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Co-composting to close the cycle of resources during rose cultivation in Kenya: An agronomic and pesticide residue assessment

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ABSTRACT

Recycling green waste through composting is a promising practice for the transition towards a bio-based circular economy in the floricultural sector of Africa, especially for Kenya where cut flower export accounts for nearly 14 % of its total export value in 2017. Rose waste is a large waste stream, but its intrinsic properties make it challenging to recycle. Composting on commercial scale was studied on a rose farm near Lake Naivasha, (Kenya). Three mixtures were examined: (1) rose waste (RW) only, (2) 80 % RW + 20 % tomato waste and (3) 90 % RW + 10 % mature rose compost. Trapezoidal piles of approximately 4000 kg green waste were composted following the turned windrow approach, samples were taken at six occasions. The nine-month composting study, including pesticide fate assessment, showed consistent performance across tested mixtures. All mixtures resulted in mature and stable compost with C/N ratios below 10 and a high fertilizing potential, meeting international sanitation requirements. Final average volume reduction was 82 %, total N values ranged between 8.1 and 8.9 mg g^{-1} compost and pH values were alkaline (8.0–8.3). Out of the approximately 50 pesticides commonly used in rose cultivation only 8–12 pesticides could be detected in the matured composts with the highest contribution of flubendiamide and fluopyram. Scenario analysis showed the feasibility of closing the resource cycle in the African floricultural sector via continuous crop rotation over eight years with an amendment rate of 11.5 kg per m^2. Overall, this study provided straightforward implementable practices for rose waste management, which facilitates the re-use of valuable green waste in Africa and thereby contributes to the transition towards a global circular economy.

1. Introduction

The cultivation of roses has shifted to the Global South in the recent decades. The Kenyan horticulture sector has steadily grown over the years and has become crucial for its socioeconomic status (Adeleye & Esposito, 2018). The export of cut flowers, mainly to Europe, accounted for almost 14 % of Kenya's total export in 2017 (Gemählich, 2022). Over 70 % of the cut flower production takes place around Lake Naivasha, where greenhouses of approximately 60 farms cover over 2000 ha (Gemählich, 2022). With a daily waste production of over 50 kg ha^{-1} this equates to over 100 t of green waste per day for just the Naivasha region (de Nijs et al., 2023). The organic waste originates from crop maintenance, rejected produce and grading and it has so far remained unused, even though this waste contains valuable nutrients such as N (2.2 %), P (0.25 %), K (2.0 %), Ca, Mg, and Fe (Idrovo-Novillo et al., 2018). Instead, this waste is incinerated or dumped, which poses severe negative effects on the environment. Either by leaching of pesticides that are used in flower production such as mancozeb, flubendiamide and pyrimethanil or through emission of the greenhouse gases CH_4, N_2O and NH_3 due to the solid waste decomposition (Awasthi et al., 2020; Lim et al., 2016). Transitioning towards a more sustainable and resilient production system is an important objective of the horticulture sector worldwide. Ideally, this includes an effective and sustainable set of biogeochemical resources with a minimal environmental impact, in

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which the production–waste cycle is virtually closed as part of a bio-based circular economy (Case et al., 2017). Within large-scale rose farming this is not yet the case, so a more sustainable waste management strategy within the daily operation is desired.

Composting is a promising waste management practice which fits the concept of a bio-circular economy since it retrieves plant nutrients while entailing low operation costs and environmental impact (Lim et al., 2016). Subsequent usage of compost can improve soil quality and thus mitigate soil exhaustion while simultaneously reduce chemical fertilizer demand (Bernal et al., 2017; Bergstrand, 2022). It is a controlled form of aerobic degradation by microorganisms that convert waste into a biologically stable form called compost (Pergola et al., 2018; Ruiz et al., 2020). A successful composting process is vital to ensure sanitization and obtain a stable compost which can enhance soil fertility, structure and soil carbon (C) sequestration while minimizing the impact of previously used pesticides (De la Guerra et al., 2017).

Green rose wastes can be characterized by high moisture content (± 80 %), low C/N ratio (± 18.1) and high lignin content (± 54 %) (de Nijs et al., 2023a; de Nijs et al., 2023b). These traits might require additives to facilitate a composting process (Bernal et al., 2017; Gavilanes-Terán et al., 2017). The addition of additives is called co-composting and is used to optimize start-up conditions as well as facilitate the subsequent composting process (Meghvansi & Varma, 2020). These amendments can range from the addition of microorganisms and easily available C and N through manure, improve aeration through structuring material such as straw or increase C/N ratio through the addition of C via *i.e.* sawdust (Awasthi et al., 2020; Bernal et al., 2017; Sharma et al., 2018). However, in Kenya, these additives are rarely locally available in large enough quantities or are too valuable for large-scale amendment. The potential of co-composting rose waste as waste management strategy was assessed in an earlier, small-scale study and showed promising results, without using the previously mentioned valuable additives such as manure (de Nijs et al., 2023). The addition of matured compost was one of the tested low-cost additives and an interesting option due to its affordability. The addition of mature compost has previously shown to improve (lignocellulosic) green waste composting by inoculation of initial wastes (Wu et al., 2015; Zhang & Sun, 2016; Yordanova et al., 2018). The mature compost caused an extended thermophilic phase, thereby enhancing degradation which resulted in a reduced time to maturity (Yang & Zhang, 2022; Zhang & Sun, 2016). Another interesting benefit of co-composting with mature compost is its feature to mitigate gaseous emissions and thereby enhancing nitrogen (N) conservation (Yang et al., 2019). The high lignin content of rose stems limits access to decomposers (Bernal et al., 2017), which can be alleviated by chopping the wastes (Yang & Zhang, 2022). However, the stems can also act as structuring material ensuring sufficient air pockets within the pile (Pergola et al., 2018). Structuring material is important for large-scale production of compost to avoid the risk of compaction and thus oxygen deprivation.

To control diseases and pests, regular application of a wide range of pesticides is an imperative practice within the floriculture sector. Applied pesticides range from less persistent fungicides like carbendazim to more persistent ones like difenoconazole (Kupper et al., 2008; Toumi et al., 2016). The presence of pesticide residues in green waste is inevitable, however, the fate of these residues during the composting process is crucial for the subsequent application potential. Furthermore, although leaching during a well-managed composting process is minimized, leachates could easily be collected to mitigate potential pollution. Compost addition to soils improves microbial activity and thereby enhances the degradation of several commonly used pesticides (Varjani et al., 2018; Siedt et al., 2021). Because of these properties, composting has been used effectively as a treatment of pesticide residues in biopurification matrices and different green waste types (Kupper et al., 2008; Wilde et al., 2010; Lashermes et al., 2012). Kupper et al. (2008) found a high dissipation rate for two thirds of the investigated, commonly used, pesticides after 112 days, which is a relatively short period for composting ligneous wastes. In their study no decrease in triazole fungicides was observed. Triazoles are known as a very persistent pesticide with long half-life times. Furthermore, since composting significantly decreases the volume, a concentration effect of the more persistent pesticides can be observed. Pesticide dissipation is highly dependent on (1) the initial waste, (2) the nature of the pesticide, (3) composting conditions and management, (4) occupation by microbial communities and (5) the duration of the composting process (Büyüksönmez et al., 1999; Karanasios et al., 2010). Composting might thus be suitable as bioremediation method for pesticide contaminated green waste such as rose waste. However, the potential presence of residues after composting raises some concern when the compost is used repeatedly as soil amendment (Kupper et al., 2008). Therefore, it is essential to assess final pesticide residue levels in the matured compost prior to repeated field application to estimate associated ecological risks to soil life and beyond (Silva et al., 2019).

Currently, the re-use of rose waste is an important missing link in the transition of rose farming towards a bio-based circular economy with reduced production costs. Previous research has shown promising results for co-composting rose waste as waste management strategy but this was either conducted on a small-scale (de Nijs et al., 2023) or using valuable amendments (Idrovo-Novillo et al., 2018). Therefore, this study focused on exploring the potential of large-scale composting of rose waste in Kenyan rose cultivation. Experimental work of this study was conducted on a large-size rose farm in the Naivasha region of 40 ha which produces at least 2000 kg of green waste on a daily basis. The objective of this study was to examine the potential of composting rose waste in this large-scale commercial setting with low operational costs, exploring its benefits and challenges. The evolution of physicochemical parameters of different compost mixtures was monitored closely throughout the composting process. After maturation, the final compost was assessed in terms of agronomic value and pesticide residue levels. This paper first discusses the physicochemical evolution and maturity assessment for the tested composts. Subsequently, pesticide residues in the matured compost are evaluated, followed by a scenario analysis to evaluate the potential for large-scale composting within rose cultivation.

2. Materials and methods

2.1. Composting experiment

The composting experiment was conducted at a rose farm located in Naivasha, Kenya. Fresh rose- and tomato waste was collected during a 5-day period from the farm. These wastes were chosen based on on-farm availability. Rose waste (RW) originated from crop maintenance, rejected produces and grading. Tomato waste (TW) was also obtained at the farm and consisted for 20 % of complete tomato plants, the remaining part came from defoliation. One year old mature rose-waste compost (MC) was produced earlier at the farm with RW as main component, other additives in small amounts (±10 % in total) were tomato, hay, kalanchoe and pumice. All wastes were mixed thoroughly with an excavator before preparation of the mixtures. The stems of cut roses were not shredded and acted as structuring material to ensure sufficient aeration. The characteristics of the separate initial wastes were not measured due to a technical failure in the laboratory causing the samples to burn completely, characteristics of the mixtures on day zero can be found in Table A.2. Characteristics of these wastes from this location have previously been measured and presented in de Nijs et al. (2023). Three mixtures were prepared based on previous studies and local availability of the waste streams with the following compositions: only RW and RW with either the addition of tomato or mature compost and were composted for nine months between October 2021 and June 2022 (Yang et al., 2019; de Nijs et al., 2023). Each mixture was prepared in triplicate on fresh weight basis: 100 % RW (R mixture), 80 % RW + 20 % TW (T mixture) and 90 % RW + 10 % MC (C mixture). Wet bulk density was determined for both the fresh wastes and the matured compost by weighing a pre-established volume of 572 cm^3 (n=12).

The turned windrow approach was used and trapezoidal piles of approximately 4000 kg with an initial base of 3 by 5 m and height of 1.5 m were prepared (Fig A.1). Piles of different mixtures were positioned randomly within a three-by-three Latin Square block design. Temperature was measured for each pile at five different points and a depth of 40 cm from the top using a portable temperature probe. Measurements were taken daily during the active phase, which was reduced to once a week during maturation. Dimensions of the piles were recorded every other week to follow volume reduction. Moisture content was monitored daily using the fist method (Van der Wurff et al., 2016). Piles were exposed to weather conditions, and moisture content was further regulated using a sprinkling system with lake water. Two microjets were located on each pile (4 L h^{-1}) ensuring a homogeneous distribution of moisture over each pile. Piles were not aerated actively but turned mechanically on seven occasions depending on the temperature development (Fig. 1). Turning was done to secure adequate oxygen levels, to reduce compaction and ensure homogeneity of the composting process. The active phase was considered finished when temperatures within the piles consistently dropped below 40 °C and no reheating occurred after turning.

Each pile was sampled six times, five times during the active phase (day 0, 14, 41, 70, 108) and once at the end of maturation (day 280). A composite sample (n=8) from each pile was taken from both sides at two locations which were 3 m apart at two heights (25 % from the top and bottom) to represent the whole profile and stored at −25 °C until further analysis. Samples were either processed fresh or air-dried (> 72 h at 40 °C) and ground to 0.5 mm prior analysis (Retsch ultra centrifugal mill ZM 200). All analyses were conducted in duplicate.

2.2. Analytical methods

Air-dried and ground samples were used for analysis unless stated otherwise. Organic Matter (OM) was determined through loss on ignition at 550 °C for 16 h (Nelson & Sommers, 1996). Carbon (C) and Nitrogen (N) were measured on an elemental analyzer (Vario El cube, Elementar). pH, EC, Dissolved Organic Carbon (DOC) and polyphenols were measured in an ultrapure-H_2O extract prepared at 1:20 (w:v) on dry weight equivalent (Manu et al., 2017). DOC was measured on a TOC analyzer (Vario TOC cube, Elementar). Polyphenols were measured according to the Folin-Ciocalteu method (Waterhouse, 2003; Blainski et al., 2013) on a spectrophotometer (Prove 300, Spectroquant). Cation Exchange Capacity (CEC) was determined in a 1:50 (w:v) 0.125 M $BaCl_2$ extract by measuring Ca^{2+}, Mg^{2+}, Na^+ and K^+ on ICP-OES (Optima 8000, PerkinElmer). Inorganic N (NH_4^+, NO_3^-, NO_2^-) was measured in a 1:30 (w:v) 0.05 M K_2SO_4 extract on an auto-analyzer (Segmented flow SAN++, Skalar).

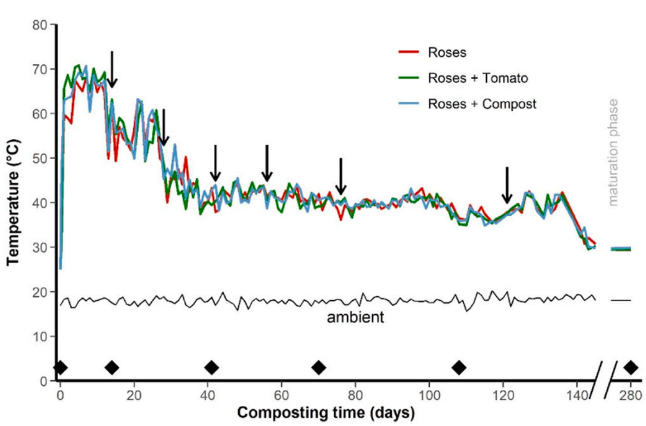

Fig. 1. Temperature changes during the composting process for the three tested mixtures and the ambient temperature. Arrows indicate mechanical turnings; diamonds indicate sampling moments.

Total and plant-available nutrient (P, Na, K, Ca, Mg, Fe, Mn, Cu, Zn) and heavy metal (Cr, Ni, Cd, Co, Pb, As, Se) concentrations were measured using ICP-OES (Optima 8000, PerkinElmer). For total concentrations, 500 mg of ground material was dissolved in 8.0 mL HNO_3 + 2.0 mL HCl through microwave digestion (Multiwave Pro, Anton Paar). Plant-available concentrations were measured on fresh homogenized sample in a 1:10 (w:v) 0.01 M $CaCl_2$ extract and inorganic N fractions were measured on an auto-analyzer (Segmented flow SAN++, Skalar). Further details on the analytical methods can be found in de Nijs et al. (2023). Maturity of the final composts was assessed based on threshold levels of specific parameters as obtained from literature (Table 1).

2.3. Pesticide residues analyses

Fresh mature compost samples of 1 kg were homogenized by hand and sent to the certified laboratory of Eurofins Zeeuws-Vlaanderen for extensive screening of pesticides used in agricultural setting (ZVP91 & ZVP92). Field replicates were used as independent replicates. Eurofins is accredited in the Netherlands under number L 010 according to the requirements of NEN-EN-ISO/IEC 17025:2017. Samples were extracted and analysed for pesticide residues with both gas chromatography (GC-MS) and liquid chromatography (LC-MS) depending on the pesticide (Eurofins, 2022). The combination of these methods covered all pesticides which are known to be used in Kenyan floriculture. The pesticides used within this rose farm are authorized under the Kenyan legislation and recorded in the Dutch MPS (‘Environment Program Floriculture’).

2.4. Data analysis

All analyses and visualizations were conducted in R version 4.0.5 using the ggplot2, lme4, stats and Agricolae packages (Bates et al., 2015; Wickham, 2016; de Mendiburu, 2021; R Core Team, 2021). Losses of OM were calculated according to Viel et al. (1987) using the initial (X_1) and final (X_2) ash concentrations in percentage (Eq. 1) and were subsequently fitted to a 1st order kinetic curve (Eq. 2) (Gavilanes-Terán et al., 2016).

$$OM\ loss(\ \ \%) = 100 - 100 * \frac{((X_1 * (100 - X_2))}{((X_2 * (100 - X_1))} \tag{1}$$

$$OM\ loss\ model = A * (1 - e^{-kt}) \tag{2}$$

A is the maximum degradation in percentage, k is the rate of degradation per day and t is the composting time in days. Model fits were evaluated on Root Mean Square (RMS) and R^2 modified (R^2m) values and differences between the fitted parameters (A & k) were tested with an Anova.

All data was expressed as dry weight equivalent. To analyse differences between mixtures during composting, the physicochemical parameters measured were standardized to the baseline change per pile. Furthermore, CEC data was corrected for the decreasing OM content over time. A Linear Mixed Modelling (LMM) approach was applied to assess the evolution of the various parameters (Crawley, 2007). One base model was used for all parameters: *lmer(parameter_baseline) ~ mixture +/* day + day*^{2} *+ (1|pile))*. A non-linear transformation was applied for the day parameter to capture curvilinear relationships. To disentangle the effects of the different waste combinations, a model without and with interaction term was tested. Anova type *III* analysis was used to test for the most suitable model (Table A.1). The LMM approach was also applied to assess the volume reduction. Significant differences where identified were $p < 0.05$. Final nitrogen, phosphorus and potassium (NPK) values and total pesticide residue levels were grouped by mixture and analysed using Anova. When significant a post hoc Tukey’s HSD test was conducted.

Table 1
Physicochemical characteristics, nutrient- and heavy metal levels of the three matured composts after nine months of composting (mean ± SE). R is 100 % roses, T is 80 % roses + 20 % tomato and C is 90 % roses + 10 % mature rose compost. The last two columns indicate optimal levels and corresponding references.

Compost mixtures[1]					
	R	T	C	Optimal level	Reference
Characteristics					
pH	8.1 ± 0.0	8.0 ± 0.1	8.3 ± 0.1	5.5 – 8.0	Idrovo-Novillo et al., 2018
EC (dS m^{-1})	5.4 ± 0.4	5.9 ± 0.8	5.7 ± 0.9	2.0 – 6.0	Awasthi et al., 2014
OM (%)	18.3 ± 0.5	14.0** ± 0.3	18.1 ± 1.7	≥ 15 %	Saveyn & Eder, 2014[2]
C/N	9.5 ± 0.4	8.4 ± 0.2	9.7 ± 0.2	< 10	Mathur et al., 1993
C (%)	9.3 ± 0.31	6.8 ± 0.1	9.5 ± 1.1	*	
N (%)	1.0 ± 0.1	0.8 ± 0.0	1.0 ± 0.1	*	
DOC (mg g^{-1})	1.8 ± 0.0	1.1 ± 0.0	2.0 ± 0.2	≤ 17 or < 4	Bernal et al., 2009; Zmora-Nahum et al., 2005
N-NH_4 (mg g^{-1})	0.07 ± 0.00	0.05 ± 0.00	0.06 ± 0.00	< 0.4	Zucconi & de Bertoldi, 1987
N-NO_3^- (mg g^{-1})	0.43 ± 0.04	0.64 ± 0.16	0.35 ± 0.09	*	
N-NH_4^+/ N-NO_3^-	0.17 ± 0.01	0.08 ± 0.02	0.19 ± 0.03	< 0.16 or < 0.5	Bernal et al., 2009; TMECC, 2002
CEC (cmol kg^{-1} OM)	348 ± 7	397 ± 8	363 ± 11	≥ 70 % increase	Gondek et al., 2020
as % increase	197	150	147		
Phenols (g EGA kg^{-1})	133 ± 6	91 ± 3	155 ± 9	*	
Macro-nutrients (g kg^{-1})					
P	1.7 ± 0.0	1.4 ± 0.0	2.4 ± 0.1	*	
Na	2.0 ± 0.2	1.9 ± 0.1	2.3 ± 0.1	2.3	Idrovo-Novillo et al., 2018[3]
K	9.9 ± 0.4	9.0 ± 0.6	10.0 ± 0.4	*	
Ca	14.2 ± 0.3	13.5 ± 0.5	17.2 ± 1.0	*	
Mg	4.3 ± 0.2	4.5 ± 0.1	4.7 ± 0.2	*	
Micro-nutrients (mg kg^{-1})					
Fe	24613 ± 431	25586 ± 499	22449 ± 341	*	
Mn	683 ± 58	650 ± 25	756 ± 2	*	
Cu	10.2 ± 0.7	15.5 ± 3.3	14.0 ± 0.7	*	
Zn	219 ± 13	173 ± 5	221 ± 11	*	
Heavy metals (mg kg^{-1})					
Cr	8.2 ± 0.7	7.7 ± 0.4	7.9 ± 0.2	< 100	Saveyn & Eder, 2014
Ni	7.8 ± 0.5	8.0 ± 0.5	8.0 ± 0.3	< 50	Saveyn & Eder, 2014
Cd	0.0 ± 0.0	0.1 ± 0.1	0.1 ± 0.1	< 1.5	Saveyn & Eder, 2014
Co	4.7 ± 0.1	4.8 ± 0.2	4.3 ± 0.0	*	
Pb	21.5 ± 4.1	18.8 ± 1.4	19.6 ± 2.1	<120	Saveyn & Eder, 2014
As	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	*	
Se	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	*	

[1] mean ±SE, dry weight basis, n=6
[2] guidelines by European Commission
[3] specifically for rose cultivation purposes
* no optimal level agreed on in literature
** optimal level not met

3. Results

3.1. The composting process

Temperatures increased rapidly for all mixtures after the start of the composting experiment, reaching thermophilic temperatures, which were maintained for over three weeks (Fig. 1). During the active phase, the composts were turned six times. After 19 weeks temperatures declined for all mixtures and the compost reached the maturation phase which was maintained for 21 weeks (Fig. 1). Volume reduced significantly during composting with no significant differences between the different mixtures ($p<0.001$, $R^2m=0.84$, Table A.1) and thus no differences in final volumes. Green waste volume reduced on average by 82 % during the nine months composting process (before and after pictures can be found in Fig. A.1). Volume reduction for the R, T and C mixtures were, respectively 84.1 ±2.3, 82.9 ±0.4 and 79.2 ±1.7 %. The accumulative loss of OM was 91–95 % in all mixtures over the nine-month composting period (RMS < 5, $R^2m > 0.95$), but with no significant differences in maximum losses (A) ($p=0.93$, Fig. 2). Maximum degradation rates (k) were respectively 0.05 ± 0.01, 0.05 ± 0.01 and 0.03 ± 0.01 for the R, T and C mixture, with no significant differences between the mixtures ($p=0.30$, Fig. 2). Final OM percentages were respectively 18.3 ± 0.5, 14.0 ± 0.5 and 18.1 ± 1.7 for the R, T and C mixtures. The T mixture did not meet the requirement of OM > 15 % as stated by the European commission (Table 1) (Saveyn & Eder, 2014).

For most of the physicochemical parameters no significant differences between the mixtures in evolution over time were observed (Table A.1). Only polyphenols ($p=0.04$, $R^2m=0.79$), CEC ($p=0.04$, $R^2m=0.92$) and N-NO_3^- ($p<0.001$, $R^2m=0.63$) showed a significant interaction term and thus a different evolution over time for the tested mixtures. The pH values peaked at the start of the maturation phase after

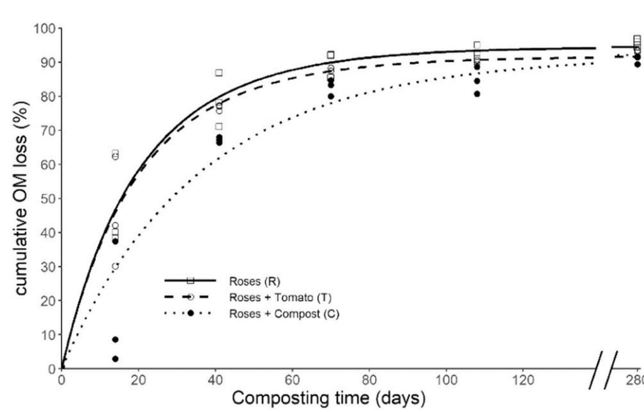

Fig. 2. Organic matter loss during composting for the three different mixtures (n=3). Curves were fitted to a 1st order kinetic curve; symbols indicate individual values per pile.

which values slightly decreased again (0.3–0.7 pH units). C/N ratio decreased gradually from 15 to 18 to below 10 during the process whereas the largest decrease in polyphenols (70–80 %) was observed during the first six weeks of composting, *i.e.* the initial phase (Table A.2). Additionally, $N\text{-}NH_4^+$ levels decreased to values below 0.02 mg g^{-1} across all mixtures after composting, whereas $N\text{-}NO_3^-$ levels decreased during the thermophilic phase, followed by rising levels during the maturation phase. $N\text{-}NO_2^-$ decreased over time and was absent in the matured composts (Table A.2).

3.2. Mature compost assessment

The quality of mature composts was assessed by both the stability and maturity of the compost (Bernal et al., 2017). The absence of reheating after turning indicated the formation of stable compost (Fig. 1). The physicochemical parameter values of the three tested composts at the end of the composting experiment were compared to optimal levels obtained from literature to assess the maturity of compost (see Table 1 for references). All compost reached a suitable degree of maturity within nine months of composting. The R and C mixtures showed very similar final characteristics, whereas the compost with the addition of tomato waste was slightly different (Table 1). The optimal range of pH was slightly exceeded with the current values ranging between 8.0 and 8.3. OM % for the T mixture was on the lower side, whereas the ratio between $N\text{-}NH_4^+$ and $N\text{-}NO_3^-$ was on the higher side for the R and C mixture (Table 1). CEC per g OM increased with ≥ 70 % for all mixtures (Table A.2). Heavy metal concentrations for all mixtures fell well below the critical levels as established by the European Commission (Table 1).

Total and plant available NPK values were measured to assess the potential fertilizing capacity of the matured composts (Table A.3). Only total P concentrations were significantly different between the different mixtures ($p<0.001$), with the highest value of 2.42 ±0.09 mg g^{-1} compost for the C mixture (Fig. 3). There were no significant differences in either total or plant-available summed NPK values between the mixtures.

3.3. Pesticide residues

Residues from 8 to 12 pesticides out of the approximately 50 pesticides used within rose cultivation were detected in the mature compost of the different piles (Fig. 4, Table A.4). These all belong to the classes of fungicides and insecticides (Table A.4). Cumulative pesticide residue levels for the R, T and C mixture were respectively 1.54 ± 0.25, 2.61 ± 0.32 and 1.83 ± 0.25 mg kg^{-1} compost with no significant differences between the mixtures ($p=0.08$). The presence of two pesticides stand out, the fungicide fluopyram and the insecticide flubendiamide (Fig. 4). Residue concentrations of fluopyram are similar for the three mixtures ($p=0.58$), whereas for flubendiamide concentrations found in the T mixture were significantly higher compared to the R and C mixture ($p=0.01$). For some pesticides, *e.g.,* emamectin and spinetoram only trace concentrations (≤ 0.01 mg kg^{-1}) were detected (Table A.4).

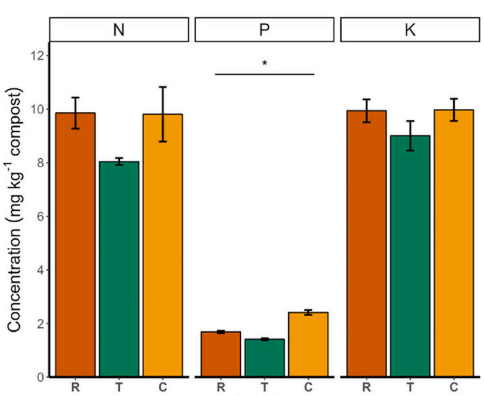

Fig. 3. Total plant available NPK concentrations for three final compost mixtures: R (100 % rose waste), T (80 % rose waste, 20 % tomato waste) and C (90 % rose waste, 10 % mature compost). Dry weight basis, n=3, mean ±SE. Significant differences between mixtures as derived from Tukey's HSD post hoc tests are indicated by an asterisk.

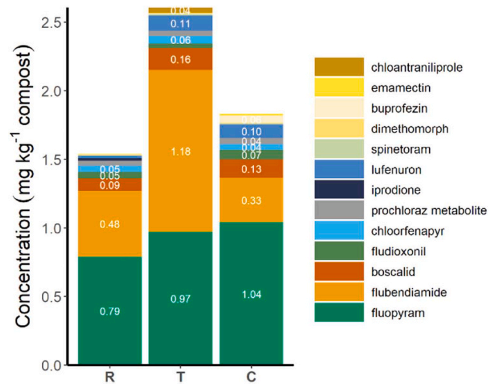

Fig. 4. Mean pesticide residue levels in mature compost for three compost mixtures: R (100 % rose waste), T (80 % rose waste, 20 % tomato waste) and C (80 % rose waste, 10 % mature compost). Dry weight basis, (n=3). Values given if concentration exceeded 0.04 mg kg^{-1}.

3.4. Closing the cycle of resources

The feasibility of recycling rose waste was assessed by large-scale implementation of composting as waste management strategy at a Kenyan rose farm. This scenario sketch was conducted for a farm with 40 ha of rose crops in continuous production where compost would be amended prior to planting rose seedlings (Fig. 5). Rose crops can remain commercially productive for approximately 8 years before they are replaced, therefore an overall assessment per 8 years was made. However, the crops cover the age spectrum and will be replaced sequentially. With a conservative estimate of a daily waste production of 50 kg per ha, this results in 2000 kg of green waste per day (de Nijs et al., 2023). Fresh green waste bulk density was established at 200 kg per m^3, which equates to 10 m^3 of green waste with a production of 2000 kg per day. Bulk density for mature compost was established at 870 kg per m^3. With an average volume reduction of 82 % during composting, this equates to a compost production of roughly 5300 m^3 per 8 years. To close the cycle of resources this amounts to a soil amendment rate of 11.5 kg per m^2 (Fig. 5). During the thermophilic phase, volume reduction occurs rapidly, this allows for the combination of windrows after 1–2 months to save space and to ensure the feasibility of this waste management strategy at Kenyan rose farms.

4. Discussion

4.1. Evaluation of mature compost

All three mixtures reached and maintained thermophilic

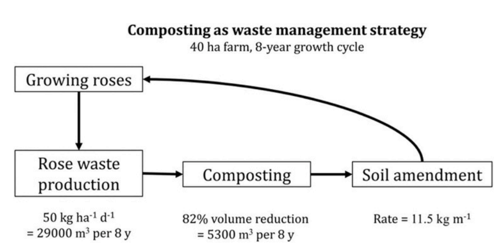

Fig. 5. Scenario sketch for a 40 ha rose cultivation farm.

temperatures for over three weeks, thereby meeting the standard sanitation requirements for safe compost, *i.e.,* temperature >55 °C for 14 days and at least five turnings during this active period (Suárez-Estrella et al., 2007; Bernal et al., 2017; Jurado et al., 2015) (Fig. 1). The rise in temperature, typical of the active composting phase, indicated high level of microorganism activity, resulting in a high degradation rate which consequently resulted in a volume reduction of over 80 %. This is comparable to values for windrow composting studies as reported in Yue et al. (2008) and relatively high when compared to a drum composting study of food waste where volume reduction was up to 50 % after composting (Manu et al., 2017). The observed decline in OM levels during the composting process was likely influenced by the mixing with mineral material during mechanical turnings. Similar trends were observed in a drum co-composting study of rose waste where maximum OM loss values varied between 68 % and 80 % (de Nijs et al., 2023). Al-Alawi et al. (2020) on the other hand, found maximum OM loss of approximately 50 %, which might be caused by the considerable shortened maturation phase. C/N ratio gradually decreased to the optimal range of <10, which is essential for stable compost (Table 1).

EC levels strongly decreased during the first months of composting from values above 20 dS m^{-1} to values below 6 dS m^{-1} (Table A.3). This decrease can be attributed to the release of base ions during microbial decomposition, and leaching facilitated by percolating rainwater (Gavilanes-Terán et al., 2016; Rasapoor et al., 2016). Elevated salt levels can impact crop growth, constraining compost application potential (Awasthi et al., 2014; Cai et al., 2014). While tomato waste compost has higher EC levels, all composts remained within the optimal agricultural ranges (Tabrika et al., 2019) (Table 1). However, composts with EC levels on the higher side of this range should be used at lower amendment rates since opinions on the upper value vary (Onwosi et al., 2017; Waqas et al., 2017). pH levels increased during active composting, attributed to the breakdown of organic acidic compounds and ammonification (Paredes et al., 2001; Rasapoor et al., 2016). During maturation, the last three months, pH levels decreased for all mixtures, reaching levels similar to other green waste composting experiments but on the high side of the optimal range (Table 1) (Gavilanes-Terán et al., 2016; Idrovo-Novillo et al., 2018; Tabrika et al., 2019). The decline in pH during maturation is a side effect of the nitrification, mainly occurring when temperatures fall below 40°C and aeration favours nitrifying bacteria (Rasapoor et al., 2016; Cáceres et al., 2018). The volatilization of NO_3^- and consumption of NH_4^+ further decreases the pH (Chang et al., 2021). Initial N-NO_3^- concentrations were relatively high for all three mixtures, probably due to high N-NO_3^- concentrations in the raw materials which is characteristic for horticultural wastes (Jurado et al., 2015). These values dropped significantly, particularly in mixtures lacking mature compost, followed by an increase due to nitrification in the maturation phase. Temporal N-NO_2 accumulation occurred after approximately six weeks of composting (Table A.2). Nitrite, an intermediate product of nitrification, can temporarily accumulate when the last nitrification step is slowed down by *i.e.* a high pH (Cáceres et al., 2018). The ratio of N-NH_4^+/ N-NO_3^- exceeds the optimal limit of <0.16 for composts of all origins as established by Bernal et al. (1998). However, it complies with the requirement of a ratio < 0.5 for 'very mature' compost according to the CCQC maturity index (TMECC, 2002). According to CCQC guidelines, 'very mature' compost can be used as direct growth medium and topsoil blends, making it suitable for general agricultural usage.

Final N-NO_3^- concentrations ranged between 350 and 640 mg kg^{-1} across mixtures, which is on the high side compared to nitrate levels achieved in various other green waste composting studies (150–300 mg N-NO_3^- kg^{-1}) as shown in a review by Cáceres et al. (2018) (Table 1). Cation Exchange Capacity (CEC) indicates humification and increased by 197, 150 and 147 % for respectively R, T, and C, surpassing the ≥ 70 % increase threshold for mature compost (Gondek et al., 2020) (Table 1). High nitrate and CEC levels, along with low phytotoxic polyphenols, indicate high plant fertilizing potential for all mixtures. Final macro- and micro-nutrient contents were similar across the mixtures (Table 1). The Na concentrations reached up to 2.3 g kg^{-1}, remaining below levels considered safe by Idrovo-Novillo et al. (2018), mitigating concerns about rose sensitivity to elevated salt levels (Cai et al., 2014). Heavy metal concentrations remained well within safe usage limits (Saveyn & Eder, 2014).

After 280 days of composting, the three tested mixtures resulted in mature and stable compost with good fertilizing capacities. Incorporating mature compost as an inoculant proved effective in enhancing OM degradation, supporting previous findings (Yang & Zhang, 2022). This suggests that incorporating mature compost could improve overall degradation efficiency. Additionally, mature compost can serve as a base layer to prevent leachate runoff and limit mineral soil contamination (Rasapoor et al., 2016). With a volume reduction of over 80 %, composting efficiently utilizes space allocated to green waste management while producing a valuable soil amendment. Although the mixture with only rose waste took slightly longer to reach high temperatures, indicating variations in microorganism activity, all three mixtures demonstrated satisfactory composting, resulting in high quality compost suitable for agricultural application. The results from this study are strongly linked to the specific conditions under which this composting experiment was conducted, which may not be directly replicable in other waste types or settings.

4.2. Pesticide residue levels in mature compost

Within rose cultivation, approximately 50 crop protection compounds (*i.e.* pesticides) are used, but only 8–12 were recovered in the various matured composts, representing about 20 % of initially applied pesticides (Fig. 4). Furthermore, residues of several persistent pesticides such as iprodione were not measured in the matured compost. The insecticide flubendiamide and fungicide fluopyram formed the largest part of the residual pesticide levels, with especially elevated levels for flubendiamide in the compost mixture with tomato. The addition of tomato waste increased overall pesticide residues mature compost, suggesting caution in using this waste type to minimize residue pressure. Degradation rates of pesticides throughout the composting process were not measured in this study.

Flubendiamide, an eco-friendly insecticide against lepidopterous insects, has low leaching potential due to its high sorption constant (Das et al., 2015). With a relatively resistant nature, it exhibits half-life times ranging from 150 to 770 days in field soil biodegradation studies, mainly depending on soil -type, -moisture level and -temperature (MacBean, 2010; Das & Mukherjee, 2012; Mukherjee et al., 2016). It is commonly used in tomato cultivation, explaining the increased concentration found in the compost where tomato waste was added. Fluopyram, effective against fungi and nematodes, shows variable half-life times between 21 and 539 days in soils under field conditions varying widely depending on soil type (Rathod et al., 2022). Rathod et al. (2022) highlights the limited understanding of fluopyram's fate in different soils and conditions, noting that its highly persistent behavior can present environmental risks. The accumulation in soils after repetitive amendment can potentially *e.g.* harm non-target organisms, cause the development of pesticide-resistant pests and cause leaching to surface waters (Siedt et al., 2021). In rose cultivation, the impact of periodic compost amendment on soil pesticide residues needs consideration against the build-up from the usual pest control regime. No comprehensive studies on the effects of fluopyram on soil organisms have been conducted yet.

Recently, pesticide residue presence in the agriculture has gained attention (Silva et al., 2019). Geissen et al. (2021) call for defining safety benchmarks regarding pesticide residues in soils. In their study, they detected pesticide mixtures in non-organic fields, with up to 16 different compounds and a maximum cumulative concentration of 12 mg kg^{-1} depending on the crops cultivated (Geissen et al., 2021). Even though their study was conducted in Europe, this 12 mg kg^{-1} is significantly higher than the cumulative values between 1.54 and 1.83 mg kg^{-1} compost found in the current study. Silva et al. (2019) found an average pesticide content of 2.05 mg kg^{-1} in 317 European agricultural topsoils, indicating the prevalence of pesticide residues within the agricultural sector. Composting effectively treated pesticide-contaminated matrices, signficantly reducing concentrations of most pesticides, only limited reduction was observed for the most persistent pesticides (*i.e.* triazole fungicides, bifenthrin, linuron) (Kupper et al., 2008; Wilde et al., 2010).

Given the absence of established maximum residue levels for pesticides, assessing the implications of pesticide residue levels in matured compost is challenging. Especially since final concentrations in the soil are highly dependent on both application rate and legacy pesticides. Compost addition enhances microbial activity and thereby degradation of several commonly used pesticides, but risks from repeated application should not be ignored (Siedt et al., 2021). Prior research highlighted composting as a promising bioremediation method for pesticide contaminated green waste from the floricultural sector (Kupper et al., 2008; Lashermes et al., 2012). Composting as waste management strategy for large-scale rose farms favours the remediation process of pesticide residues in green wastes. A better understanding of pesticide residues in compost and soils will help to formulate recommendations for growers interested in composting. Additionally, switching from persistent pesticides to those with better degradation prospects can reduce environmental risks and human exposure.

4.3. *Composting: benefits and challenges*

Implementing composting practices at large-scale rose farms will enhance ecological sustainability of the sector by managing green waste and re-using this waste resource. Understanding the balance between potential compost production and its application is crucial for evaluating the viability of this practice.

Rose cultivation, with an average crop rotation cycle of 8 years, allows for compost amendment once per cycle. A scenario sketch for a 40 ha farm indicated a soil amendment rate of 11.5 kg per m^2 prior to planting, thereby closing the cycle of resources. In the majority of the cases, crop patches were gradually taken into production, leading to a continuous cycle of crop replacement and thus continuous demand for and production of compost. Literature shows varying compost amendment rates ranging from 0.4 to 15 kg compost per m^2 (Meena et al., 2016; Idrovo-Novillo et al., 2019), with reasoning based on *e.g.* OM percentage (Idrovo-Novillo et al., 2019), mineralization rates comparable to mineral fertilization (Bedada et al., 2014), or a certain level of total N (Rothé et al., 2019). Governmental limits in the European Union on compost amendment rates differ between countries and the type of compost used. Generally, limits are based on maximum heavy metal concentration or N concentration (European Parlement, 2019). However, these often assume annual reapplication of compost, whereas within rose cultivation, topdressing of compost could be used for interim reapplication while the main compost amendment would be done once every 8 years. Idrovo-Novillo et al. (2019) and Forge et al. (2015) investigated the effect of compost amendment on perennial crops (*i.e.* roses and raspberry) with favourable results for application rates between 9 and 15 kg m^{-2}, aligning with the presented scenario (Fig. 5). This emphasizes the potential for closing the cycle of resources by utilizing the green waste as a soil amendment source.

Compost amendment can improve soil structure, exert plant pathogen suppression, sequester C into the soil, but also maintain or increase soil fertility thereby potentially reducing chemical fertilizer demand (Bernal et al., 2017; Milinković et al., 2019; Siedt et al., 2021). Several studies investigated the (partial) replacement of conventional fertilizer with organic amendments with promising results. Meena et al. (2016) used compost in combination with 25 % of the recommended fertilizer which also lowered soil EC levels. Bedada et al. (2014) reported improved soil properties and crop productivity for compost + fertigation treatments compared to only fertigation. Idrovo-Novillo et al. (2019) did not find increased yield when substituting conventional fertilizer for compost, but this could also be attributed to the elevated pH of the irrigation water compared to the fertigation. Adopting composting in large-scale rose farms can promote a more sustainable and ecologically friendly production system by reducing reliance on chemical fertilizer. Future research should explore the long-term effects of compost application within the production cycle of cut roses, considering net mineralization rates and nutrient release over multiple years.

Currently the re-use of compost within the production of cut roses in Kenya is limited. To our knowledge, no studies have explored Kenyan farmers' perceptions of composting. Case et al. (2017) found that Danish farmers had positive views on composting, recognizing its potential for soil improvement and economic benefits. However, both lack of knowledge and costs were identified as the main barriers to adoption and farmers desired clear evidence of increased yields and reduced dependence on chemical fertilizers. Case et al. (2017) suggested a targeted educational approach to overcome these obstacles and promote resource recycling through composting.

5. Conclusion

The (co-)composting of rose waste within a large-scale commercial setting was effective. The resulting mature compost met the sanitation requirements for safe agricultural application in terms of pathogens and contaminants, and also showed high fertilizing capacity. Composting could be an effective bioremediation method for pesticide-contaminated green wastes, as only 8–12 pesticides were recovered in the matured composts from 50 pesticides known to be used within Kenyan rose cultivation. However, caution should be taken with annually amending the compost to prevent pesticide residue accumulation in soils, and usage of green wastes high in pesticide residues should still be avoided. These promising findings endorse the adoption of turned windrow composting within the flower cultivation sector. These results will support the implementation of policy decisions by the local government. The implementation of composting practices at large-scale rose farms offers space-efficient waste management, and generates a valuable organic fertilizer thereby promoting resources circularity within the sector.

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. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.clwas.2024.100154.

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