Rhizosphere 29 (2024) 100850

Contents lists available at ScienceDirect

Rhizosphere

journal homepage: www.elsevier.com/locate/rhisph

Variability in decomposition rate of sorghum cultivar residues linked to lignin content

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ARTICLE INFO

Keywords:
Decomposition
Residue quality
Carbon emissions
Carbon storage
Nutrient cycling

ABSTRACT

Crop residue decomposability in soils is of major importance for maintaining soil carbon (C) stocks and nitrogen (N) mineralization, which are vital for soil fertility and climate change mitigation. The impact of biochemical quality on decomposition and N mineralization of sorghum cultivars and/or crop residue parts is not well documented. In the present study, field and laboratory experiments spanning 168 and 120 days, respectively, were used to assess the rate of decomposition and N mineralization in soils from five sorghum cultivars and to relate the results with residue quality (i.e. lignin: N ratio) over time. High-quality cultivars (i.e., Mamolokwane and OS-Potch) exhibit rapid decomposition (>50% DM loss) and elevated carbon dioxide emissions in shoots, attributed to a low lignin-to-nitrogen ratio. Low-quality residues (i.e., AS8 and KZ5246) initially undergo net nitrogen immobilization, transitioning to mineralization at later stages. Notably, shoots consistently release more nitrogen than roots, with distinct NO_3^--N mineralization values ranging from 22.7 to 11.5 mg N/kg for OS-Potch and KZ5246 shoots and 20.6 to 9.3 mg N/kg for their root residues. Results suggest that low-quality sorghum residues, particularly KZ5246 and AS8 roots, release carbon and nitrogen at a slower rate, providing potential for carbon storage and limited nitrogen availability compared to high-quality residues like OS-Potch shoots.

1. Introduction

The release of carbon (C) and nitrogen (N) compounds in the form of CO_2 and nitrous oxide (N_2O) into the atmosphere due to decomposition from agricultural land is leading to reduced soil fertility and exacerbating climate change in South Africa and globally (Bedeke, 2023; Muñoz et al., 2010; Follett, 2001). Chaplot and Smith, (2023) pointed out that globally, exports of nutrients from soils which also occur through crop harvest are major contributors to soil organic matter loss, leading to ecosystem degradation. The CO_2 released from agro-ecosystems accounted for 13% of total anthropogenic productions in 2019 according to Intergovernmental Panel on Climate Change (IPCC) (Nguyen and Kravchenko, 2021). Nitrogen trace gas emissions and leaching linked to agriculture saw substantial increases of 21.5% for nitrogen oxide (N_2O) and 17.0% for ammonia (NH_3) due to straw returns. These increases were primarily attributed to enhanced N nitrification and/or denitrification processes, as well as heightened enzymatic activity such as soil urease (Xia et al., 2018). The World Meteorological Organisation (WMO) found the levels of CO_2 emissions from January to May 2022 to be 1.2% greater than those recorded during the same period in 2019 (https://public.wmo.int/en/resources/united_in_science).

Climate change is often associated with high temperatures and variability in annual precipitation, which severely alter nutrient cycling and crop productivity, particularly in rain-fed agricultural systems of sub-Saharan Africa (SSA) (Goche et al., 2020). The decomposition linked with CO_2 emissions and N mineralization is often used as a proxy for appraising the potential SOC stocks and the fate of N in soils. There is a significant amount of organic carbon and plant nutrients in crop residues (Surekha et al., 2003). The potential for soil carbon and nitrogen availability depends primarily on the chemical composition and biodegradability (tannins and metabolites) of the crop residues (Kumar and Goh, 1999). Sorghum is regarded as one of the principal cereal crops in Africa (Andiku et al., 2022). Its agricultural productivity, resilience, and biochemical and genetic controls in partitioning carbon to various compositional constituents (i.e., lignin, cellulose, and hemicellulose) are distinguishing factors for its decomposition (Brenton et al., 2016).

The crop residues left on the surface in the off-season are burned, fed

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https://doi.org/10.1016/j.rhisph.2024.100850
Received 12 April 2023; Received in revised form 8 January 2024; Accepted 8 January 2024
Available online 18 January 2024

to livestock, or incorporated through tillage in most low-income small-scale farms of SSA (Wang et al., 2018, 2020). Burning of crop residuals mostly leads to air pollution, and loss of plant nutrients and organic matter (Sandhu et al., 2022). Conversely, crop residue C can be transported to soils via residue retention after harvest and/or through root turnover and exudation (Henning et al., 1996; Menichetti et al., 2015). el Zahar Haichar et al. (2014), found that plants can transfer about 5–21% of total photosynthetically fixed carbon into the rhizosphere through root exudates. About 68 % of residue C mineralization was observed from surface-placed and 86 % from buried residues by Lynch et al. (2016). However, residues may vary in decomposition or mineralization patterns due to their biochemical qualities (i.e., tannins and secondary metabolites; lignin, and N contents; lignin: N and C: N ratios) and the existence of genotypic variation by environmental effects (Kriaučiūnienė et al., 2012; Prakasham et al., 2014; Stewart et al., 2015; Zengeni et al., 2021). The lignin biomarker biochemistry is significantly different between C3 (soybean, sunflower, and wheat) and C4 crops (sorghum and corn), depicting supplementary structural complexity and biochemical recalcitrance (Hatfield et al., 2009). Residues with more tannins and secondary metabolites might decompose slowly. However, the decomposition of high lignin residues can be higher in soils with greater N concentration, due to enhanced enzymatic activity (i.e., ligninolytic enzymes) (Stewart et al., 2015; Ntonta et al., 2022). Thus, previous studies have assumed measurable organic pools in the root and shoot residues to have different decomposition patterns, ranging from faster labile fractions to slower recalcitrant molecules (Shahbaz et al., 2017; Ntonta et al., 2022).

Srinivas et al. (2020) observed the roots of 8 rainfed crops (sorghum, green gram, sunflower, maize, castor, pigeon pea, cowpea, and horse gram) to have a 2 to 3 times higher lignin: N ratio than shoots, resulting in higher C mineralization (31.4%) in roots compared to shoots (50.2%) after 120-day of decomposition in soils. These observations agreed with other studies suggesting root litter to be an influencing factor in below-ground carbon turnover (Abiven et al., 2005; Almagro et al., 2021). In a 12-month decomposition experiment, Xu et al. (2017), reported higher initial C retained in wheat residues (43%), followed by maize (40%) than soybean (37%); with 78, 73, and 69% of the N remaining in wheat, soybean and maize residues, respectively. The higher initial N concentration in leguminous plants, due to biological nitrogen fixation, decreased the C: N ratio leading to faster initial decomposition and C loss (Zeng et al., 2010). Ruhland et al. (2018) examined the pattern of decomposition of four sorghum cultivars in a 160-day field study and discovered that over half of their initial mass had been lost by the end of the experiment. Wild-type cultivars showed the slower average mass loss (50.8%), followed by brown-midrib-6 (57.4%), brown-Madrib-12 (61.7%), and double mutant litter having the fastest (58.4%). These observations were consistent with initial residue chemistry, as lower initial lignin concentrations and C: N ratios with higher N were observed in brown-midrib cultivars, hence, the faster decomposition rate as compared to the wild-type.

Additionally, Hadas et al. (2004) proposed the C: N ratio of crop residues often plays a significant role in evaluating whether the residues will mineralize or immobilize inorganic N. Hence, materials with a low N or high C: N ratio resulted in initial N immobilization (Jensen et al., 2005). Thus, Huang et al. (2004) found sugarcane stalks with a high C: N ratio to stimulate NH_4^+-N immobilization, while Fageria et al. (2005) found cover crops and leguminous crop residues to mostly have a higher mineralization rate, due to their N fixation capacity. Comparable results were found by Li et al. (2020), with leguminous cover crops (clover and vetch) showing an average net N mineralization of 33% which was higher than non-legume (20%). Hence, this study builds towards the selection of superior cultivars and/or plant parts that will contribute to soil C stocks and N cycling in soils. The focus was on studying residue digestibility in non-ruminants, where high lignin content is associated with low-quality crops. The underlying hypotheses were that the decomposition rate and mineralization of root and shoot residues of different sorghum cultivars would vary significantly over time. Decomposition potential is expected to be slower in the roots of AS8 and KZ5246 sorghum cultivars, leading to reduced carbon and nitrogen mineralization in both controlled experimental and field conditions.

2. Materials and methods

2.1. Site description

The litterbag study was conducted on an arable field located at Ukulinga Research Farm of the University of Kwa-Zulu Natal, South Africa (29.67′S and 30.41′E, altitude 811 m above sea level). The soils at this site were loam in texture (Phophi and Mafongoya, 2017; Chikuvire et al., 2018) and were classified as Dystric Regosols according to the Soil and Terrain Database for southern Africa (McGranahan et al., 2016), dominated by Westleigh soil form determined by Soil Classification Working Group-1991 (Turner, 2013) or Plinthic Acrisols according to the International Soil Classification System (IUSS Working Group WRB-2014) (Schad, 2016). This area has warm to hot summers with a mean monthly maximum temperature of 26 °C, mild winters with a mean monthly minimum temperature of 8.8 °C (Swemmer et al., 2007), and annual rainfall of 694–738 mm (Morris and Fynn, 2001; Mwadzingeni et al., 2016). The average temperatures and rainfall of the litterbag trial site during the study period are shown in Table 1. Supplemental irrigation was applied using sprinkler irrigation, while weed control was done by hand hoeing, when necessary.

A sub-sample (0.5 kg) was taken for the determination of the soils' physical and chemical properties (Table 2). The hydrometer method explained by Okalebo et al. (2002) was used for particle size analysis and pH (in 1 M KCl) was measured by Hanna pH microprocessor meter (Model 211). Total C and N were determined using an automated LECO-Trumac CNS Auto-analyzer version 1.1× (St. Joe, MI, USA (United States)). The AMBIC-2 method, as modified by Hunter, (1975), Manson and Roberts, (2000), was used for P determination. The extractable (1 M KCl) calcium and magnesium in the soil were displaced with a neutral 1.0 N NH_4OAc solution (Maral, 2010). The soil bulk density was determined on the undisturbed field soils (0–10 cm depth) following the core method (Blake and Harte 1986).

2.2. Studied crop residue materials

The residues were selected from ten cultivars of sorghum crops that proved to have high biomass production from a previous biomass allocation study (Zengeni et al., 2021). The sorghum accessions were used to represent a considerable genetic pool as they were collected from different provinces across South Africa and possibly exhibit divergent adaptation (Table 3). They were still in developmental stages and were previously evaluated for drought tolerance and diversity (Zengeni et al., 2021) and the sorghum residues were analyzed for initial acid detergent lignin and cellulose content using the filter bag technique (ANKOM-200 technology method) (AOAC, 1984). Total initial C and N contents were also determined using an automated LECO Trumac CNS Auto-analyzer Version 1.1 ×. The results informed the selection and categorization of five cultivars based on their biomass production, and lignin: N ratio (Table 4). Thus, in the end, we had two varieties with high quality (low lignin: N ratio (<1: 10) and high N content), two with low quality (high lignin: N (>1: 10) and N content), and one with medium quality parameters, as per Vahdat et al. (2011).

2.3. Litterbag experimental design

This experiment was designed in a randomized complete block design in plots of a growing BWI62 winter-wheat cultivar, replicated into three blocks based on slope position (top-, mid-, and bottom slopes considered). The trial land was tilled and supplemented with a basal fertilizer (2:3:2); N: P: K, at 25 kg N ha^{-1} after disking, as recommended

Table 1
Average temperatures and rainfall at Ukulinga Farm-Pietermaritzburg (https://www.worldweatheronline.com/pietermaritzburg-weather-averages/kwazulu-natal/za.aspx).

	July	August	September	October	November	December	January
	Year 2019						Year 2020
Temperatures (°C)	17	18	19	21	20	21	22
Rainfall (mm)	2.8	14.2	41.2	37.4	236	145	236

Table 2
Soil physicochemical properties for incubation study.

Soil Property	Values ± SD
Bulk density (g cm^{-3})	1.24 ± 0.006
Sand (%)	30.0 ± 0.061
Silt (%)	34.9 ± 0.058
Clay (%)	35.1 ± 0.015
Texture	Loam
pH (KCl)	4.8 ± 0.015
Exchangeable acidity (cmol kg^{-1})	0.047 ± 0.001
Total carbon %	1.9 ± 0.067
Total nitrogen %	0.18 ± 0.01
Phosphorus (mg kg^{-1})	11 ± 0.051
Potassium (mg kg^{-1})	114 ± 0.168
Calcium (mg kg^{-1})	1294 ± 0.176
Magnesium (mg kg^{-1})	389 ± 0.156

for normal rain-fed wheat growth (Panhwar et al., 2019). Each plot was 5 × 5 m in size, with 1 m separating the distance between the plots. Each plot was made up of 10 wheat rows, with 45 cm inter-row and 10 cm intra-row spacing.

The shoot and root residues of the five selected sorghum cultivars were oven-dried at 65 °C temperature for approximately 72 h and chopped into 2–4 mm pieces before 10 g of either root or shoot residues were filled into each litterbag (20 × 40 cm nylon organza bag of <1 mm pores). The materials were closed by stapling and evenly distributed within the bags. In each of the three blocks, there were eight plots. Two slots (holes) about 10 cm deep, with a width of the size of the dimension of the litterbags were opened in each plot using a spade, with 1 m spacing separating the slots. Within each slot, 5 litterbags of roots and 5 shoots were evenly placed separately per cultivar and/or plant part (limited contact to each other, to avoid contamination). They were then buried using the surrounding soils to create contact between the litterbags and the soil. At 0, 14, 28, 42, 56, 84, 112, and 168 sampling days, litterbags were collected using a destructive sampling method and gently brushed to ensure that the adhering soil was removed, then transported to the laboratory. The samples were oven-dried at 70 °C for 48 h and measured for dry weight remaining and ash-free dry matter as described by Parker et al. (1984); and Daudu et al. (2009). The residue biomass loss was described by the simple exponential model (Table 4).

2.4. Incubation experiment

The incubation experiment was set up in a completely randomized design with 11 treatments replicated 3 times. These were soils amended with the root or shoot residues of five genotypes of cultivars AS8, KZ5246, LP4303, Mamolokwane, and OS-Potch, plus an unamended control. The soil samples used were collected at 0–15 cm depth from the same arable field used for the litterbag study before the experiment was initiated. These were air-dried and ground to pass through a 2 mm sieve. About 0.25 g of each residue treatment was mixed with 100 g of soil in 100 ml plastic containers (including a non-biomass treated control), slowly wetted to fill up 50% pore space, and placed in a 500 ml airtight plastic container.

2.4.1. CO_2-emission determination

A vial containing 25 ml of 1 M NaOH solution was placed inside the plastic container to trap CO_2 (Zibilske, 1994). The containers were closed so that they were airtight with aeration allowed every 3 days and incubated in the dark, in a constant temperature room set at 25 °C. The amount of CO_2–C trapped in the NaOH solution was determined by titration against 0.5 M HCl with phenolphthalein indicator, after precipitating with $BaCl_2$ at 0, 7, 14, 28, 42, 56, 84, and 120 days of incubation. The crop residues had different amounts of C in their tissues, therefore the results of CO_2–C emitted were normalized by expressing them as mg CO_2–C kg^{-1} C added. The emitted net CO_2–C was obtained by calculating the differences in the values of the biomass-treated soil and control, while net cumulative CO_2–C was calculated as the sum of all previous measurements (Table 6).

2.4.2. Mineral nitrogen determination

The experiment was set up exactly as for CO_2 emission except that the treatments and sampling times were set to allow for destructive sampling. In separate containers, the incubated treatments were analyzed for NH_4^+-N and NO_3^--N per sampling time (destructive sampling method). Samples (2.0 g) from each treatment were removed from the plastic containers at different incubation times (0, 7, 14, 28, 42, 56, 84, and 120 days) and suspended in 20 ml of 2 M KCl, shaken for 1 h at 400pm followed by 10 min of filtration. The concentration of NH_4^+-N and NO_3^--N in the extracts was analyzed using a Thermo Scientific Gallery Discrete Autoanalyzer (2014 model). Immobilization was determined by the initial available nitrogen minus the final available nitrogen. Net NH_4^+-N and NO_3^--N were obtained by the difference between the control and the biomass-treated soil. The net mineral N was calculated as the sum of NH_4^+-N and NO_3^--N content of total inorganic N (mg N kg^{-1} soil) released from the treatment after subtracting the control. Different residues contained different concentrations of N in their tissues therefore, the results of N mineralized were normalized and presented as mg N kg^{-1} N added.

2.5. Statistical analyses

All the data collected were subjected to a two-way analysis of variance (ANOVA) with interactions (plant part × cultivar), and treatment means were separated using the least significant difference (LSD) test at $p < 0.05$, using GenStat 20th addition. The correlation matrix was calculated among the variables to determine the strength of associations between biochemical properties and percentage residue remaining in the litterbag study at $p < 0.05$, using Statistica 10.0 software (Tables 5 and 7). Spearman rank correlations were determined between cumulative CO_2–C or total mineral N in the incubation study and the biochemical properties of sorghum cultivars, using SPSS.

3. Results

3.1. Weight loss in litterbags

The regression analysis revealed notable variations in root development across treatments after 168 days of experimentation. The R^2 values ranged from 0.847 for Mamolokwane roots to 0.961 for AS8 roots, indicating a high degree of variability explained by the model. AS8 roots exhibited the highest variance, as evidenced by the superior R^2 value compared to other treatments (Table 4). A significant decrease in DM remaining was observed from all treatments over time (Fig. 1a).

Table 3
The source and biochemical properties of the shoot and root residues of selected sorghum cultivars.

Part	Genotype	Source	Attributes	Biomass	Total C	Total N	Lignin	Cellulose	C: N	Lignin: N
				($g.m^{-2}$)	%					
Root	**AS8**	ACCI	Experimental hybrid	1692^{bc}	38.88^{bcde}	1.237^{cde}	29.91	6,33	29.75^{ab}	24.44^{ab}
Root	**OS-POTCH**	ARC	Experimental hybrid	1464^{bc}	41.31^{abcde}	2.298^{a}	25.56	7,04	18.06^{de}	11.15^{d}
Root	**LP 4303**	Limpopo	Landrace	1960^{abc}	41.79^{abcd}	1.991^{abc}	30.57	8,40	21.84^{cde}	16.21^{bcd}
Root	**KZ5246**	KwaZulu-Natal	Landrace	1128^{c}	36.02^{de}	1.149^{def}	29.31	7,92	31.43^{ab}	25.64^{a}
Root	**MAMOLOKWANE**	ARC	Landrace	1032^{c}	42.09^{abcd}	2.246^{ab}	26.54	8,53	18.84^{de}	11.80^{d}
Shoot	**AS8**	ACCI	Experimental hybrid	2468^{ab}	36.50^{cde}	1.430^{cd}	28.77	8,67	27.22^{abc}	20.10^{abcd}
Shoot	**OS-POTCH**	ARC	Experimental hybrid	2052^{abc}	41.35^{abcde}	2.367^{a}	26.12	4,39	17.87^{de}	11.40^{d}
Shoot	**LP 4303**	Limpopo	Landrace	2800^{a}	42.14^{ab}	1.985^{c}	29.05	4,76	21.26^{cde}	14.64^{cd}
Shoot	**KZ5246**	KwaZulu-Natal	Landrace	1560^{bc}	30.33^{ef}	1.357^{cd}	32.40	6,96	22.47^{bcd}	24.30^{ab}
Shoot	**MAMOLOKWANE**	ARC	Landrace	2212^{ab}	42.12^{ab}	2.050^{abc}	28.18	6,15	22.18^{bdc}	14.21^{cd}

*The alphabets represent the significant difference at $p < 0.05$.

Table 4
Regression equations of percentage of the shoot and root residues of sorghum cultivars remaining over time (x = incubation time in days).

Cultivar	Part	Equation	R^2
AS8	Shoot	$y = 132.63e^{-0.019x}$	0.876
AS8	Root	$y = 111.57e^{-0.012x}$	0.961
KZ5246	Shoot	$y = 127.24e^{-0.021x}$	0.905
KZ5246	Root	$y = 104.59e^{-0.013x}$	0.930
LP4303	Shoot	$y = 114.15e^{-0.022x}$	0.899
LP4303	Root	$y = 101.95^{-0.014x}$	0.878
OS POTCH	Shoot	$y = 105.58e^{-0.024x}$	0.900
OS POTCH	Root	$y = 88.585e^{-0.015x}$	0.914
MAMO	Shoot	$y = 97.527e^{-0.025x}$	0.942
MAMO	Root	$y = 91.291e^{-0.019x}$	0.847

The plant variety seems to be more important at the early stage, while the plant part seemingly becomes more important at a mid and late stage of decomposition. Precisely, 60.6 and 62.9% of the initial DM remained for OS-Potch and Mamolokwane shoots respectively at day 14, with this decrease being lower in root compared to shoot substrate. AS8 roots had only decomposed 3% of the initial mass (Fig. 1a). At day 42, high-quality residues (i.e., high N and low lignin: N, and C: N ratios) had less than 50% DM remaining compared to low-quality residues. For instance, Mamolokwane and OS-Potch shoots had the lowest DM remaining (26.9 and 31.8%, respectively), followed by their root residues (34.3 and 43.4%). The percentage weight loss decreased sharply at day 56, with Mamolokwane and OS-Potch shoots showing the lowest (16.79 and 22.27 % DM remaining, respectively), followed by Mamolokwane roots (25.65% DM remaining), then LP4303 shoots (26.05% DM remaining). Days 112–168 showed the third phase of sharp weight loss for all the treatments. Hence, at the end of this litterbag study (day 168), there was <12.5% residue DM remaining for all the treatments. In comparison, Mamolokwane and OS-Potch shoots had the lowest DM remaining (0.88 and 0.91 %) of all treatments which were much lower than their roots (1.8 and 4.5%), respectively.

Table 5 showed positive correlations between DM remaining and initial lignin content ($r = 0.14$), C: N ($r = 0.21$), and lignin: N ratios ($r = 0.20$). However, negative correlations were observed between DM and temperature along with the rainfall ($r -0.81$ and $r = -0.75$ at $p < 0.05$, respectively). The dry matter remaining showed no significant correlations with initial total C, N, and P.

3.2. CO_2 emissions incubation

In the incubation study, CO_2–C emissions peaked at day 14 with the highest value of 157 mg CO_2–C g^{-1} C added for OS-Potch shoots, followed by Mamolokwane shoots (144 mg CO_2–C kg^{-1} C added) (Fig. 1b). The CO_2 emissions were generally higher for shoot than root residues throughout the incubation (Fig. 1b). At the later stages of incubation (after 42 days), all treatments showed constant decreasing trends of CO_2 emissions, with OS-Potch shoots emitting the highest CO_2 of 98.6 mg CO_2–C kg^{-1} C added (day 56) compared to other treatments, with no significant difference between its parts. By the end of the incubation, all treatments had less than 50 mg CO_2–C kg^{-1} C added, with KZ5246 shoots showing the lowest CO_2 emission (5.8 mg CO_2–C kg^{-1} C added, at day 120), insignificantly different from its roots.

Significant differences in net cumulative CO_2–C emissions were also observed among the sorghum residues ($p < 0.001$) (Table 6). Thus, OS-Potch shoots released the highest net cumulative CO_2–C emissions of 771.5 mg kg^{-1} soil, followed by its roots (734.5 mg kg^{-1} soil), while KZ5246 shoots had the lowest net cumulative CO_2–C emissions (282,5 mg kg^{-1} soil) than all treatments, but did not differ with its roots. The LP4303 roots exhibited intermediate net cumulative CO_2–C emissions (average 487.5 mg kg^{-1} soil) in comparison to other cultivars, also with no significant difference with its shoots.

Table 5
Correlation matrix table of percent dry matter and initial biochemical properties of the roots and shoots residues of different sorghum cultivars, under litterbag study.

	Total C	Total N	Total P	Lignin	C: N	Lignin: N	Biomass	DM remaining
Total C	1.00							
Total N	**0.79***	1.00						
Total P	**0.31***	0.29	1.00					
Lignin	**−0.70***	−0.72	−0.19	1.00				
C: N	**0.51***	−0.92	−0.17	0.51	1.00			
Lignin: N	**−0.84***	**−0.99***	**−0.30***	**0.77***	**0.88***	1.00		
Biomass	**0.11***	0.01	0.18	**0.24***	0.05	0.03	1.00	
DM remaining	−0.14	−0.22	-.,15	**0.14***	**0.21***	**0.20***	0.02	1.00

-DM remaining: Dry matter remaining of residues of different sorghum cultivars of the shoot and root after 168 days; - Total C: Initial residue total carbon, - Total N: Initial residue total nitrogen; Biomass: initial residue biomass; -*: Marked correlations are significant at $p < 0.05$.

Table 6
Net mineral N and cumulative CO_2 emission of the shoot and root residues of different cultivars of sorghum residues, after 120 days of incubation.

Treatment part	Cultivar	net CO_2–C	net cumulative CO_2–C	Net NH_4^+-N	Net NO_3^--N	Net mineral N
Root	AS8	38.97^{d}	305.6^{d}	4.19^{de}	3.33^{cd}	8.25^{c}
Root	KZ5246	38.85^{d}	319.5^{d}	2.67^{e}	1.92^{d}	4.59^{d}
Root	LP4303	61.99^{bcd}	487.5^{c}	11.82^{bc}	9.15^{abc}	20.97^{abc}
Root	OS-POTCH	92.97^{a}	734.5^{b}	14.67^{ab}	11.01^{ab}	25.68^{a}
Root	MAMOLOKWANE	81.52^{ab}	645.4^{b}	12.07^{abc}	8.02^{abcd}	20.09^{abc}
Shoot	AS8	47.23^{cd}	378.6^{d}	8.38^{cd}	6.47^{abcd}	14.85^{bcd}
Shoot	KZ5246	35.53^{d}	282.5^{d}	3.03^{de}	4.86^{bcd}	10.89^{cd}
Shoot	LP4303	63.90^{abcd}	509.5^{c}	12.38^{abc}	10.56^{ab}	22.94^{ab}
Shoot	OS-POTCH	93.62^{a}	771.5^{a}	17.12^{a}	12.56^{a}	29.68^{a}
Shoot	MAMOLOKWANE	75.04^{abc}	649.7^{b}	11.92^{bc}	10.88^{bc}	22.80^{ab}
	LSD	5.87	108.3	3.18	4.04	6.56

LSD = least significant differences at 5%; figures with the same letter within a column are not different at 5% LSD.

Table 7
Correlation matrix of cumulative CO_2–C emissions, total N mineralization, and initial biochemical properties of the root and shoot residues of incubated sorghum cultivars, under the incubation study.

	CO_2–C	Net min N	Initial C	Initial N	Lignin	C: N	Lignin: N	Biomass
CO_2–C	1.00							
Net min N	0.86*	1.00						
Initial C	0.74*	0.70	1.00					
Initial N	0.95*	0.95*	0.76	1.00				
Lignin	−0.86	−0.65	−0.66	−0.72	1.00			
C: N	−0.82*	−0.89*	0.47	−0.92*	0.51	1.00		
Lignin: N	−0.95*	−0.95*	−0.79	−0.99*	0.77	0.88	1.00	
Biomass	−0.07	0.36	0.12	0.07	0.07	−0.05	−0.13	1.00

*Marked correlations are significant values at $p < 0.05$.

3.3. N mineralization rate incubation

Initially, net N immobilization was observed from roots of KZ5246 (−3 to −1.8 mg N kg^{-1}) and AS8 (−2 to −0.5 mg N kg^{-1}), while mineralization, producing ammonium (NH_4^+-N), was observed for other treatments from day 0 to day 7 of incubation (Fig. 1c). In each cultivar, shoot residues showed higher NH_4^+-N content than their roots. Both roots and shoots of OS-Potch showed the highest NH_4^+-N release, while KZ5246 roots had the lowest, throughout the incubation. The NH_4^+-N content peaked at 28.8 mg N kg^{-1} for OS-Potch shoots, while KZ5246 shoots peaked at 14.4 mg N kg^{-1} on day 42. In the roots, OS-Potch showed the highest NH_4^+-N content of 25.6 mg N kg^{-1} added N, followed by Mamolokwane (peaked at 23.4 mg N kg^{-1} added N), whereas KZ5246 and AS8 roots had lower values (8.6 and 10.6 mg N kg^{-1} added N, respectively), at day 42. After that, sharp decreasing trends of NH_4^+-N mineralization were observed up to day 56, following the pattern of high OS-Potch shoots (22.4 mg N kg^{-1}), Mamolokwane, then LP4303 treatments, while KZ5246 roots had the lowest N mineralized (6.7 mg N kg^{-1}), then steady decreasing trends were observed towards the end of the incubation. By day 120, the OS-Potch cultivar had the maximum N mineralized of 18.9 and 16.6 mg N kg^{-1} from both shoots and roots, respectively, the roots of KZ5246 and AS8 exhibited a minimum of 3.9 and 5.7 mg of nitrogen per kilogram, respectively, with relatively minor variations observed among their different components (Fig. 1c).

Immobilization of nitrate (NO_3^- –N) was observed for KZ5246 (−6 to −2.1 mg N kg^{-1}) and AS8 roots (−5.1 to −1 mg N kg^{-1}), from day 0 to day 14 (Fig. 1d). Higher NO_3^--N was observed in shoots compared to roots for each cultivar, throughout the incubation (Fig. 1d). Generally, OS-Potch residues exhibited the highest NO_3^--N, while KZ5246 followed by AS8 shoots showed the lowest NO_3^--N release in comparison to the shoots of other cultivars. Moreover, KZ5246 roots had significantly lower NO_3^--N mineralization than all treatments throughout the incubation. Increasing trends of NO_3^--N were observed in all high-quality residue treatments from day 0 and peaked at day 56 with a maximum value of 26.9 mg N kg^{-1} for OS-Potch shoots, while KZ5246 shoots were significantly lower (peaked at 14.1 mg N kg^{-1}), with KZN5246 roots showing the lowest (9.5 mg N kg^{-1}) NO_3^--N release than other treatments. Then all the treatments showed steady NO_3^--N release patterns towards the later stages of incubation (from 84 to 120 days). OS-Potch followed by Mamolokwane shoots had higher NO_3^--N (22.7 and 20.6 mg N kg^{-1} N added, respectively), while KZ5246 roots had the lowest NO_3^--N release (9 mg N kg^{-1}) than other treatments, at day 120.

Net mineral N was lowest in the treatment with KZ5246 roots (4.59 mg kg^{-1} soil), followed by AS8 roots (8.25 mg kg^{-1} soil), while OS-Potch

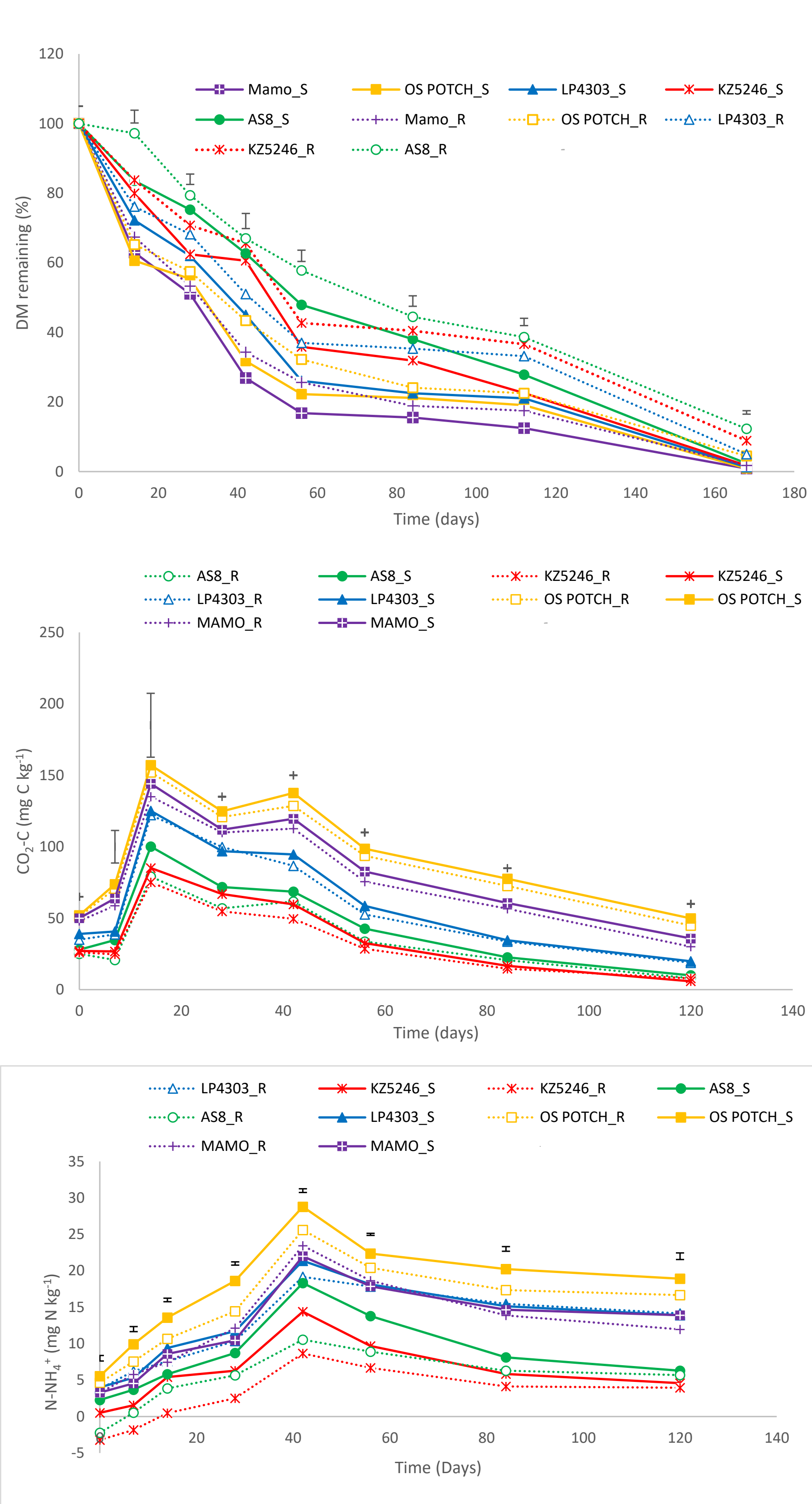

Fig. 1. (a) Change in dry weight remaining over a 160-day period, (b) CO_2–C emission, (c) NH_4^+-N, and (d) NO_3^--N concentrations of different sorghum residue treatments (Mamo is Mamolokwane: "R" is root and "S" is shoot) incubated over 120 days. *Error bars* represent the least significant difference (LSD) at p < 0.001.

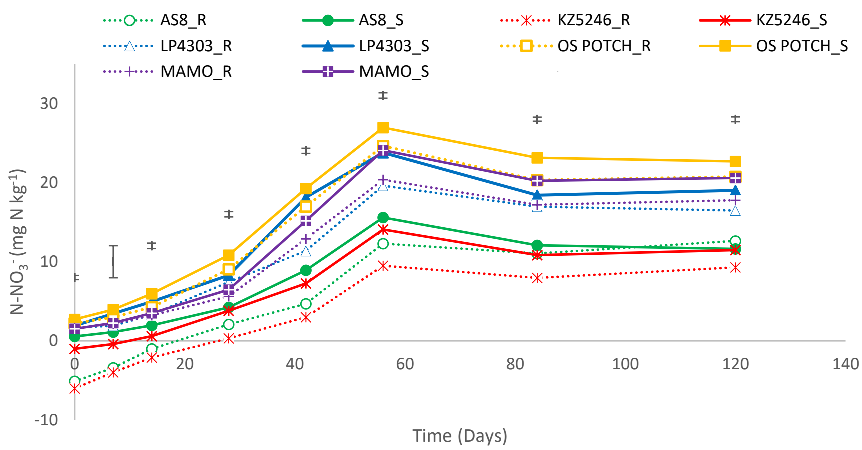

Fig. 1. (*continued*).

shoots had significantly higher net N mineralization (29.68 mg/kg soil) compared to other treatments, although it did not differ with its roots (Table 6).

3.4. CO_2 and N incubation correlation

Positive significant correlations were observed between cumulative net CO_2–C and initial N and C concentrations (r = 0.95; r = 0.74 respectively) (Table 7). Similar positive relationships were further observed between net N mineralization with CO_2–C emissions (r = 0.86) and initial N concentration (r = 0.95). There were negative significant correlations between CO_2–C emissions with C: N ratio (r = −0.82), and lignin: N ratios (r = −0.95), at $p < 0.05$, over 120 days. Net mineral N was negatively correlated with C: N and lignin: N ratios (r = −0.89; r = −0.95), respectively, over the incubation period.

4. Discussion

4.1. Litterbag study

There was a rapid increase in mass loss of all residues remaining in field conditions during the initial 42 days of decomposition was attributed to soil proximity. This promotes microbial interaction with fresh residue addition, which further fastens their response to soluble residue substrates (Gorissen and Cotrufo, 2000; Johnson et al., 2007). The decreasing trend of dry matter by the 56th day with less than 50% remaining in high-quality residues treated with Mamolokwane and OS-Potch showed similarities to the earlier research conducted by Villegas-Pangga et al. (2000), who indicated variations in decomposition patterns among different crop cultivars, leading to the release of more than 50% of cumulative carbon within 42 days. As a result of this decelerated decomposition, the nutrients they contain could potentially become accessible to subsequent plants at later stages, specifically after 42 days (Kriaučiūnienė et al., 2012). By the end of the incubation period in this study, all treatments exhibited less than 12.5% residue dry matter, a phenomenon attributed to the delayed degradation of recalcitrant constituents. It is important to note that the decomposability of lignin by specialized fungi is hindered in agricultural plots due to the regular shredding of hyphae. However, the favourable rainfall (236 mm) and temperature (22 °C) in the later stages of litterbag sampling in January 2020 (Table 1), might have simulated microbial activity and contributed to the later decomposition observed. Similarly, Daudu et al. (2009) suggested that temperature and moisture fluctuation (including drying and wetting cycles) were responsible for high residue decomposition. Consequently, the higher activation energy required for enzymatic reactions can be activated by elevated temperatures, which tempers the recalcitrant compartment and intensifies the decomposition process (de Almeida et al., 2022).

Variation in DM remaining was also observed between the root and shoot residues, with KZ5246 and AS8 roots showing higher values than their shoots over time. These observations could have been influenced by complex mass fractions in root materials (Freschet et al., 2015). Bending et al. (1998) and Abiven et al. (2005) also explained the highly recalcitrant C pool in root materials by the presence of suberin, which forms complex barriers when associated with lignin substrates, leading to a reduced rate of decomposition. Our results are consistent with the highlighted slower decomposition rate for the root part in different crops observed by Kriaučiūnienė et al. (2012), and supported by the findings of Yanni et al. (2011). On the other hand, shoot materials commonly have higher N concentrations, carbohydrates, and soluble constituents, which constitute the most labile components of the plant residues (Bending et al., 1998).

4.2. CO_2 emissions

The study reveals considerable differences in CO_2–C emission patterns, notably with the OS-Potch treatment exhibiting the highest cumulative CO_2–C compared to KZ5246. This disparity could stem from KZ5246's initial N content of below 2%, potentially constraining decomposer activity, leading to an elevated C: N ratio and consequently a reduced decomposition rate (Nicolardot et al., 2001). The peak in CO_2–C emissions observed during the initial incubation stages (day 14) can be attributed to the presence of labile organic carbon substrates. These substrates are characterized by their high availability and easy degradability once the residues are introduced into the soil. As the residues are incorporated, the labile organic carbon compounds quickly become accessible to soil microorganisms. These microorganisms, primarily decomposers, readily utilize the labile carbon as a nutrient source, leading to accelerated microbial activity and subsequent CO_2 release (Smith et al., 2015). In a global review, Ntonta et al. (2022) reported the large variations in CO_2 emissions of different crop types to be a result of their quality, such as tannins, metabolism, lignin, and N contents. Jones et al. (2009), Weier and MacRae (1993), associated the carbon assimilation in residues with microbial genetic control, which is affected by internal C metabolism and growth dynamics.

Furthermore, a gradual decrease in CO_2–C of up to <50 mg CO_2–C kg^{-1} C was added in all treatments by the end of our incubation study. This was consistent with the findings of Hu et al. (2018), where a net C release of 58% from root and shoot residues was observed in the final 90–120 days of incubation. These observations were associated with the higher initial N concentration as it tends to favour the formation of recalcitrant chemical complexes with lignin, which inhibits mass loss at the later stages (Bonanomi et al., 2013).

Noticeable differences in the biochemical composition of shoot and root tissues were evident in our incubation study. Despite minor variations in lignin content within each species, shoot residues may contain labile syringyl-unit linkages embedded in lignin, potentially leading to easier decomposition. In contrast, the guaiacyl units present in root tissues form more resistant polymers with condensed aryl-aryl lignin linkages (Bahri et al., 2006; Talbot et al., 2012; Xu et al., 2017). Consistent with our findings, Hu et al. (2018) observed that during the initial phase of decomposition, shoot C mineralized at a faster rate than root C. These observations may be connected to the presence of a highly resistant C pool, influenced by the suberin fractions as explained by Bending et al. (1998), Abiven et al. (2005), and Li et al. (2020). Additionally, it is worth noting that an intact root system has been recognized to retain more organic C in the soil compared to surface materials, as highlighted by Lu et al. (2003).

4.3. Residue decomposition and N cycling

The conversion of ammonium and nitrate into nitrogen immobilization has been observed, and this phenomenon was noted in the roots of both KZ5246 and AS8, spanning from day 0 to day 14. In line with our results, Abiven et al. (2005) observed the highest net immobilization of wheat leaf (−31.8 mg N kg-1 dry soil) on day 17. Similarly, Cookson et al. (1998) reported net N immobilization in wheat during the initial stages (0–14 days) and enhanced net N mineralization in the later stages (90–150 days). This could be attributed to potential external nitrogen sources, such as native soil nitrogen and nitrogen fixation. As a result, nitrogen becomes sequestered within microbial biomass and organic matter in the soil, rendering it inaccessible for uptake by crops. Notably, nitrogen immobilization is a common occurrence during the introduction of low-nitrogen, high C: N ratio crop material into the soil. Conversely, straw returns from rice paddies in a global agroecosystem by Xia et al. (2018) supported by Villegas-Pangga et al. (2000), showed significantly reduced N losses (17.3%, 8.7, and 25.6) in the form of nitrous oxide (N_2O) emissions, N leaching, and runoff, respectively, due to enhanced microbial N immobilization. Nicolardot et al. (2001) claim that N dynamics remain constant in the absence of nitrogen limitation since they are governed by the C content and the C: N ratio of the compartments. Hence, the lack of N immobilization beyond 14 days in our study can be attributed to enough C released as CO_2, lowering the C: N ratio to a range that is favourable for mineralization.

In the current study, high-quality residues exhibited increasing trends of N mineralization which peaked at days 42–56. Precisely, OS-Potch shoots showed maximum NH_4^+-N and NO_3^--N mineralization. Thereafter, all treatments gradually decreased, and then steady trends of N mineralization were observed towards the end of the incubation. Bending et al. (1998) also found a rapid release of mineral N within 30 days of incorporation of cover crop shoot residues, while a slower rate of N turnover was observed for the root residues within 7 days. The N mineralization rates were higher in shoot than root residues as supported by Abiven et al. (2005); Johnson et al. (2007), and Hu et al. (2018). The root exudates can inhibit nitrification by soil nitrifiers through the priming effect of exudates in the rhizosphere towards SOM degraders (el Zahar Haichar et al., 2014). These observations were attributed to the initial N concentration of the residue which has a linear relationship with N mineralized. Moreover, microbial turnover also plays a significant role in N immobilization and mineral N release during the decomposition of residue C (Abiven et al., 2005).

5. Conclusion

In comprehensive field litterbag and lab incubation studies examining various sorghum cultivars, distinct patterns emerged in the rates of decomposition, CO_2 emissions, and N mineralization, particularly influenced by residue quality. Notably, low-quality sorghum cultivars like KZ5246 and AS8, characterized by low N content and elevated lignin: N ratios, exhibited N immobilization into microbial biomass, resulting in reduced N mineralization during incubation. Furthermore, roots of these cultivars with complex mass fractions, featuring recalcitrant components and high lignin: N ratios, demonstrated a higher proportional contribution of C and slower N release compared to their corresponding shoot parts. Additionally, the intricate interplay of climatic and soil factors was evident, with the study revealing that high rainfall and summer temperatures in January 2020 at 22 °C induced increased decomposition and elevated C and N mineralization. Overall, these findings underscore the nuanced dynamics between sorghum cultivars, residue quality, and environmental factors in shaping decomposition processes.

CRediT authorship contribution statement

S. Ntonta: Writing - original draft. **R. Zengeni:** Supervision. **P. Muchaonyerwa:** Supervision. **V. Chaplot:** 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.

Acknowledgments

The authors are grateful to the Water Research Commission (WRC) of South Africa (under WRC Project No. K5/2721/4) for funding this project.

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