose waste at 20% fresh weight basis (total 6 kg, Table 2). The composite rose waste, on fresh weight basis, consisted of 20% flowers, 50% stem and 30% leaves. For the CL mixture the stem and leaf percentages were exchanged. The R, T & K mixtures will be indicated as green waste (GW-) mixtures throughout this text and the C and CL mixtures as C-mixtures. Characteristics of the initial composition of the five mixtures were measured on day zero of the incubation experiment and can be found in table A2.

The first two months of the composting experiment were performed in 30 L buckets with lids, which were modified with holes for aeration (Manu et al., 2017). Hereafter the compost was transferred to 7.5 L buckets due to reduction in volume. The 30 L buckets were provided with a total of 70 holes of 8 mm to facilitate air flow, four layers at an even spacing and five holes in both the bottom and lid. The 7.5 L buckets were provided with proportionally less holes. Volume reduction was regularly monitored during the whole experiment. The first three months of the experiment were conducted in a climate room at 30 °C and relative humidity of 70%. After these months the compost was moved to a greenhouse for further curing (avg 24 °C) due to limited availability of

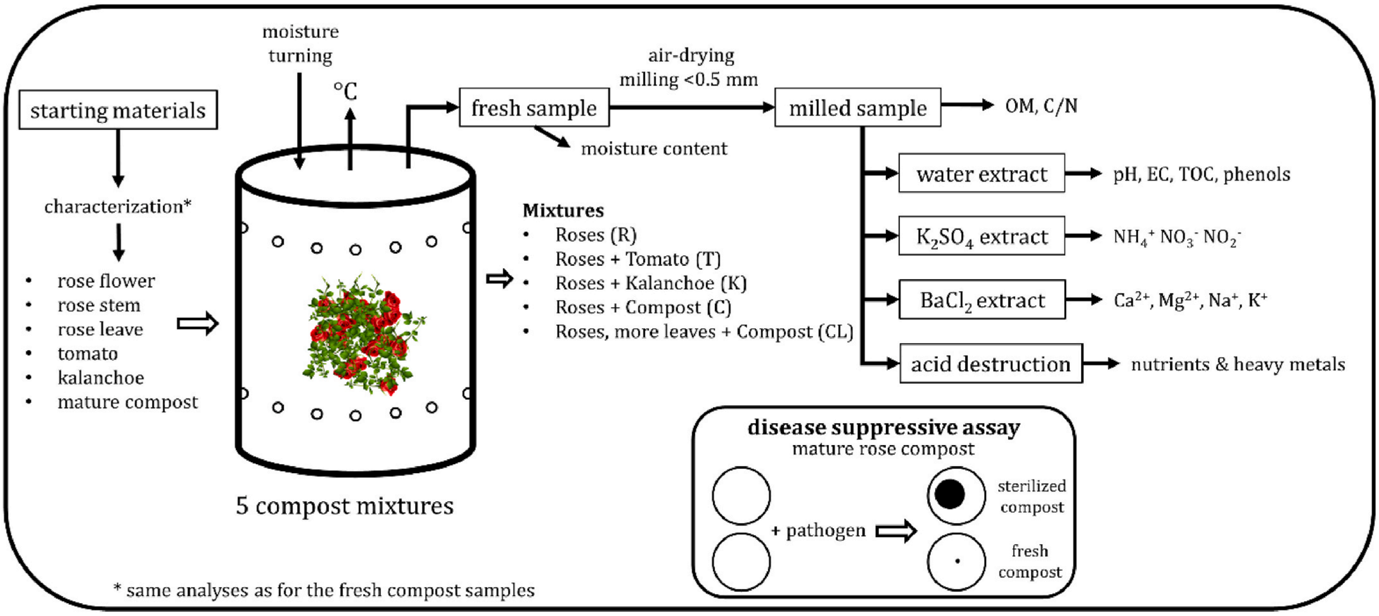

Fig. 1. Schematic overview of the experimental set-up and laboratory analyses conducted.

Table 2
Green waste mixture ratios of the five tested composting mixtures on fresh weight basis.

Compost mixtures		
ID	Mixture	Mix ratio (fw basis)
R	Roses	20% flower, 50% stem, 30% leaves
T	Roses + Tomato	16% flower, 40% stem, 24% leaves, 20% tomato
K	Roses + Kalanchoe	16% flower, 40% stem, 24% leaves, 20% kalanchoe
C	Roses + Compost	16% flower, 40% stem, 24% leaves, 20% compost
CL	Roses, more leaves + Compost	16% flower, 24% stem, 40% leaves, 20% compost

the climate room.

Temperature of the composts in the buckets was measured with a temperature probe at three different spots. During the active phase, temperature was recorded at least four times per week, followed by weekly to monthly measurements. The mixtures were turned manually at each sampling moment. Water was added in equal amounts when moisture content fell below 40% (Bernal et al., 2009). Samples of approximately 80 g were taken at an increasing interval (d 0, 7, 15, 23, 35, 58, 90, 181) from each bucket by combining 5-subsamples from the whole profile. The periodically collected samples were split and either processed fresh or air-dried at 40 °C (>72 h) and milled <0.5 mm prior to analysis (Retsch ultra centrifugal mill ZM 200) (Fig. 1).

2.3. Analytical methods

Moisture content of respectively fresh and air-dried samples were determined gravimetrically after 24 h at 105 °C and expressed on dry mass basis (Schmugge et al., 1980). OM was determined by loss on ignition at 550 °C for 16 h (Nelson and Sommers, 1996). Total carbon (C) and total nitrogen (N) were measured on a CNS analyzer (Vario El cube, Elementar) using approximately 10 mg of sample (Yeomans and Bremner, 1991).

Losses of OM were calculated according to the equations of Viel et al. (1987) by using the initial and final ash concentrations in percentage, respectively X_1 and X_2 (Eq. (1)).

$$OM\ loss\ (\%) = 100 - 100 * \frac{((X_1 * (100 - X_2))}{((X_2 * (100 - X_1))} \quad \text{[Eq. 1]}$$

A 18 MΩ-H_2O extract at 1:20 (w:v) on dry weight equivalent was prepared. pH and EC were measured before filtration over 0.45 µm. After filtration, Dissolved Organic C (DOC) was measured on a TOC analyzer (Vario TOC cube, Elementar). Total phenolic content was measured according to the Folin-Ciocalteu method (Waterhouse, 2003; Blainski et al., 2013). In short, 0.5 mL Folin-Ciocalteu reagent and 6.0 mL 10.75% Na_2CO_3 was added to 0.2 mL sample and diluted to 12.5 mL with 18 MΩ-H_2O. Absorbance was measured after 30 min at 760 nm (Prove 300, Spectroquant). Gallic acid was used to prepare the calibration curve.

A 0.05 M K_2SO_4 extract at 1:30 (w:v) was prepared to measure inorganic N (NH_4^+, NO_3^-, NO_2^-) (Brookes et al., 1985). Extracts were shaken for 2 h, filtered over 0.45 µm and measured on an auto-analyzer (Segmented flow SAN++, Skalar).

The $BaCl_2$ method was used to estimate Cation Exchange Capacity (CEC) (Hendershot and Duquette, 1986). 1:50 (w:v) 0.125 M $BaCL_2$ extracts were shaken for 2 h, filtered over 0.2 µm and measured on an ICP-OES (Optima 8000, PerkinElmer). CEC was expressed as the sum of Ca^{2+}, Mg^{2+}, Na^+ and K^+ in cmol(+) per kg dry wt.

Microwave acid digestion was used to determine total macro- and micro-nutrients (P, Na, K, Ca, Mg, Fe, Mn, Cu, Zn) as well as heavy metals (Cr, Ni, Cd, Co, Pb, As, Se) in the initial wastes and for the assessment of the final composts (Epa and of Resource Conservation, 2007). Extracts were prepared with 500 mg sample, 8.0 mL HNO_3 and 2.0 mL HCl and underwent microwave digestion (Multiwave Pro, Anton Paar, Organic A protocol). Digested extracts were measured on an ICP-OES (Optima 8000, PerkinElmer).

2.4. Respiration

To assess biological stability of the compost, respiration rates were measured after six months of composting (Bernal et al., 2009). Approximately 5 g fresh compost was incubated at 20 °C in 150 mL incubation bottles purged with synthetic air before sealing. CO_2 concentrations were measured after 18 h from a 5.0 mL gas subsample and analysed on a gas chromatograph (Trace GC Ultra, Thermo Scientific).

2.5. Disease suppressive capacity

In-vitro disease suppressive capacity of the mature rose compost was tested against five common rose pathogens. Four fungal and one bacterial pathogen were obtained: *Botrytis cinereae* (CBS125.58), *Fusarium oxysporum Schltdl. Flora* (CBS 798.95), *Phytophthora infestans* (T30-2), *Rhizaoctonia solani (*CBS 115.20) and *Agrobacterium tumefacies* (C58). 18 MΩ- H_2O extract at 1:10 (w:v) on dry weight equivalent was shaken overnight in an end-over-end shaker (Neher et al., 2013). Extracts were split in two, of which one was sterilized for 20 min at 121 °C to act as control. Extracts were cooled to 40 °C whereafter mixed (1:10 v/v) with potato dextrose agar (PDA) or yeast maltose-extract dextrose agar (YMBA) and petri-dishes were prepared (Neher and Weicht, 2018). Fungal pathogens were inoculated on PDA plates, *A. tumefaciens* bacteria was inoculated on YMBA plates. All disease suppressive assays (DSA) were conducted in triplicate and incubated at 21 °C. The growth of *A. tumefaciens* was recorded after two day as either growth or no growth. For the fungi, the radius of the colony was measured from four angles to acquire the average growth rate after one week (for *B. cinereae* and *F. oxysporum*) or two weeks (*R. solani* and *P. infestans)* of incubation.

2.6. Data analysis

All analysis and visualization was performed using R version 4.0.5, visualizations were created using the ggplot2 and gt package (Wickham, 2016; R Core Team, 2021; Iannone et al., 2022). OM losses were fitted per bucket to a 1st order kinetic curve (Eq. (2)).

$$OM\ loss\ model = A * \left(1 - e^{-kt}\right) \quad \text{[Eq. 2]}$$

A is the maximum OM degradation in percentage, k is the degradation rate per day and t is composting time in days. The fits per bucket were evaluated on RMS-values and R^2-values, fitted parameters (A & k) were averaged per mixture for visualization. Differences between mixtures for the parameters were tested with an Anova followed by a Tukey HSD test.

All data was expressed on dry weight equivalent of the compost samples. Linear mixed effect models (LMM) were used to analyze the evolution of the relationship between measured parameters and mixture types using lme4 package (Crawley, 2007; Bates et al., 2015). One base model was chosen for all parameters to create unity:

lmer(parameter_baseline_change ~ mixture +/* day + day^2 + (1|bucket))

Day and mixture type were entered as fixed effects into the model. Day was non-linear transformed to a 2nd order polynomial to capture the observed curvilinear relationships. Field triplicate buckets were added as random effect. Parameters were corrected as baseline change per bucket with day zero as starting point. For each parameter a model with and without interaction term was tested to disentangle the effect of green waste additives on parameter evolution over time. Residuals were visually inspected to evaluate the normality assumption, the marginal R^2 was used to evaluate each model fit. An Anova type *III* analysis was done for each model to test significance for the different model parameters (Table A.5). Average growth per pathogen DSA was compared with a Wilcox test.

3. Results

3.1. Changes in physicochemical parameters during composting

3.1.1. Organic matter degradation

Temperatures increased rapidly in all buckets during the first days of composting, reaching thermophilic phase (>40 °C) within five days (Fig. 2). The R and CL mixture experienced a thermophilic phase of approximately eight days compared to five days for the T, K and C mixtures. Maturation phase started when temperatures stabilized around 30 °C (climate room temperature) in all buckets after approximately 20 days. Temperatures continued to follow close to ambient temperatures for the remaining composting time (Fig. A.1).

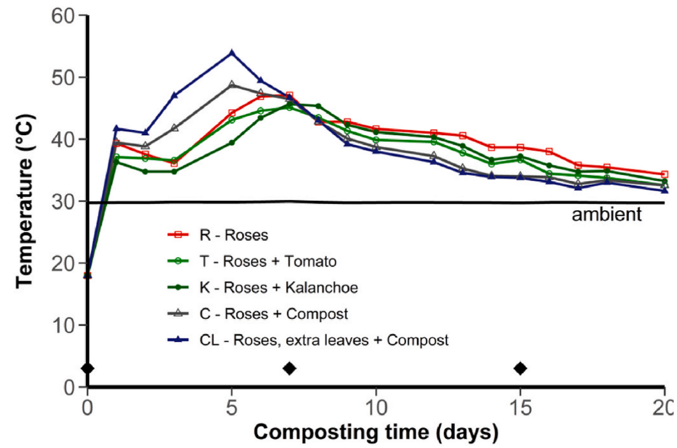

Fig. 2. Temperature profile for all five mixtures (mean, n = 9) of the first 20 days of the composting process. Diamonds indicate the sampling moments. The black line indicates the climate room temperature during the composting process.

Composting reduced the volume significantly for all mixtures. The largest reduction in volume was observed for respectively the tomato and kalanchoe mixtures which decreased by 88% and 91% during composting. The starting volume of the other mixtures was reduced by 81–86%. The OM concentrations started around 95% for the GW-mixtures, whereas the mature compost mixtures started significantly lower with values of around 80% (Table A3). These differences can be attributed to the addition of the mature compost which contained inorganic pumice and thereby lowered overall OM levels. Initial differences in OM levels increased over time due to variations in OM degradation rates. For all mixtures 68–80% OM was lost during composting, with the CL showing significant higher losses than the R mixture ($p = 0.044$, Fig. 3). Final OM levels of all mixtures met the compost requirements of OM ≥ 15% as set by the European Commission (Table 2) (Saveyn and Eder, 2014). All 1st order kinetic curve fits of OM loss had a $R^2 > 90\%$ (Fig. 3). The OM degradation loss stabilized during the maturation phase, that had started on average after 50–70 days. The OM degradation rate k ranged from 0.06 ± 0.01 for the C mixtures to 0.19 ± 0.02 for the CL mixtures. There were no significant differences in OM degradation rate k between all five mixtures.

pH levels started between 5.5 and 6.0 for all mixtures and significantly increased to 6.6–7.5 (Table A3), thereby also meeting the requirements for agricultural application and staying within range supporting good microbial activity (Gavilanes-Terán et al., 2016; Bernal et al., 2017). The addition of tomato waste resulted in the highest final pH of 7.5. An interaction effect was observed between mixtures and composting time as indicated by Linear Mixed Model (LMM) analysis ($p < 0.001$, $R^2m = 0.82$, Table A5). The EC levels also showed a gradual increase during composting with different patterns for the different mixtures ($p < 0.001$, $R^2m = 0.91$, Table A3 & A.5).

3.1.2. C/N, DOC dynamics and fertilizing potential

The initial C/N differed between the mixtures, with variation in C content as its main driver ($p < 0.001$, $R^2m = 0.65$, Table A3 & A5). Initial C content of the C-mixtures was ±8% lower compared to the GW-mixtures (Fig. 4A). The C/N decreased from 20 to 25 at the start to ±8 at the end for the GW-mixtures mainly attributed to the relative increase in N content by 150% (from 2 to 5%) due to mass loss over the 181 d incubation experiment. The C/N decreased respectively from 18.3 ± 1.3 to 7.5 ± 0.2 and from 15.5 ± 1.8 to 6.6 ± 0.1 for the C and CL mixture. The lower initial C/N levels of the C-mixtures were caused by the 20%

Table 3
Physicochemical characteristics and nutrient levels of the compost mixtures after six months of composting with in the last two columns optimal levels for the different parameters from literature.

Compost mixtures[a]	R	T	K	C	CL	Optimal level	Reference
Characteristics							
pH	6.8 ± 0.1	7.5 ± 0.1	7.2 ± 0.1	6.6 ± 0.0	7.1 ± 0.0	6.0–7.5	Gavilanes-Terán et al. (2016)
EC (dS m^{-1})	5.9 ± 0.2	7.2* ±0.1	6.4* ±0.2	4.0 ± 0.2	4.2 ± 0.1	2.0–6.0	Awasthi et al. (2014)
OM (%)	81.9 ± 0.3	76.1 ± 0.8	78.5 ± 0.6	48.6 ± 0.5	47.4 ± 0.9	≥15%	Saveyn and Eder (2014) [b]
C/N	8.6 ± 0.0	8.0 ± 0.2	8.0 ± 0.1	7.5 ± 0.2	6.6 ± 0.1	<10	Mathur et al. (1993)
C (%)	42.9 ± 0.2	40.0 ± 0.3	41.4 ± 0.4	24.0 ± 0.4	23.0 ± 0.5	*	
N (%)	5.0 ± 0.0	5.0 ± 0.1	5.2 ± 0.1	3.2 ± 0.1	3.5 ± 0.1	*	
DOC (mg g^{-1})	36.4** ±2.4	39.6** ±3.0	43.4** ±2.2	6.4 ± 0.3	7.2 ± 0.3	≤17 mg g^{-1}	Bernal et al. (2009)
$N\text{-}NH_4$ (mg g^{-1})	0.17 ± 0.02	0.12 ± 0.00	0.13 ± 0.00	0.08 ± 0.01	0.06 ± 0.00	<0.4 mg $^{-1}$	Zucconi and de Bertoldi (1987)
$N\text{-}NO_3$ (mg g^{-1})	8.02 ± 0.57	8.29 ± 0.21	7.87 ± 0.62	6.43 ± 0.08	6.37 ± 0.18	*	
$N\text{-}NH_4^+/N\text{-}NO_3^-$	0.02 ± 0.00	0.01 ± 0.00	0.02 ± 0.00	0.01 ± 0.00	0.01 ± 0.00	<0.16	Bernal et al. (2009)
CEC (cmol kg^{-1})	221 ± 2	256 ± 2	245 ± 11	156 ± 3	163 ± 3	≥70% increase	Gondek et al. (2020)
Phenols (g EGA kg^{-1})	3.3 ± 0.3	2.9 ± 0.3	3.2 ± 0.1	0.4 ± 0.0	0.4 ± 0.0	*	
Respiration (mg CO_2 kg^{-1} h^{-1})	88 ± 18	103 ± 4	107 ± 9	57 ± 1	49 ± 4	≤120 mg CO_2 kg^{-1} h^{-1}	Bernal et al. (2009)
Macro-nutrients (g kg^{-1})							
P	6.8 ± 0.4	8.1 ± 0.2	7.8 ± 0.3	5.7 ± 0.0	6.0 ± 0.3	*	
Na	1.6 ± 0.1	1.6 ± 0.0	1.6 ± 0.1	2.6 ± 0.1	2.5 ± 0.1	*	
K	49.4 ± 1.0	60.2 ± 0.5	55.7 ± 1.5	30.0 ± 0.7	32.3 ± 0.9	*	
Ca	22.1 ± 1.0	31.4 ± 2.0	27.9 ± 0.8	21.9 ± 0.5	26.2 ± 0.7	*	
Mg	6.2 ± 0.2	7.4 ± 0.2	7.3 ± 0.2	5.8 ± 0.1	6.3 ± 0.2	*	
Micro-nutrients (mg kg^{-1})							
Fe	434 ± 21	446 ± 44	414 ± 11	8255 ± 100	8007 ± 183	*	
Mn	189 ± 8	219 ± 9	215 ± 7	478 ± 3	502 ± 5	*	
Cu	19.5 ± 1.2	21.0 ± 0.8	21.6 ± 3.1	23.6 ± 0.8	21.7 ± 0.4	*	
Zn	179 ± 4	178 ± 9	183 ± 9	183 ± 4	186 ± 4	*	

Disease suppressive assays showed that m*No optimal level agreed on in literature.
**Optimal level not met.
[a] mean ± SE, dry weight basis, n = 3.
[b] Guidelines by European Commission.

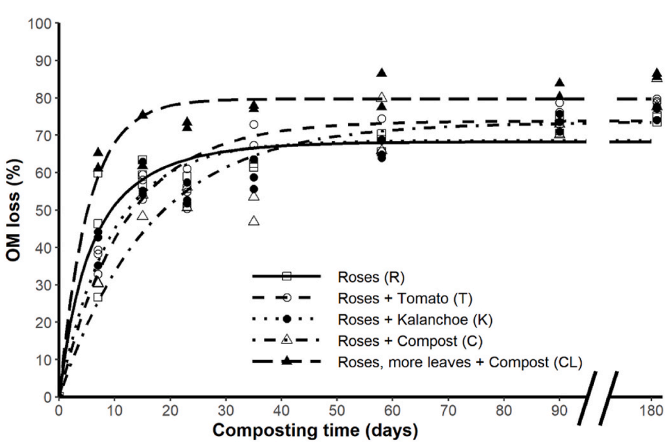

Fig. 3. Organic matter loss during composting for the different mixtures. Symbols indicate the different replicates per mixtures. Curves were fitted by 1st order kinetic function.

mature compost addition with a low C/N (Table 1). Decrease in C/N occurred mostly during the first three weeks of composting, when the OM loss was most pronounced (Fig. 3). A strong relative increase of 50% in N content in the first week for the C-mixtures can mainly be attributed to volume reduction of over 80%, hereafter the N content remained stable (Table A3). The evolution of DOC concentration showed two distinctive patterns, an initial increase with subsequent slight decrease for the GW-mixtures whereas a gradual decrease was observed for the mixtures with compost addition (Fig. 4B). LMM analysis supported this with significant interaction between DOC concentration and composting time ($p < 0.001$, $R^2m = 0.48$, Table A5).

CEC increased for all mixtures (Fig. 4C), with a stronger increase for the composts with GW addition ($p < 0.001$, $R^2m = 0.96$, Table A5). CEC increased with more than 200% to 221, 256, 245 cmol kg^{-1} for R, T and K respectively whereas the increase was approximately 100% to 156 and 163 cmol kg^{-1} for the C and CL mixture (Fig. 4C). Initial polyphenolic levels started around 12.5 g EGA kg^{-1} but decreased for all mixtures significantly over time (Fig. 4D). No interaction effect between mixture and time was observed ($p < 0.001$, $R^2m = 0.81$, Table A5).

3.1.3. Nitrogen dynamics

Net mineralization rates (mg $N\text{-}NO_3^- + N\text{-}NH_4^+$ g^{-1} d^{-1}) varied greatly between the different compost mixtures during the first six weeks of composting (Fig. 5A). Hereafter the GW- and C-mixtures became distinctly different. The $N\text{-}NO_3^-$ formation started after respectively two and five weeks for the C- and GW-mixtures and quickly became the dominant driver for net mineralization rates (Table A3). Evolution of $N\text{-}NH_4^+$ concentrations showed no significant differences between the mixtures ($R^2m = 0.61$, Table A5), whereas it was the case for $N\text{-}NO_3^-$ concentrations ($p < 0.001$, $R^2m = 0.94$, Table A5). The GW-mixtures showed temporal accumulation of the $N\text{-}NO_2^-$ concentrations between week three and eight (0.5–2.0 mg g^{-1}, Table A3). Steady net nitrification for the GW-mixtures started after approximately three weeks, whereas this started for the C-mixtures after approximately one week (Fig. 5B). The formation of $N\text{-}NO_3^-$ was still ongoing after six months of composting with a steady net nitrification rate around 0.05 mg $N\text{-}NO_3^-$ g^{-1} d^{-1} for the GW-mixtures and around 0.02 mg $N\text{-}NO_3^-$ g^{-1} d^{-1} for the C-mixtures.

3.2. Final compost assessment

The maturity of the final composts was assessed regarding its stability and whether it met common quality requirements (Table 3). Respiration rate was used as indicator for stability and it varied between the different mixtures after six months of composting ($p < 0.001$). Respiration rates were significantly higher in the T & K mixtures compared to the R, C and CL mixtures (Table 3). Rates for all mixtures were below the maturity requirement of 120 mg CO_2 kg^{-1} h^{-1},

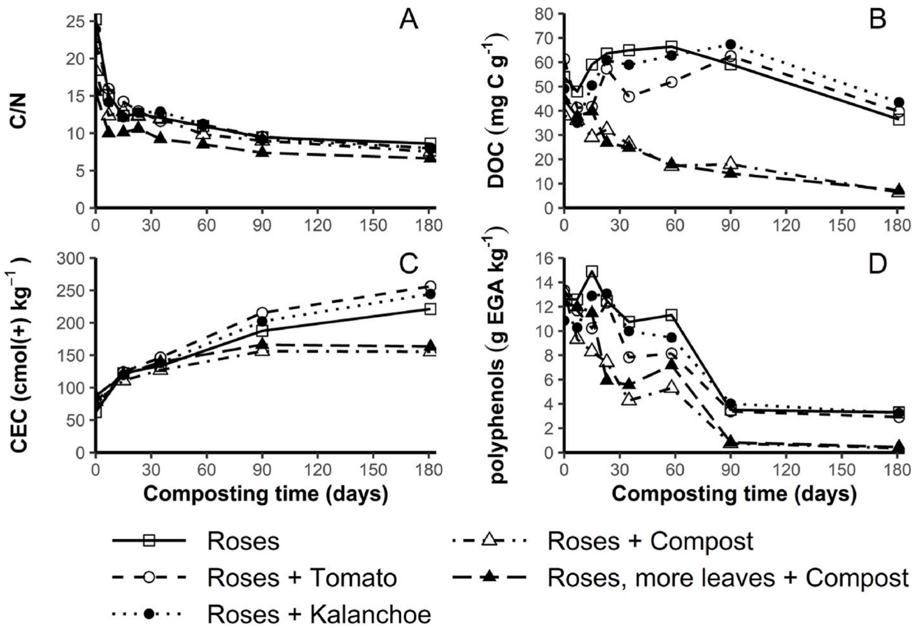

Fig. 4. Changes in physicochemical parameters during composting for the five different mixtures. (A) C/N, (B) DOC (mg C g^{-1}), (C) polyphenols (g EGA kg^{-1}), (D) CEC (cmol(+) kg^{-1}). Mean, n = 3 per mixture, expressed on dry weight basis.

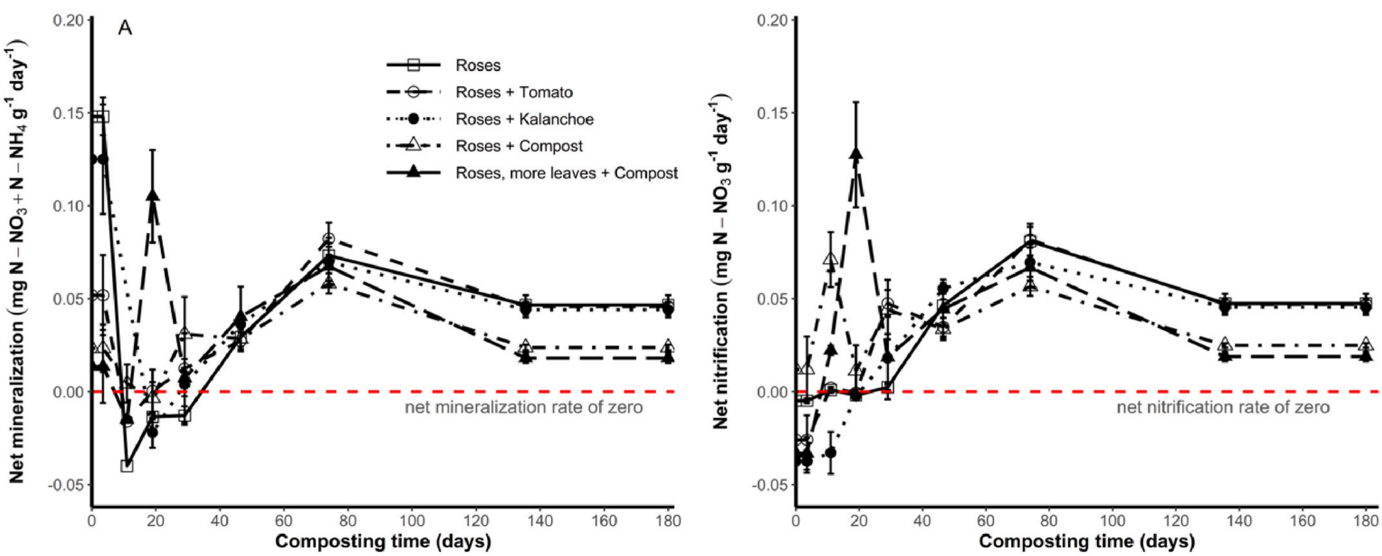

Fig. 5. Net mineralization rates (A) and net nitrification rates (B) during composting in respectively mg (N-NO_3^- + N-NH_4^+) and mg N-NO_3^- per g dry weight compost per day. Mean ± SE, n = 3 per mixture.

indicating biologically stable compost (Bernal et al., 2009).

Optimal levels to assess compost quality were collected from literature when available (see Table 3 for references). All (co-)compost mixtures achieved a suitable degree of maturity after six months of composting (Table 3). Only the final levels for DOC of the GW-composts did not meet the reference concentration of ≤17 mg g^{-1} as found in literature. The continuously decrease during the last months might indicate an unfinished process. Nutrient content differed slightly between the mixtures, with higher levels of P and K for the GW-mixtures. The addition of the Fe-rich mature compost explains the higher Fe content of the C-mixtures (Table 1). Heavy metal content stayed below the critical levels as set by the European commission for most mixtures (Table A.4). Solely the C-mixture exceeded the optimal level for both Cr and Ni with respectively 26 and 40%.

3.3. Disease suppressive effects

Mature compost extract completely inhibited the growth of bacteria *A. tumefaciens*, whereas growth was observed in the sterilized petri dishes (data not shown). Growth rate of the fungal pathogens was likewise strongly impaired when inoculated on mature compost (Fig. 6). A complete growth prevention was observed for *B. cinerea* and *P. infestans* whereas strong growth reduction was observed for *F. oxysporum* and *R. solani* ($p < 0.001$ for all pathogens).

4. Discussion

4.1. Composting performance changes during composting

Highest temperatures during the thermophilic phase were observed

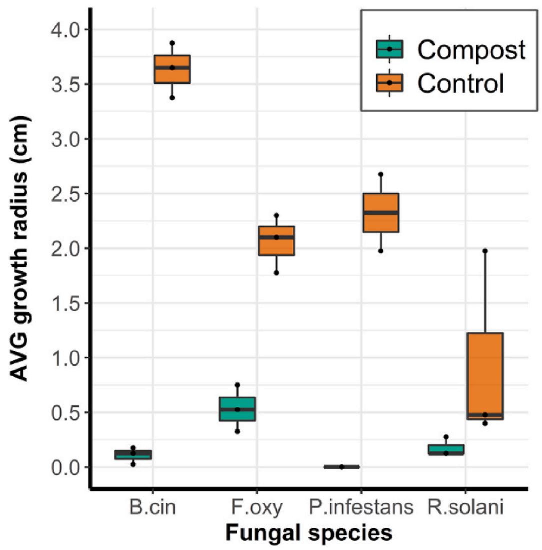

Fig. 6. Disease suppressive assay of mature rose compost on the growth of four common fungal rose pathogens; *B. cinereae, F. oxysporum, P. infestans, R. solani.* Tested *in-vivo,* as control sterilized compost extract was used.

for the mixtures with the addition of mature compost (C-mixtures). This was followed by an earlier onset and faster decline in temperatures compared to the GW-mixtures. These differences can be attributed to the addition of microorganisms from the mature compost and, for the CL mixture, the increased ratio of easily degradable leaves compared to the more ligneous stems (50% leaves and 30% stem). In this study the established sanitation requirement of temperatures of at least two weeks above 55 °C were not met due to the short thermophilic phase (Bernal et al., 2017). It is therefor not certain that the mature compost is totally free of pathogens and weed seeds (Lim et al., 2016). Compost sanitation can also take place via production of anti-microbial compounds during the composting process and colonization of the compost with microorganisms which either compete for nutrients or produce antibiotics. This was shown in a study by Suárez-Estrella et al. (2007) where infected compost, which did not meet traditional temperature sanitation requirements, was still found free of pathogens after only five days of composting.

The initially high OM degradation rates and rapid C/N decrease (Figs. 3 and 4A) were in line with patterns previously observed for green waste composting studies (Gavilanes-Terán et al., 2016; Idrovo-Novillo et al., 2018; Yin et al., 2021; Yang and Zhang, 2022). The addition of mature rose compost enhanced total OM degradation as indicated by a faster decline in % C in the C-mixtures. Similar results for the addition of mature compost were found by Yang and Zhang (2022). The increase in leaf-to-stem ratio increased OM degradation as indicated by a higher degradation rate (k) for the CL mixture compared to the C mixture. The elevated degradation rates found in this study compared to other green waste composting studies could be explained by differences in operational scale (Bustamante et al., 2008; Gavilanes-Terán et al., 2016; Idrovo-Novillo et al., 2018). Dissolved Organic Carbon (DOC) is a commonly used indicator for the presence of simple organic compounds and thus degree of degradation (Meghvansi and Varma, 2020). DOC concentration showed two distinctive patterns for the GW- and C-mixtures during the process. An increase of DOC levels during the thermophilic phase was previously observed in other composts by Idrovo-Novillo et al. (2018). These composts also contained relatively high levels of (hemi-)cellulose. The authors attributed the initial increase and posterior decrease to the degradation of (hemi-)cellulose releasing compounds, which were subsequently used by microbial communities as energy source. Surprisingly, in our study the addition of mature compost counteracted these effects, irrelevant of the leaf-to-stem ratio. A potential explanation could be that the addition of microbial communities from mature compost levelled out the degradation effect by simultaneously consuming the released compounds for growth.

Rising pH levels during composting were observed for all mixtures and can be attributed to the breakdown of acidic compounds and formation of NH_3^+ (Paredes et al., 2001). During maturation, the pH decreased for all mixtures, a known side-effect of nitrification (Cáceres et al., 2018). Elevated pH levels when co-composting with tomato waste can be attributed to the breakdown of organic acids in the tomato plants, which is known to raise pH (Tabrika et al., 2019). An increase in salt content is often observed during composting, since degradation processes produce inorganic compounds. This is enhanced by the concentration effect which occurs as a results of decreasing volume and thus dry weight reduction (Paredes et al., 2001; Bernal et al., 2009). The observed high EC levels should be taken into account when considering potential application of these composts, as high EC levels might inhibit plant growth (Paredes et al., 2001). High EC levels were previously observed in small-scale home composting settings, whereas in a large-scale experiment EC levels decreased due to leaching (Faverial and Sierra, 2014; Gavilanes-Terán et al., 2016). These low EC levels are also measured in the mature compost obtained from Kenya (Table 1). Rose flowers are known for their high polyphenol levels (Table 1) which have phytotoxic effects on plants (Min et al., 2015). Polyphenols levels decreased substantially during the incubation period (Fig. 4D) and final concentrations for all mixtures were in line with normal levels between 0.5 and 4.8 g kg^{-1} found for vegetable composts (Cascant et al., 2016). The mature compost obtained from Kenya showed very low polyphenol values (Table 1), indicating that extended maturation might have further broken down these components.

The observed increase of total N during composting, with final levels between 3.3 and 5.0%, show that limited N was lost, but this can also be partly attributed to the relative concentration effect. Bernal et al. (2009) advocated to look at the change of N-fractions to assess the quality of the composting process. Nitrification is the conversion of NH_4^+, produced though mineralization, via NO_2^- to NO_3^- and the pathway by which N is preserved in the compost (Bernal et al., 2009; Cáceres et al., 2018). Final N-NO_3^- levels in this study were relatively high compared to other composting studies of various experimental scales. Sun et al. (2016) did find similar NO_3^- levels and attributed the high levels mainly to the small-scale set up and associated shortened thermophilic phase. The temporal accumulation of NO_2^- (Table A3), the intermediate product of nitrification, was likely caused by the relatively high pH and high NH_3^+ levels suppressing the last nitrification step (Cáceres et al., 2018). It has recently been debated whether nitrification only takes place during the maturation phase or that specific nitrifying bacteria can withstand higher temperatures (>40 °C) during the thermophilic phase (Zhang and Sun, 2014; Cáceres et al., 2018). With regard to enhancing plant available N in soils, the high NO_3^- levels in the final composts together with the ongoing nitrification for all mixtures indicates high plant fertilizing potential for the tested mixtures.

Cation Exchange Capacity (CEC) is an indicator of humification since the formation of functional groups provide sorption sides for cations and thereby result in the increase in CEC (Bernal et al., 2009; Gondek et al., 2020). The CEC of the C-mixtures stabilized after three months indicating a further stage of maturation compared to the GW-mixtures (Zhang and Sun, 2016).

4.2. Stability and quality of mature compost

At the end of the experiment all mixtures reached a suitable degree of maturity, since most physicochemical parameters complied with optimal levels indicated in literature (Table 3). Respiration rates were below the established critical level indicating the univocal formation of stable compost. This is important since the application of unstable compost to soil has the potential disadvantage that it might cause oxygen deficiency due to high oxygen demand because of microorganism activity. Furthermore, microorganisms may compete with plants for N, reducing available N for crop growth (Bernal et al., 2017). The ratio between N-NH_4^+ and N-NO_3^- is a commonly used indicator to assess compost maturity, a good nitrification process will result in a low ratio (Moral et al., 2009). The critical value of $\leq$0.16 for the ratio of N-NH_4^+/N-NO_3^- for composts of all origins was met for all mixtures (Table 3). Only DOC levels of the GW-mixtures (R, T and K) were higher than the suggested optimal level. The consistent reduction in combination with low DOC levels found in the original compost from Kenya (Table 1) indicate that a prolonged maturation phase to further raise compost quality would be preferred for rose waste.

All mixtures reached micro- and macronutrient levels comparable to those found in other composting studies, indicating good plant fertilizer potential (Lim et al., 2016; Van der Wurff et al., 2016; Idrovo-Novillo et al., 2018). This was further supported by the high CEC levels with increases between 100 and 200%, far exceeding the minimum prerequisite for mature compost (Table 3). Low levels of heavy metals are also acceptable since some of those spore elements are essential for plant growth. Despite some heavy metals being essential for plant growth, their accumulation in soil should be avoided (Awasthi et al., 2014). The elevated heavy metal concentration in the compost obtained from Kenya stress the need of closely monitoring their fate in commercial settings to avoid unwanted accumulation in soil.

The selection of critical parameters and optimal values for the assessment of compost is an ongoing debate. Variations in quality and maturity parameters for different waste types and composting systems were thoroughly identified by Azim et al. (2018) and Bustamante et al. (2010). The C/N is commonly seen as an essential indicator for compost maturity, but within the same review article optimal C/N values of either below 20, 12 and 10 without specifying the initial waste compositions were stated (Bernal et al., 2009). Similar with CEC levels, were both levels above 67 meq per 100 g are used and a CEC increase of at least 70% to assess degree of maturity (Bernal et al., 2009; Gondek et al., 2020). The latter likely being less prone to ambiguity in the analysis protocol such as extraction fluid or included cations. The controversy in standardizing optimal values for compost maturity can mainly be attributed to specific differences experimental conditions and the wide variety in assessed wastes (Jiménez and García, 1992; Vargas-García et al., 2010). This is important to keep in mind when assessing the maturity or quality of compost and stresses the need for *in-vivo* assays ahead of field application.

4.3. Rose waste potential

Idrovo-Novillo et al. (2018, 2019) investigated the suitability of rose waste compost as organic soil amendment in the rose cut industry. The application of composted rose waste had a positive effect on the cultivation, whereas this was not the case for the un-composted freshly chopped rose waste (Idrovo-Novillo et al., 2018). Their composts consisted for 15% of manure and 35% of sawdust, valuable soil amendments in itself making it an unfeasible approach for large-scale farming. In the current study the aim was to test the potential of composting solely rose waste with and without green waste or mature compost additives to minimize production costs. All three GW-mixtures reached good maturity and quality, solely the addition of tomato might increase salts levels above acceptable levels and thus its proportion in the mixture should be limited. The current study found that mature compost addition indeed kickstarted the composting process, but the heavy metal content should be monitored to ensure that final concentrations remain within the suitable range for save horticultural application. The increased leaf-to-stem ratio in the CL mixture showed earlier and an increase in activity in terms of temperature development. This supports the hypothesis that the ligneous character of rose waste does hinder rapid decomposition by, presumably, limiting physical accessibility. Importantly, the results of this study showed that the ligneous character is not decisive for an effective composting process even with a relatively short thermophilic phase. However, an increased maturation phase might be favored for more optimal results.

4.4. Diseases and pesticides

Amending soils with compost can result in the suppression of soil pathogens, a valuable feature for the large-scale horticultural sector since this can be a step towards reduction of pesticide application (De Corato et al., 2019). This study indicated significant disease suppressive capacities of mature rose compost against the tested pathogens, all common rose diseases. These are promising results for the sector and can mainly be attributed to the microbial communities inhabiting mature rose waste compost. Suppressive effects of horticultural compost on tomato and cress have previously been shown for both *Fusarium* and *Rhizoctonia* strains (Cotxarrera et al., 2002; Pane et al., 2013). Although several studies found suppressive effects of other types of compost against the growth of P*hytophthora* and *Agrobacterium*, this was not yet demonstrated for rose waste compost (Blaya et al., 2016; De Corato et al., 2019; Milinković et al., 2019). To further evaluate the ability of rose compost to suppress common rose pathogens, *in vivo* bioassays should be conducted.

A wide range of pesticides is used to control diseases and pests, an imperative practice in the horticultural sector (Toumi et al., 2016). Presence of pesticide residues in the rose waste used for composting is inevitably seen as result of the regular application of varying combinations of pesticides in large-scale rose farming. Ranging from *i.e.* a less persistent fungicide like carbendazim to more persistent ones like difenoconazole (Kupper et al., 2008). For the matured compost no pesticide residues were analysed since this went behind the scope of this study. For future research it is recommended to include pesticide degradation analysis during composting since this will help move the sector towards a more sustainable cycle of resources. By, for instance, switching specific fungicides known for their persistence to ones with better degradation prospects.

4.5. Practical implications

Green waste originating from rose cultivation is a major waste stream within the sector. Almost 55,000 t of green waste was produced within the Kenyan rose sector in 2016 (Kazimierczuk et al., 2018). In a commercial setting the composition of the total generated waste is fixed. However, since waste is produced at different stages of the production process some influence on the composition can be exerted. This study found that composting rose waste with or without low-cost additives did result in mature and stable compost within six months, the minimal reduction of compost volume was 81%, with some co-composting mixtures additionally reducing this volume by another 10 pp. This highlights that the rose cultivation waste stream reduction potential in a farm setting could reach up to 90%. The actual potential and feasibility (*e.g.*, is enough of a specific co-composting material available) of rose compost mixtures should be further researched in a large-scale study. Larger pile volumes lead to higher temperatures for a prolonged period of time, causing more volume reduction and a more complete composting process (Lashermes et al., 2012). This will then results in meeting the sanitation requirement as established by Bernal et al. (2017). On the farm-scale, composts will be exposed to a natural temperature and precipitation regime, which can cause increased leaching in wetter climate regimes with reduced salt levels as result. This study found that the overall characteristics of the matured compost of this study and that obtained from Kenya were comparable (Tables 1 and 3). The compost from Kenya did have EC and DOC levels well within the optimal range, two characteristics which were not yet optimal in composts resulting from this (small-scale) incubation study. Further research on the large-scale application of co-composting rose waste is recommended to investigate the true applicability of the proposed recycling method within a full commercial rose farm setting.

5. Conclusion

This study demonstrated that the ligneous character of rose waste does not hinder an effective composting process as shown by the mature compost obtained after six months of composting with five mixtures. Co-composting rose waste can convert a waste stream into a valuable organic fertilizer with low polyphenol levels, high nutrient contents and CEC levels of >150 cmol kg^{-1}. Solely the addition of mature rose compost and increasing the leaf-to-stem ratio significantly accelerated the rose waste composting process. Optimization of compost ratios can be achieved by combining different sources of rose waste since they come at different waste ratios, *i.e.* from the greenhouse or grading. Implementing these findings inthe rose cultivation sector could improve the efficiency of the composting process and thereby process the green waste more effectively. Further research should assess the potential implementation of composting within large-scale rose farming. This study demonstrated for the first-time the strong disease suppressive effects of rose compost on five common rose pathogens. Overall, these results provide clear guidance for globally straight forward implementable improvements for (co-)composting rose waste as sustainable waste management strategy and its re-use within the widest agricultural settings.

CRediT authorship contribution statement

E.A. de Nijs: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft. **L.M.E. Maas:** Methodology, Investigation, Writing – review & editing. **R. Bol:** Conceptualization, Writing – review & editing. **A. Tietema:** Conceptualization, Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2023.136685.

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