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Mulch effects of a seedless *Leucaena* Hawaiian hybrid on growth and productivity of okra (*Abelmoschus esculentus [L.] Moench)* in pots

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Leucaena spp. (*Leucaena*) may be pruned and the biomass applied to the soil to improve soil quality in crop production. This pruned biomass may improve soil water retention and contribute plant nutrients as it decomposes. However, traditional seeded *Leucaena* accessions and cultivars can become invasive weeds. *Leucaena* cv. "KX4-Hawaii" is a seedless interspecific cultivar that cannot become invasive, but no studies have used its biomass as a soil amendment. A full factorial pot study was conducted in 2020 to evaluate combinations of *Leucaena* leaf mulch (0, 100, 200, 300, 400g) and repeated applications of 20-20-20 NPK synthetic fertilizer (0, 2.5, 5g) to promote the growth and yield of okra (*Abelmoschus esculentus [L.], Moench*) and to investigate its soil effects during growth. "KX4-Hawaii" mulch treatments increased okra pod yield and vegetative biomass production by up to 22 and 21%, respectively. Mineralization of nutrients from the mulch appeared to be slow and most recorded variables only responded to synthetic fertilizer. The highest mulch application also increased soil CO_2 respiration by 91.5% (an indicator of soil health and microbial activity), as determined by a Solvita® lab test.

KEYWORDS

growth, KX4-Hawaii, *Leucaena*, mulching, okra, productivity

1 Introduction

Mulches are materials applied to the soil surface to reduce soil moisture loss, contribute plant nutrients, and/or for ornamental purposes, among other uses (El-Beltagi et al., 2022; Kuonen and Norgrove, 2022; Demo and Bogale, 2024). *Leucaena* spp. (*Leucaena*) grow abundantly under tropical conditions (Sharma et al., 2022) and tree clippings can be applied as an organic mulch for soil improvement (Chen et al., 1989; Ceccon et al., 2015; Meena et al., 2023; Suhag et al., 2025).

Organic mulches release plant nutrients as they decompose and can be used to support crop production by reducing the need for fertilizers and water (El-Beltagi et al., 2022; Demo and Bogale, 2024). As organic mulches decompose, they can also serve as a resource for soil fauna that provide agroecological services, such as soil aeration through burrowing earthworms and nutrient acquisition by mycorrhizal fungi, thereby reducing the need for crop producers to provide these services or inputs themselves. *Leucaena spp*. have favorable carbon to nitrogen (C: N) ratios (11:1-14) and high nitrogen content (2.3-4.4%) which promote rapid decomposition and nutrient release, particularly of

leafy or green biomass (Jama and Nair, 1996; Isaac et al., 2000; Suhag et al., 2025). Therefore, *Leucaena* mulch may be an option to increase the sustainability of agroecosystems that often rely solely on synthetic chemical inputs.

Okra (*Abelmoschus esculentus (L.) Moench*) is primarily grown for its fruit and is adapted to tropical lowland conditions, while responding well to nitrogen application (Coutinho-Miranda et al., 2019; Fatima et al., 2019). Since okra pods are produced continuously, the yield over time may help illustrate any effects of soil amendments, such as biomass inputs. Nonetheless, there are few studies on the effects of applying *Leucaena* biomass as a surface mulch for okra production (Chen et al., 1989; Palada et al., 1992; Firoz et al., 2012). Okra is a multifunctional crop, readily accessible to smallholders, and has beneficial agro ecological effects when intercropped on small farms or in agroforestry settings (Amin et al., 2023). Studies have shown that *Leucaena* mulch increases okra yield and, when combined with synthetic fertilizers, yields greater than those in control treatments with no mulch application. Research with other crops has also had positive results when applying Leucaena biomass as a mulch (Sharma and Behera, 2009; Youkhana and Idol, 2016; Xiu-Canché et al., 2023; Nyuma et al., 2025). Some studies have also indicated that residual nitrogen is released to subsequent crops in field studies and that nitrogen from *Leucaena* biomass may be just as effective as that from synthetic fertilizers for crop production, but over a prolonged period (Read et al., 1985). However, these studies incorporated the *Leucaena* biomass into the soil as a green manure rather than simply applying it to the soil surface as a mulch. These studies used conventional cultivars rather than seedless cultivars such as "KX4-Hawaii", but differences in nitrogen and mimosine (an allelopathic, non-essential amino acid) content among cultivars have been reported (Honda et al., 2022). "KX4-Hawaii" was not specifically bred for green biomass production like other cultivars used in the literature, such as KX2, which are noted for their forage production (Brewbaker, 2008). Therefore, it remained to be seen if there would be similar crop responses to "KX4-Hawaii" biomass applications.

Generally, *Leucaena* is classified into three types: Hawaiian, Peruvian, or Salvadorian, based on its bushiness and woody characteristics (Mello and Oliveira, 2016; Sharma et al., 2022). However, wild accessions and older varieties of *Leucaena* are seeded, have a high reproductive capacity, and have become problematic in several countries as invasive weeds (Mello and Oliveira, 2016; Potter et al., 2022; Sharma et al., 2022; Witt, 2024). Therefore, there has been considerable interest in seedless *Leucaena* cultivars due to their higher potential for biomass production and less invasive characteristics (Brewbaker, 2013; Idol et al., 2019; Real et al., 2019, 2022). "KX4-Hawaii" is a seedless interspecific triploid hybrid between *L. leucocephala* ssp. glabrata (Rose) S. Zárate "K636" and *L. esculenta* (Mociño et Sesse ex DC) Benth. L K838′ (Brewbaker, 2013; Bageel et al., 2020; Belgrave et al., 2024) and may be a suitable replacement for traditional seeded *Leucaena* cultivars, without presenting potential weed challenges. This study sought to investigate the ability of *Leucaena* "KX4-Hawaii" leaf mulch to promote the growth and yield of okra, with or without supplemental synthetic fertilizer, in a pot study. This study is the first to examine its suitability as a soil amendment. Findings may be applied to greenhouse crop production or extended to small field applications, such as alley cropping.

2 Methods

2.1 Experimental design

A full-factorial experiment with four replicates was conducted as a pot study at the University of the West Indies Cave Hill Campus in 2020. Experimental treatments comprised of five levels of *Leucaena* "KX4-Hawaii" mulch and three levels of 20-20-20 fertilizer (N 20%, P 8.7%, K 16.6%) alternated with magnesium sulfate heptahydrate (MgSO4.7H2O [Mg 9.6%]) (Table 1). A 1:1 mixture of loam, topsoil, and construction sand was placed into two, 1 L plastic nursery pots, which were arranged in a staggered formation with 75cm between pots. The substrate was a sandy loam characterized by a pH of 8.2 ± 0.056, electrical conductivity of 163.6 $\mu S \pm 29.3$, and soil organic matter of $3.7\% \pm 0.11$ (mean $\pm$ standard deviation) based on three samples tested before planting. Two okra seeds (cv. Clemson Spineless) were planted per pot, and the pots were thinned to the most vigorous seedlings. Next, a baseline application of 5g of 20-20-20 fertilizer and 2.5g of $MgSO_4.7H_2O$ was applied to all pots, regardless of assigned experimental treatment, at two and three WAP, respectively. The basal fertilizer application was equivalent to 104kg/ha of nitrogen, and the 2.5g and 5.0g fertilizer treatments would have provided an additional 208kg/ha and 416kg/ha of nitrogen, respectively, over the course of the experiment. Due to moisture loss before application, each 100g of *Leucaena* mulch contained only 41.2% dry matter, and this was equivalent to 155g of freshly picked fresh "KX4-Hawaii" biomass and 73.1kg/ha of nitrogen based on crude protein content (Honda et al., 2022). To control pests, 1.5 mL/L Newmectin (a.i. abamectin; Marketing Arm International, Inc., USA) was sprayed weekly. The pots were watered as required (2L and 4L, before and after six WAP) and fertilizer, when applied, was dissolved in the irrigation water.

2.2 Plant growth and yield measurements

Repeated measures were recorded at 42, 55, 69, and 83 days after planting (DAP). Plant height was measured using a ruler (1Meter) and the vertical absolute growth rate was calculated using the difference between plant heights across 2 week intervals. A chlorophyll index meter (SPAD 502, Spectrum Technologies, USA) was used to record the Leaf SPAD index (LSI) of the youngest mature leaf from the shoot apex. Soil moisture was recorded using a soil probe (Hydraprobe, Stevens Water Monitoring Systems, Inc., USA) inserted 7 cm into the substrate. Every 2 to 3 days, any okra pods ($\geq$4cm in length) were counted, harvested, and weighed. These cumulative data were tallied to give the number of okra pods produced and the pod yield per plant.

The experiment was terminated at 83 DAP, and the plants were cut at the base and weighed to record the fresh vegetative biomass. The number of leaves produced was determined by counting leaves, leaf scars, and branches.

2.3 Soil analysis

Immediately after the experiment ended (84 DAP), *in situ* linear soil respiration (CO_2 release) rate was measured using a CO_2

gas analyzer and a soil respiration chamber (EGM-5, PP Systems International, Inc., USA). A Hydra Probe was used simultaneously to record the soil moisture, content, and soil temperature for use as covariates. Soil samples were taken from the top 10cm of the soil and dried in a convection oven at 40 °C for 48 h. The soil samples were then prepared for further analysis by grinding and sieving using a soil grinder (SA-45, Gilson Company, Inc., USA) equipped with an integrated sieve with 2 mm-diameter pores. Soil respiration was also measured in the laboratory using 40g of prepared soil via the Solvita® CO_2 burst lab test (Woods End Laboratories, Inc., USA) using the 2013 methodology (Solvita, 2013). Soil pH and electrical conductivity were measured by creating a slury by mixing 20g of prepared soil with 40 mL of distilled water, which was allowed to sit for 10 mins. Probes (Field Scout pH 600 meter with ISFET probe and Field Scout EC 450 meter with conductivity probe, Spectrum Technologies Inc., USA) were then used to record the pH and electrical conductivity of the soil slurries.

2.4 Data analysis

The 'jamovi' 2.5.6 software with the GAMLj: General analyses for linear models 3.3.4 module (Gallucci, 2019; The jamovi Project, 2024) was used for mixed model analysis, and polynomial contrasts were applied for trend analysis. The Tukey honest significant difference *post hoc* test was applied to the mixed model results at the $p \leq 0.05$ significance level for pairwise comparisons of means. These models assumed normality of the residuals, which was tested via Shapiro-Wilk normal tests and quantile-quantile plots. When normality assumptions were violated, a Kruskal-Wallis test was conducted.

3 Results

3.1 Okra response to experimental treatments

Notably, there were no mulch × interaction effects for any of the measured variables. The application of 400g of mulch significantly increased fruit yield (22.2%) 83 days after planting (DAP), resulting in a linear increase in okra pod production with mulch application at that time (Figure 1). However, no other mulch effect on fruit production was noted. Fertilizer application significantly increased fruit yield with the 2.5 and 5.0g fertilizer rates at 69 (33.4 and 30.0%, respectively) and 83 (53.2 and 64.0%, respectively) DAP, although the 5.0g fertilizer rate did not significantly improve fruit yields beyond the 2.5g fertilizer rate (Figure 1).

There was a significant mulch effect, but no mulch × DAP effect on soil moisture content, and the application of 200, 300, and 400g of mulch significantly reduced soil moisture by 13.5, 14.9, and 19.1%, respectively (Figure 2). There were no differences in soil moisture content between fertilizer application rates at 42 DAP, but application of fertilizer resulted in reduced soil moisture at all other dates. Soil moisture was notably low at 55 DAP due to dry conditions at the time. The 5.0g fertilizer rate resulted in a reduction in soil moisture of 40.4% at 55 DAP, and 15.5% at 69 and 83 DAP. There were negative linear responses ($p < 0.001$) of soil moisture content to both mulch and fertilizer application (Figure 2).

As the conclusion of the experiment, Okra vegetative biomass increased linearly with mulch and fertilizer application ($p < 0.001$). Application of 300 and 400g of mulch significantly increased okra vegetative biomass by 17.0 and 20.9%, respectively, while fertilizer rates of 2.5 and 5.0g significantly increased okra vegetative biomass by 94.2 and 165%, respectively (Figure 3).

There were no significant effects of mulch on the other measured okra variables, but all responded significantly to fertilizer. The vertical growth rate, leaf SPAD index and number of fruits produced established strong linear responses to fertilizer rate by 69 DAP (Table 2). Additionally, at the end of the experiment, there were strong linear responses ($p < 0.001$) of okra leaf and branch production to fertilizer rate, although quadratic responses were notable in plant height ($p = 0.042$) and branch production ($p = 0.024$) (Table 3).

3.2 Soil properties at conclusion of experiment

There were no significant treatment effects on soil pH or electrical conductivity at the end of the experiment. However, there was a significant effect of mulch on Solvita respiration and of fertilizer on *in-situ* respiration at the conclusion of the experiment, but the reverse was not seen. Only the application of 400g of mulch significantly increased Solvita respiration (91.5%), and only the 5.0g fertilizer rate significantly increased *in-situ* respiration (40%) (Figure 4).

4 Discussion

4.1 Mulch decomposition and nutrient release

Mulch application with KX4-Hawaii did not seem to mineralize fast enough to significantly influence most recorded variables, although the 300g (219.3kg/ha N) and 400g (292.4kg/ha N) mulch treatments potentially could have provided more nitrogen than the 2.5g fertilizer treatment (208kg/ha N). Nonetheless, soil moisture content, fruit yield, vegetative biomass, and Solvita respiration responded to mulch application over time. Additionally, apart from the *in-situ* respiration rate, all recorded variables responded to fertilizer or the interaction between fertilizer and DAP. Many of these growth and yield variables have been shown to increase in response to nitrogen applications (Coutinho-Miranda et al., 2019; Fatima et al., 2019), and the lack of responses to mulch alone suggests that nitrogen was not released quickly enough to promote okra plant growth and leaf chlorophyll production. Some researchers report rapid mulch degradation and nitrogen release (Budelman, 1988; Suhag et al., 2025). However, these were field studies, whereas the current work was conducted in pots. This is further supported by the LSI numbers, which are indicators of leaf chlorophyll and nitrogen content in okra (Coutinho-Miranda et al., 2019), and which declined after 55 DAP in the absence of fertilizer, whereas the 2.5g and 5g fertilizer treatments remained at similar levels. Mulch application could not compensate for the lack

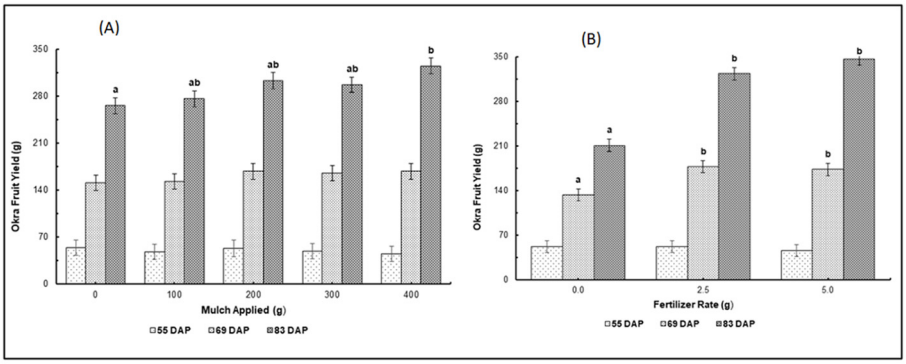


FIGURE 1
Okra fruit yield: **(a)** in response to mulch application ± standard error ($F_{8,87.3} = 3.61$, $p = 0.001$). **(b)** in response to fertilizer application ± standard error ($F_{4,87.3} = 50.59$, $p < 0.001$). DAP, days after planting; All means on the DAP with a common attached letter are not statistically different via Tukey HSD *post-hoc* testing; letters are only shown if there is a significant effect at that DAP.

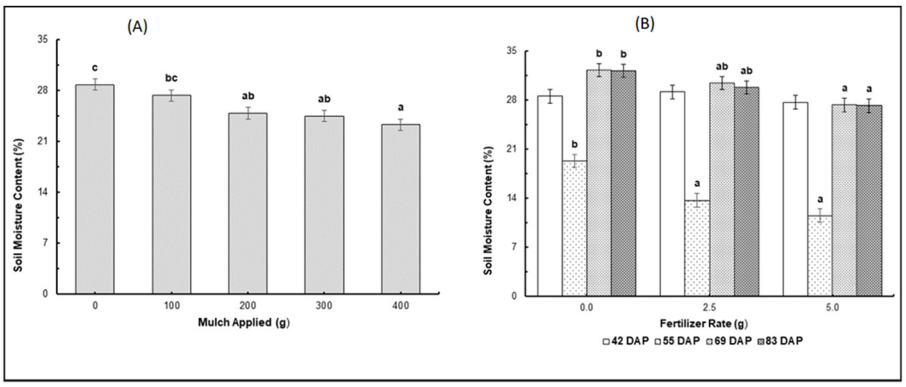


FIGURE 2
Soil moisture content: **(a)** in response to mulch application ± standard error ($F_{4,41} = 9.17$, $p < 0.001$). **(b)** in response to fertilizer application ± standard error ($F_{6,132} = 3.73$, $p = 0.002$). DAP, days after planting; All means on the DAP with a common attached letter are not statistically different via Tukey HSD *post-hoc* testing; letters are only shown if there is a significant effect at that DAP.

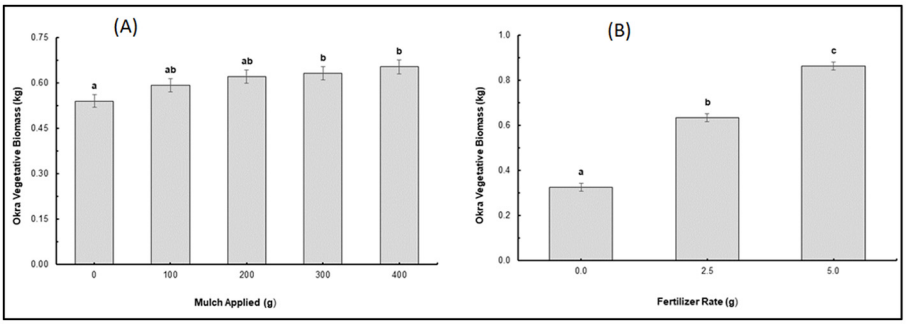


FIGURE 3
Okra vegetative biomass at the conclusion of the experiment: **(a)** in response to mulch application ± standard error ($F_{4,42} = 9.17$, $p < 0.008$). **(b)** in response to fertilizer application ± standard error ($F_{2,42} = 249.24$, $p < 0.001$). Means with a common letter are not statistically different according to Tukey HSD *post hoc* testing.

of repeated fertilizer applications, and it is likely that at this point, the nutrients from the baseline fertilizer application were depleted.

Increased fruit yield was only observed at the highest mulch rate at the end of the experiment, indicating low nitrogen mineralization from the *Leucaena* mulch. The mulch was applied in two split applications at 3 and 4 WAP, and it had only 9 weeks and 8 weeks, respectively, to decompose and contribute nitrogen before the experiment concluded. A greenhouse study where *Leucaena* mulch was incorporated into the soil found that only 17.6% of the nitrogen in *Leucaena* biomass was released

TABLE 1 Experimental treatments.

Fertilizer rate (g)	Mulch rate (g)				
	0	100	200	300	400
0.0	M0-F0.0	M1-F0.0	M2-F0.0	M3-F0.0	M4-F0.0
2.5	M0-F2.5	M1-F2.5	M2-F2.5	M3-F2.5	M4-F2.5
5.0	M0-F5.0	M1-F5.0	M2-F5.0	M3-F5.0	M4-F5.0

Mulch was applied in two equal split applications of half the specified rate at 2 and 3 WAP. The primary fertilizer (20-20-20) was applied at the specified rate at 4, 6, 8, and 10 WAP, and the accessory fertilizer (MgSO4.7H2O) was used at half the specified rate at 5, 7, 9, and 11 WAP. Each 100 g of mulch applied was equivalent to a mulch height of 2 cm. Numbers in bold indicate probability values which are significant at the P 0.05 level.

TABLE 2 Okra growth and yield variables in response to days after planting and fertilizer rate, ± standard error, and polynomial trend analyses.

Okra growth variable	Days after planting	Fertilizer rate (g)			Polynomial trend analysis (*p* Statistic)	
		0.0	2.5	5.0	Linear	Quadratic
Vertical absolute growth rate (cm/day)	55	2.53 ± 0.104a	2.70 ± 0.104a	2.44 ± 0.108a	0.585	0.092
	69	2.08 ± 0.104a	2.60 ± 0.104b	2.49 ± 0.108ab	**0.007**	**0.016**
	83	1.52 ± 0.104a	1.69 ± 0.104a	1.87 ± 0.108a	**0.023**	0.971
Leaf SPAD index	42	36.9 ± 0.75a	40.7 ± 0.75b	43.6 ± 0.77b	**<0.001**	0.568
	55	34.7 ± 0.75a	39.9 ± 0.75b	42.7 ± 0.77b	**<0.001**	0.200
	69	27.4 ± 0.75a	39.1 ± 0.75b	43.8 ± 0.77c	**<0.001**	**<0.001**
	83	25.9 ± 0.75a	39.6 ± 0.75 b	43.2 ± 0.77c	**<0.001**	**<0.001**
Cumulative number of fruit	55	3.15 ± 0.54a	3.00 ± 0.54a	2.31 ± 0.55a	0.173	0.607
	69	6.25 ± 0.54a	8.10 ± 0.54ab	8.63 ± 0.55b	**<0.001**	0.210
	83	9.30 ± 0.54a	15.3 ± 0.54b	14.91 ± 0.55b	**<0.001**	**<0.001**

Means in the same row with a common letter are not significantly different via Tukey HSD *post-hoc* testing. The growth rate at a particular date was determined over the preceding two weeks using the change in plant height between the two dates. Plant height measurements were initiated 42 DAP; thus, growth rate data were unavailable until 55 DAP. Vertical absolute growth rate $F_{4,88} = 2.85$, $p = 0.028$; leaf SPAD index $F_{6,130.8} = 18.18$, $p < 0.001$; cumulative number of fruit $F_{4,129} = 18.69$, $p < 0.001$. Numbers in bold indicate probability values which are significant at the P 0.05 level.

TABLE 3 Okra plant response to fertilizer rates ± standard error and the polynomial trend analysis.

Means	Fertilizer rate (g)	Plant height (cm)	Number of leaves	Number of branches
	0.0	126 ± 3.42a	56.1 ± 4.52a	2.10 ± 0.195a
	2.5	139 ± 3.42b	82.4 ± 4.52b	3.15 ± 0.195b
	5.0	134 ± 3.42ab	99.3 ± 4.59c	3.15 ± 0.200b
Polynomial trend analysis (*p* Statistic)	Linear	0.121	**<0.001**	**<0.001**
	Quadratic	**0.042**	0.212	**0.024**

Means in the same column with a common letter are not significantly different via Tukey HSD *post hoc* testing. Plant height $F_{2,44} = 3.50$, $p = 0.039$; number of leaves $F_{2,41.1} = 50.78$, $p < 0.001$; number of branches $F_{2,41.2} = 10.98$, $p < 0.001$. Numbers in bold indicate probability values which are significant at the P 0.05 level.

within 9 weeks (Fox et al., 1990), unlike field studies that showed rapid mineralization (Jama and Nair, 1996; Isaac et al., 2000; Pandey and Kumar, 2013; Casanova-Lugo et al., 2024; Suhag et al., 2025). Furthermore, surface-applied mulches, as used in the current work, have been shown to have slower nitrogen mineralization rates than when the *Leucaena* biomass is incorporated into the soil in some studies (Kang et al., 1981; Mafongoya and Nair, 1996) and soil incorporation of *Leucaena* biomass has been shown to promote okra growth and yield (Mohammed et al., 2023). Mulch mineralization in this work was likely insufficient to sustain maximum okra growth and be comparable to fertilizer application, as observed in other studies, such as those by Chen et al. (1989); Palada et al. (1992) and this may be related to reduced soil moisture, making conditions unfavorable for prolonged rapid mineralization of the *Leucaena* biomass (Liu et al., 2021; Kumar et al., 2023). However, slow nitrogen mineralization could result in residual nitrogen available to subsequent crops (Read et al., 1985; Xu et al., 1993; Sharma and Behera, 2009).

4.2 Effects on okra performance

Leucaena contains allelopathic substances such as the non-essential amino acid mimosine and tannins, which have been

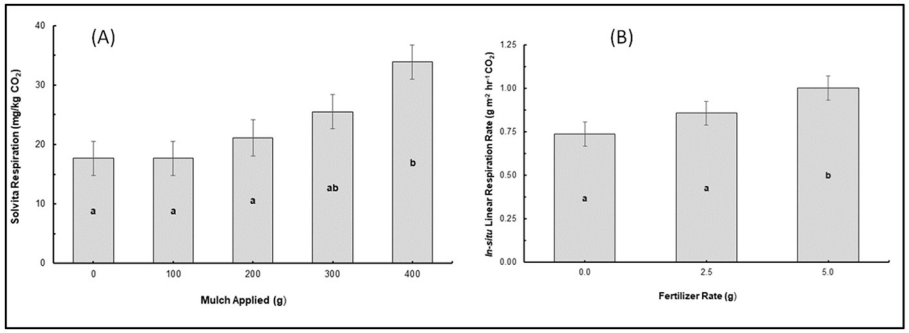


FIGURE 4
Soil respiration at the conclusion of the experiment: **(a)** Solvita respiration in response to mulch application ± standard error ($F_{4,44} = 5.57$, $p = 0.001$). **(b)** *in-situ* linear respiration in response to fertilizer application ± standard error ($F_{2,38.3} = 10.31$, $p < 0.001$). Means with a common letter are not statistically different according to Tukey HSD *post hoc* testing.

shown to reduce okra germination and early growth in *in vitro* studies (Abugre et al., 2011). In fact, allelopathic effects show increased weed control and nematode or pest control in studies with okra (Adekunle and Akinlua, 2007). Agroforestry models suggest that planting okra in combination with *Leucaena* is profitable for farmers in India (Amin et al., 2023) Research has also shown that okra has a positive response to *Leucaena* in tropical soils (Mohammed et al., 2023). Further, studies also support this finding in Latin America and Africa (Palada et al., 1992; Isaac et al., 2000; Mohammed et al., 2023). Preliminary and unpublished research by the authors applying 240 mL aqueous extract from "KX4-Hawaii" (1-part fresh leaves to 5-parts water w/v for 24 h) 1 week after planting to potted okra did not reduce okra growth. In the current study, there was no mulch × fertilizer interaction effect, indicating an allelopathy × nutrient availability interaction. The highest mulch biomass production and yield occurred at the highest application rate, which would be unexpected if the mulch material exerted significant allelopathy. Therefore, the allelopathic influence of these substances in *in vitro* studies, when seeds are soaked in extracts, may not reflect allelopathy in soil cultivation.

Although the number of pods produced was not affected by mulch application in this work, mulch promoted larger fruits, resulting in higher yields. This may be related to the moisture content of the fruit, as mulch appeared to encourage root growth visibly, at the top of the substrate, and soil moisture decreased with higher mulch applications, perhaps due to the higher moisture content of larger plants. Normal expectations would be that mulch increases soil moisture (Sharma et al., 1998), although this may vary by crop (Zhang et al., 2020). The use of pots in the current study may have influenced this result, as pots can only contain a limited amount of soil water, regardless of mulch application, compared to field soil.

4.3 Soil biological response

That *in-situ* soil respiration rate increased only with increasing fertilizer rates may have been due to greater root respiration from fertilized plants with larger root systems. Root respiration increases with root growth, particularly fine root mass, and is a significant fraction of total soil respiration (Reth et al., 2005; Borden et al., 2021; Jian et al., 2022). Fine root respiration is correlated with the nitrogen content of leaf residues (Kumar et al., 2023), but this was not apparent in the current study most likely to the lack of a mulch effect.

Unlike *in-situ* respiration, Solvita respiration responded linearly to "KX4-Hawai" mulch application but not to fertilizer. Solvita respiration uses a lab method where temperature and moisture are controlled and indicates soil health (Solvita, 2013). Processed soil samples are used in the Solvita method, so there would be no impact from root respiration. Based on the Solvita results, the *Leucaena* mulch did contribute to soil microbial respiration, but this was likely masked by root respiration in the *in-situ* measurements, and only the 400g mulch treatment could be interpreted as supporting a moderate nitrogen mineralization rate (45-75kg/ha/year) and moderate microbial biomass level (600-1500ppm). This level of mulch application reflects a limited need for supplemental nitrogen, depending on the crop (Solvita, 2013). Lower mulch application rates resulted in moderate-low nitrogen mineralization rates (25-45kg/ha/year) and medium-low microbial biomass (250-600ppm), indicating supplemental nitrogen may be required for crop production (Solvita, 2013). These results support those of the cumulative pod yield, in which only the 400g mulch treatment significantly increased pod yield by the end of the experiment.

4.4 Study implications

"KX4-Hawaii" mulch increased okra fruit yields (source of profit) and vegetative biomass (potential forage). However, the decomposition and nitrogen mineralization of the applied "KX4-Hawaii" biomass was slow, as highlighted by soil respiration results and the okra growth response. A major limitation of this study was that soil nutrient content was not measured directly. However, as okra responded strongly to fertilizer application, it was unlikely that the substrate fertility was high and confounded any mulch effects. Therefore, slow nutrient release seems to be a characteristic of "KX4-Hawaii" mulch when applied to the soil surface in pots. Pot trials simulate field conditions in controlled environments (Sithole et al., 2021; Montesinos, 2024) and have been used to demonstrate the effects of *Leucaena* on nutrient loss and cycling in a grassland

environment (Sithole et al., 2021). These results may vary under field cultivation, where each plant has more resources available, depending on the geographic location of the field and soil fertility (Kang et al., 1981).

Sustainability is a key aspect of crop ecology, and sustainable agriculture is the second United Nations Sustainable Development Goal (Wezel et al., 2020). "KX4-Hawaii" as a seedless *Leucaena* cultivar requires more effort than seeded cultivars for propagation, but once established, it cannot escape to become a weed and can be grown on marginal land under drought conditions (Belgrave et al., 2024). It can be grown near greenhouses and pruned for mulch, increasing crop productivity. Therefore, it can be used as a low-cost alternative to synthetic fertilizers, avoiding their negative environmental impacts (Tang et al., 2022; Litskas, 2023). The moderate response of okra to the mulch treatments suggests that "KX4-Hawaii" may be more suitable for low-input agriculture than large-scale conventional cultivation.

5 Conclusion

"KX4-Hawaii" *Leucaena* mulch promoted okra pod yield and vegetative biomass, but only at the highest mulch application rate and at the end of the experiment. Positively associated growth and biomass variables that correlate with nitrogen application in the literature did not respond to mulch application; however, they did respond to synthetic fertilizer treatments. Nitrogen mineralization from "KX4-Hawaii" mulch applied in pots might not be available rapidly enough to promote optimal plant growth for short-term cash crops, but may provide residual nitrogen to subsequent crops, if the growing medium is continuously used. However, the increase in okra yields shows promise for optimizing the application of "KX4-Hawaii" biomass to the soil. "KX4-Hawaii" mulch may be an option to increase soil health and microbial activity. Further studies on how its biomass is processed and applied to soil are planned to optimize nitrogen mineralization for crop production.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

JB: Data curation, Formal analysis, Investigation, Methodology, Resources, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. FL: Conceptualization, Funding acquisition, Methodology, Project administration, Resources, Supervision, Validation, Writing – original draft, Writing – review & editing. AA: Funding acquisition, Resources, Supervision, Visualization, Writing – original draft, Writing – review & editing.

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