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EDITED BY
Praveen Guleria,
DAV University, India

REVIEWED BY
Jiban Shrestha,
Nepal Agricultural Research Council, Nepal
Amandeep Brar,
DAV University, India

*CORRESPONDENCE
Godfrey Adolph Kessy
✉ kessygodfrey709@gmail.com

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Agronomic performance of mung bean (*Vigna radiata*) with the application of extracts from *Clausena anisata*, *Clutia abyssinica*, and *Lobelia giberroa* under field conditions

Godfrey Adolph Kessy[1,2]*, Angela Gerald Mkindi[1], Papias Hongera Binagwa[2] and Patrick Alois Ndakidemi[1]

[1]The Nelson Mandela African Institution of Science and Technology (NM-AIST), School of Life Sciences and Bioengineering, Arusha, Tanzania, [2]Department of Research and Innovation, Tanzania Agricultural Research Institute (TARI) Selian, Arusha, Tanzania

This study investigated the effects of four plant extracts on the agronomic performance of mung bean (*Vigna radiata*) during the 2020 growing season at two sites in the northern highlands of Tanzania, namely Miwaleni and TARI Selian, located in the Kilimanjaro and Arusha regions, respectively. The extracts tested included *Tephrosia vogelii*, *Clutia abyssinica*, *Clausena anisata*, and *Lobelia giberroa*, using a randomized complete block design with four replications. Extract concentrations ranged from 0 to 10,000 mg, with the mung bean variety "*Imara*" being used. The results indicated that the Miwaleni site significantly outperformed SARI Selian in grain yield, with 762 and 279 kg ha^{-1}, and plant height, with 59.6 and 58.6 cm, respectively. Notably, *L. gibelloa* produced the highest grain yield at 583.6 kg ha^{-1}, significantly ($p = 0.011$) greater than that of *C. anisata* (434.7 kg ha^{-1}). Yields from *T. vogelii* (542.8 kg ha^{-1}) and *C. abyssinica* (521.6 kg ha^{-1}) were not significantly different from *L. gibelloa*. For plant height, *C. abyssinica* and *L. gibelloa* had the tallest averages at 60.1 and 60.3 cm, respectively, although these differences were not statistically significant. The interaction between extract concentrations and their effects on yield and height was also examined. At 0% concentration, *L. gibelloa* had the highest yield (648.8 kg ha^{-1}) and height (65 cm). A concentration of 100 mg generally improved yields for the majority of extracts, particularly *C. abyssinica* (569.8 kg ha^{-1}), while higher concentrations (1,000 and 10,000 mg) led to significant reductions in yield and height, especially for *C. anisata*. These findings highlight the importance of optimizing extract levels and considering site-specific factors for enhancing mung bean productivity and sustainability, emphasizing the potential of *L. gibelloa* in improving yields.

KEYWORDS

biofertilizer-based extracts, food security, improved livelihoods, mung bean, strategic legume production, Tanzania

1 Introduction

Mung bean (*Vigna radiata*) is increasingly recognized in Tanzania for its adaptability to various agro-ecological zones, making it an important crop for smallholder farmers. Its production offers significant economic benefits, enhancing livelihoods and income generation. However, mung bean cultivation remains suboptimal due to challenges such as limited access to quality seeds, inadequate extension services, pest and disease pressures, and traditional farming practices.

Mung bean is a rich source of protein, essential amino acids, vitamins (especially folate and vitamin C), and minerals such as iron, potassium, and magnesium (Kumar and Pandey, 2020; Lande et al., 2024). This nutritional profile makes mung bean an excellent food source for combating malnutrition, particularly in developing countries where protein deficiency is prevalent (Rasheed and Azeem, 2024; Odeku et al., 2024). The crop's short growth cycle allows farmers to harvest multiple times a year, increasing income potential and food security (Assefa et al., 2022; Dikr, 2023). Furthermore, the ability of mung bean to fix atmospheric nitrogen improves soil fertility, reducing the need for chemical fertilizers and promoting sustainable agricultural practices (Sharma et al., 2024; Parveen et al., 2023). Its marketability ensures a steady income stream for farmers, contributing to poverty alleviation in rural areas.

The diverse climatic conditions and vast arable land in Tanzania provide a favorable environment for mung bean cultivation. The crop's resilience to drought and its ability to thrive in low-fertility soils further enhance its production potential (Yoseph Ganta et al., 2021; Mishra et al., 2022). However, challenges such as limited access to quality seeds, inadequate extension services, pest and disease pressure, and suboptimal agronomic practices hinder the full realization of this potential. The lack of market infrastructure and fluctuating prices also pose significant challenges (Hazra and Basu, 2023; Shah et al., 2024).

Despite the recognized potential and importance of mung bean, its production in Tanzania remains low (Sena et al., 2024). Smallholder farmers, who are the primary producers, encounter various challenges that impede productivity and profitability. A significant issue is the reliance on traditional farming practices and limited use of modern inputs, resulting in low yields and poor-quality produce that negatively impact farmers' income and food security (Miani et al., 2023). In addition, the prevalence of pests and diseases, coupled with limited knowledge of effective management strategies, exacerbates the problem. Limited access to improved seed varieties and inadequate extension services also prevent farmers from adopting better techniques (Domingo, 2023; Singh et al., 2023). These constraints threaten the sustainability and expansion of mung bean cultivation in Tanzania.

In this context, the potential of botanical extracts such as *C. anisata*, *C. abyssinica*, and *L. giberroa* as bio-pesticides and growth enhancers offers a promising avenue for improving mung bean production. These extracts are known for their pesticidal and growth-promoting properties, providing viable alternatives to synthetic chemicals. However, research on their efficacy in enhancing mung bean production under Tanzanian conditions is limited.

Conducting research on the agronomic performance of mung bean with botanical applications is vital for several reasons. The increasing demand for organic and sustainably produced food necessitates exploring natural alternatives to chemical inputs (Singh, 2023; Pathirana and Carimi, 2022). Botanical extracts are environmentally friendly and support sustainable agricultural practices. Enhancing mung bean productivity directly improves the livelihoods of smallholder farmers in Tanzania (Kidane, 2024). Identifying effective agronomic practices and inputs can help to increase yields, improve product quality, and boost farmers' incomes (Mmbando et al., 2021; Garg et al., 2024). Furthermore, using botanical extracts can reduce production costs associated with synthetic pesticides, thereby benefiting farmers economically (Singh et al., 2024).

This research addresses a critical knowledge gap regarding the use of indigenous plant extracts in mung bean cultivation (Lengai et al., 2020; Ngegba et al., 2022). By generating scientific evidence on the efficacy of *C. anisata*, *C. abyssinica*, and *L. giberroa*, the study aimed to inform policy decisions and extension services, promoting the wider adoption of these natural inputs among farmers. The general objective of this research is to improve food security and the livelihoods of smallholder farmers. The primary hypothesis is that applying botanical extracts from *C. anisata*, *C. abyssinica*, and *L. giberroa* could significantly enhance the growth and yield of mung bean compared to traditional farming practices.

The purpose of this experiment was to address the pressing need for sustainable agricultural practices that can enhance mung bean productivity and farmer livelihoods. By exploring the use of indigenous plant extracts, this research aimed to provide smallholder farmers with effective and environmentally friendly alternatives to traditional agronomic practices. The objective of this study was to evaluate the impact of botanical extracts on the growth and yield of mung bean, thereby determining their potential role in improving agricultural outcomes. By generating scientific evidence on the efficacy of *C. anisata*, *C. abyssinica*, and *L. giberroa*, the study aimed to inform policy decisions and extension services, promoting the wider adoption of these natural inputs among farmers. Ultimately, this research aimed to improve food security and the livelihoods of smallholder farmers, hypothesizing that the application of these botanical extracts could significantly enhance the growth and yield of mung bean compared to traditional farming practices.

2 Materials and methods

2.1 Description of the study sites

The study was conducted during the 2020 cropping season at two primary locations: the Selian Agricultural Research Institute (TARI Selian) experimental site in Arusha and the Miwaleni farm of the Tropical Pesticides Research Institute (TPRI) in Moshi (Figure 1).

TARI Selian is situated in the Arumeru district of the Arusha region in northern Tanzania. The geographical coordinates are 03° 22′ S and 40° 10′ E. The site is positioned at an altitude of 1,378 m above sea level, which contributes to its unique

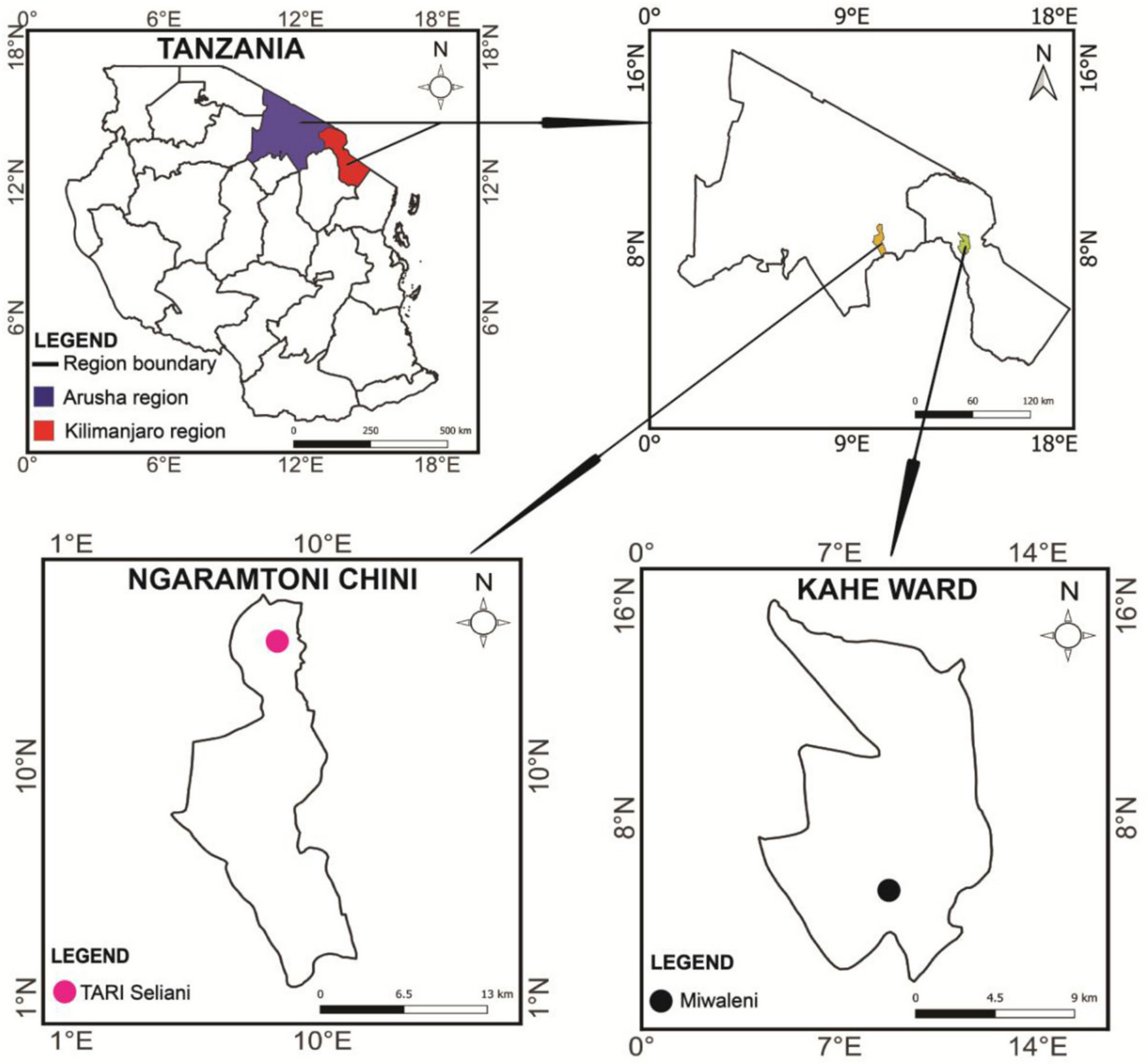

FIGURE 1
Map showing TARI Selian and Miwaleni areas constituting study sites.

climatic conditions. The climate at TARI Selian is classified as a tropical highland climate, characterized by distinct wet and dry seasons. The mean annual temperature is 19.2°C, providing a relatively cool environment that is suitable for various agricultural activities. The area receives an average annual rainfall of 1,103 mm, with the wet season occurring from March to May. During this period, the region experiences substantial rainfall, which is critical for crop growth. The dry season extends from June to October, characterized by minimal rainfall and higher temperatures, necessitating efficient water management practices for continuous agricultural productivity. The soils at TARI Selian are predominantly volcanic in origin, contributing to their fertility and suitability for agriculture. These volcanic soils are rich in essential nutrients and organic matter, which are important for plant growth. The soil texture is loamy, providing an excellent balance of drainage and water-holding capacity. This loamy texture supports a wide range of crops, including mung bean, by ensuring adequate root development and nutrient uptake. The high organic matter content in the soil enhances its structure and fertility, making TARI Selian a highly productive agricultural area.

Miwaleni is located in the Moshi district of the Kilimanjaro region, also in northern Tanzania. The geographical coordinates are 03° 25′ 19.7" S and 37° 26′ 59.0" E. The site is positioned at an altitude of 736 m above sea level, which influences its climatic and soil conditions. The climate in Miwaleni is slightly warmer than at TARI Selian, with a mean annual temperature of ∼23°C. This region experiences a bimodal rainfall pattern, receiving ∼950 mm of rain annually. The two main rainy seasons are the long rains from March to May and the short rains from October to December. The bimodal distribution of rainfall provides multiple opportunities for planting and harvesting crops, thereby enhancing agricultural productivity. The warmer temperatures and reliable rainfall patterns make Miwaleni an ideal location for the cultivation of crops such as mung bean, which thrive in such conditions. The soils in Miwaleni are primarily alluvial, formed from volcanic ash and lava deposits from Mount Kilimanjaro. These alluvial soils are well-drained, preventing waterlogging and promoting healthy root development. The fertility of these soils can vary depending on the specific location within the farm, but they are generally rich in minerals and organic matter. This richness in nutrients supports the cultivation of high-yielding crops, including mung bean. The soil texture in the Miwaleni site ranges from sandy loam to clay loam and provides different advantages for water retention and aeration, which is essential for crop growth.

2.2 Soil sampling and laboratory analysis

In each site, TARI Selian and Miwaleni, composite soil samples were collected following a reconnaissance field survey conducted before the actual field experiment. The composite soil samples were collected from a depth of 0–30 cm at various sampling points determined along transects. These subsamples were thoroughly mixed and quartered to produce a representative 1-kg composite surface soil sample for laboratory analysis. The physical and chemical properties of the soil were determined using standard procedures compiled by Okalebo et al. (2002). This included particle size analysis using the hydrometer method, soil bulk density measurement, and the determination of soil pH and electrical conductivity in a soil-to-water suspension. Soil organic carbon (OC) was analyzed using the Walkley and Black method, available phosphorus (P) using the Bray and Kurtz P-1 method, and total nitrogen (N) content using the micro-Kjeldahl distillation method. Cation exchange capacity (CEC) was measured using the ammonium acetate saturation method, along with exchangeable bases (K^+, Mg^{2+}, Ca^{2+}, and Na^+). Extractable micronutrients, including iron (Fe), copper (Cu), zinc (Zn), and manganese (Mn), were analyzed following the diethylenetriaminepentaacetic acid (DTPA) extraction method (Table 1).

At the Miwaleni site, soil conditions present a mixed scenario for mung bean cultivation. The pH is neutral, which is generally favorable for mung beans. However, calcium levels are very low, potentially impacting root development and overall plant health. Magnesium levels are also low, which could lead to deficiencies affecting photosynthesis and growth. The levels of potassium, which is an important nutrient for water regulation and disease resistance, are also low, thus supplementation may be required. Sodium levels are low, which generally poses no direct threat but should be monitored. Cation exchange capacity (CEC) is low, indicating limited nutrient retention, which may require frequent fertilization. Nitrogen levels are very low, which is critical for growth, necessitating additional nitrogen sources. Phosphorus levels are a medium level, which is adequate but might benefit from slight enhancement. Copper levels are high, which could be toxic to plants if not managed properly. Iron levels are high, potentially causing toxicity and nutrient imbalances. Manganese levels are high, which could also lead to toxicity if not controlled. Zinc levels are high, and excess zinc is potentially harmful, so it is essential to monitor them.

At the TARI Selian site, the soil conditions present different challenges. The pH is slightly acidic, which is still suitable for mung beans but could be marginally less optimal than neutral conditions. Calcium levels are very low, indicating a need for calcium amendments. Magnesium levels are high, which supports healthy plant growth but should be balanced with other nutrients. Potassium levels are low, which may limit plant health and yield, making potassium fertilization advisable. Sodium levels are very low, with minimal impact expected. CEC is low, indicating limited nutrient holding capacity, similar to the Miwaleni site, and frequent fertilization may be needed. Nitrogen levels are very low, necessitating additional nitrogen sources for optimal growth. Phosphorus levels are low, potentially limiting root development and growth, so phosphorus supplementation could improve results. Copper levels are high, which should be managed to avoid toxicity. Iron levels are high, which, while less extreme than at Miwaleni, still requires monitoring to prevent toxicity. Manganese levels are high, and excessive levels could affect nutrient uptake. Zinc levels are high, therefore careful management is required to prevent potential toxicity.

2.3 Experimentation approaches

The mung bean seed of the variety "Imara" was sourced from the Tanzania Agricultural Research Institute (TARI) Ilonga in Morogoro. This variety is well-adapted to local conditions and offers high yields, making it a reliable source of quality seed. In addition, botanical plant materials were collected from various locations within the Kilimanjaro region, including Same, Mwanga, Usangi, Kisangara, and Ugweno. Each of these areas was chosen due to its rich biodiversity and the presence of indigenous plant species known for their pesticidal and growth-enhancing properties. Each location provides unique plant species with distinct properties that can be leveraged to enhance the growth and yield of mung bean crops. Fresh leaves of these plants were collected, dried under shade, and ground into a fine powder. The powder was then mixed with water at different concentrations (v/w) for a 16 L solution. This solution was soaked overnight, sieved to remove particles, and sprayed onto the mung bean plots every 7 days throughout the growing season (Mkindi et al., 2015).

2.4 Experimental design

The experiments were designed using a randomized complete block design with four replications. A single variety of mung bean, Imara, was used throughout the experiment. Four types of growth and yield-promoting plants were used, and four application rates for each plant were tested (Table 2). The study was conducted during the main mung bean cropping season from March to August 2020, coinciding with the rainy season in the study areas. Field preparations, including plowing and harrowing, were completed in March before planting. Each experimental plot measured 3×3 m and contained six rows, with a 1.0-m separation between plots and a

TABLE 1 Soil properties of the study sites.

Soil properties	Miwaleni site		TARI Selian site	
	Values	Ratings*	Values	Ratings*
pH (H_2O) 1:2.5	6.6	Neutral	7.1	Slightly acid
Ca ($cmol_{(+)}$ kg^{-1})	1.27	Very low	2.04	Very low
Mg ($cmol_{(+)}$ kg^{-1})	0.36	Low	4.31	High
K ($cmol_{(+)}$ kg^{-1})	0.31	Low	1.41	Low
Na ($cmol_{(+)}$ kg^{-1})	0.05	Low	0.14	Very low
CEC ($cmol_{(+)}$ kg^{-1})	12.6	Low	21.1	Low
N (%)	0.061	Very low	0.071	Very low
P (mg kg^{-1})	11.81	Medium	16.14	Low
Cu (ppm)	21.74	High	0.56	High
Fe (ppm)	147.91	High	51.13	High
Mn (ppm)	131.10	High	92.41	High
Zn (ppm)	5.71	High	1.37	High

*Ratings are based on the compilation of Okalebo et al. (2002).

TABLE 2 Plants and their concentrations used in the experiment.

Treatment code	Plants	Concentration (%)	Weight equivalent (mg)
T1	*Clausena anisata*	0%, 0.1%, 1%, 10%	0, 100, 1,000, 10,000
T2	*Clutia abyssinica*	0%, 0.1%, 1%, 10%	0, 100, 1,000, 10,000
T3	*Lobelia giberroa*	0%, 0.1%, 1%, 10%	0, 100, 1,000, 10,000
T4	*Tephrosia vogelii*	0%, 0.1%, 1%, 10%	0, 100, 1,000, 10,000

1.5-m separation between replications. The recommended planting spacing used was 50 cm between rows and 20 cm between plants, with two seeds planted per hill, hence 30 plants in a row and 180 plants per plot (equivalent to 200,000 plants per hectare). Four rows in each plot were designated for data collection.

2.5 Data collection

The data collected included both climate data and plant growth and yield data (Figure 2). Climate data, such as rainfall and temperature, were recorded at the Miwaleni and TARI Selian sites throughout the experiment period. Maximum and minimum temperatures, as well as monthly rainfall totals, were documented to assess the environmental conditions. Concurrently, data on the growth and yield of mung bean plants were gathered by monitoring their development stages, growth rates, and overall yield under these varying climatic conditions. This approach allowed for an analysis of how different climate factors influenced mung bean growth and productivity. In addition, plant growth (plant height) and yield data were collected by monitoring variables such as the number of pods per plant, the number of seeds per pod, 100-seed weight, and grain yield.

Data on the agronomic performance of mung bean were also gathered from emergence to harvest. To assess the impact of varying concentrations of botanical extracts on the growth and yield of mung bean, a series of agronomic variables were meticulously measured. These variables included germination percentage and days to 50% maturity measured to determine the number of days taken for 50% of the plants to reach maturity, reflecting how different treatments affect the growth cycle. Plant height was recorded at various growth stages to understand the vegetative growth and vigor of the mung beans. The total number of plants per unit area was counted to assess the plant density and survival rate after germination, providing insights into stand establishment and competition among plants. Detailed measurements of plant height, including both the stem and foliage, were taken to gauge overall plant growth and health. The number of seeds per pod was counted to measure reproductive success, indicating potential yield. Seed yield per plant was measured to understand productivity at the plant level, reflecting how treatments affect seed formation and maturation. Finally, the overall seed yield was extrapolated to a per-hectare basis, allowing for yield assessment and comparison of treatment impacts on a field scale.

2.6 Statistical data analysis

Statistical data analysis was performed using GenStat (20th edition). A two-way analysis of variance (ANOVA) was conducted,

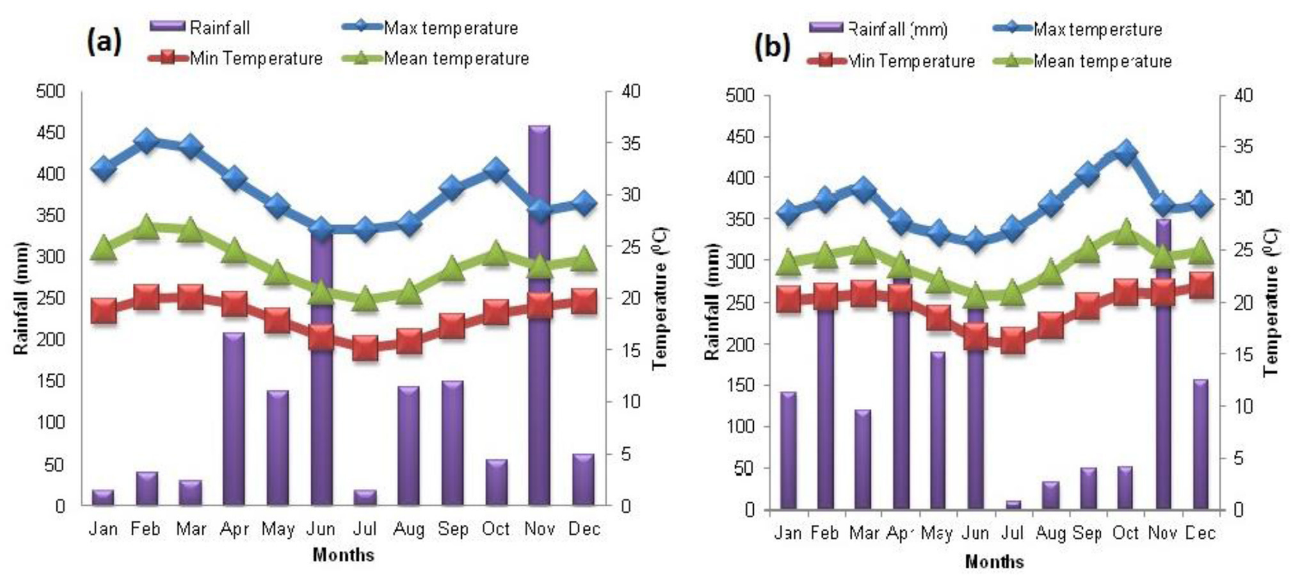

FIGURE 2
Climatic conditions of **(A)** Miwaleni and **(B)** TARI Selian as the study sites during the period of the experiment (January–December 2020).

with sites constituting the main plots and genotypes as the sub-plots, while replication was considered a random effect. The significance of site effects on measured parameters relied on probability thresholds and the least significant difference (LSD) due to the involvement of only two sites. Conversely, the significance of genotype effects and/or interactions with sites on the measured parameters was assessed through multiple comparisons using standard errors of differences of means (S.E.D.) via Tukey's *post-hoc* test.

3 Results and interpretations

The agronomic performance of mung bean varied significantly across different sites, plant varieties, and extract concentrations, revealing important insights into the factors affecting its growth and yield (Tables 3–5). Germination percentage was consistent across both Miwaleni and SARI Selian sites, showing no significant difference ($p = 0.353$). *T. vogelii* had a germination percentage of 76.0%, while *C. abyssinica* had 74.8%, with no significant ($p = 0.881$) impact from the type of botanics. Similarly, application rates did not significantly ($p = 0.676$) affect germination percentages, with 77% at 0% and 74% at 10%, suggesting that germination is relatively stable across these variables.

Days to 50% maturity did not vary significantly ($p = 0.84$) between sites. Among botanics, days to maturity ranged from 50 days for *C. anisata* to 57 days for *C. abyssinica*, with no significant ($p = 0.554$) differences observed. However, the extract concentrations had a notable effect, with the highest rate of 10,000 mg significantly ($p < 0.001$) delaying maturity to 60 days compared to lower rates. This indicates that higher concentration may slow down the development process of mung bean, potentially influencing harvest times. Plant height was consistent across different sites, with no significant ($p = 0.787$) difference observed. Among botanics, *L. gibelloa* showed the greatest plant height at 60.3 cm, though the differences were not significant ($p = 0.435$). However, extract concentrations had a significant effect on plant height, with the highest concentration of 10,000 mg resulting in significantly taller plants ($p = 0.002$), reaching 62.0 cm. This indicates that higher concentrations may promote vertical growth in mung bean plants.

The number of pods per plant did not differ significantly ($p = 0.121$) between the sites, with Miwaleni having 15.5 pods per plant compared to 11.6 at SARI Selian. Among botanics, *L. gibelloa* produced the highest number of pods at 15.57, suggesting that specific botanics can enhance pod production, potentially improving overall yield ($p = 0.06$). Extract concentration did not significantly ($p = 0.9$) impact the number of pods per plant, with values being relatively similar across different rates. Plant height showed a significant difference between the sites, with Miwaleni having longer plants at 59.6 cm compared to 58.6 cm at SARI Selian ($p = 0.787$). Among the botanics, *L. gibelloa* showed the most substantial plant height at 60.3 cm, indicating that certain botanics can positively influence plant size ($p = 0.435$).

The number of seeds per pod remained consistent across different sites and botanics, with no significant ($p = 0.391$) differences observed. This consistency suggests that seed production per pod is not heavily influenced by these factors. The 100-seed weight differed significantly between the sites, with SARI Selian producing slightly heavier seeds at 4.7 g compared to 4.4 g at Miwaleni ($p = 0.008$). Among botanics, *T. vogelii* had the heaviest seeds at 4.6 g ($p < 0.001$), indicating that certain botanics can enhance seed weight. Higher extract concentrations also led to significantly ($p < 0.001$) heavier seeds, particularly at the highest rate of 10,000 mg, suggesting that concentrations can influence seed development. Seed yield per plant was significantly ($p < 0.001$) higher at the Miwaleni site at 10.19 g compared to 1.4 g at the SARI Selian site. Among botanics, no significant ($p = 0.068$) differences were observed in grain yield

TABLE 3 Agronomic measured variables as affected by the sites and botanics.

Factors	Factor levels	Agronomic measured variables							
		Germ%	D50%Mat	PH	NoPplnt	NoSYPod	100SWt	SYplnt	SYHa
Sites	Miwaleni	76.1a	53a	59.6a	15.5a	11.7a	4.4b	10.19a	762a
	SARI Selian	75.1a	55a	58.6a	11.6a	24a	4.7a	1.4b	279b
	$LSD_{(0.05)}$	3.4	23.7	11.15	5.8	39.22	0.17	1.02	81.3
	p-value	0.353	0.84	0.787	0.121	0.391	0.008	<0.001	<0.001
Botanics	*Tephrosia vogelii*	76.0a	56a	57.05a	16.14a	11.29a	4.6a	6.0a	542.8ab
	Clutia abbsynica	74.8a	57a	60.1a	12.15a	36.5a	4.4b	6.1a	521.6ab
	Clausena anisata	75.6a	50a	59.0a	10.24a	11.3a	4.4b	4.9a	434.7b
	Lobelia giberroa	75.8a	55a	60.3a	15.57a	12.2a	4.7a	6.2a	583.6a
	$LSD_{(0.05)}$	3.4	11.2	4.6	4.9	36.8	0.1	1.1	83.4
	p-value	0.881	0.554	0.435	0.06	0.409	<0.001	0.068	0.011

Germ%, germination percentage; D50%Mat, days to 50% maturity; PH, plant height; NoPplnt, total number of plants per unit area; NoSYPod, number of seeds per pod; 100SWt, weight of 100 seeds; SYplnt, seed yield per plant; SYHa, seed yield extrapolated to a per-hectare basis; LSD, least significant differences of means.
Means along the same column within a specific category of factor levels and measured variable sharing different letter(s) differ significantly at a 5% error rate.

per plant, with yields ranging from 4.9 g for *C. anisata* to 6.2 g for *L. gibelloa*.

Grain yield per hectare was significantly ($p < 0.001$) higher at the Miwaleni site, at 762 kg, compared to the SARI Selian site at 279 kg. Among botanics, *L. gibelloa* showed the highest seed yield per hectare at 583.6 kg, indicating its significant ($p = 0.011$) performance in overall yield. Extract concentration also showed significant ($p = 0.015$) differences in grain yield, with the highest rate of 10,000 mg yielding the most at 572.7 kg, highlighting the positive impact of higher application rates on overall productivity.

The result reveals interesting interactions between different botanical extracts and their concentrations, particularly regarding grain yield and plant height (Table 6; Figure 3). When there is no extract applied, all extracts demonstrate relatively high yields, with *L. gibelloa* achieving the highest at 648.8 kg ha^{-1}, closely followed by *C. abyssinica* at 502.2 kg ha^{-1}. This suggests that when no extracts are applied, plants thrive under optimal conditions, as reflected in their height, with *L. gibelloa* again leading at 65 cm.

At a concentration of 100 mg, there is a noticeable increase in yields for most extracts. The *C. abyssinica* stands out with a yield of 569.8 kg ha^{-1}, indicating that low concentrations may enhance growth. However, at the 100 mg concentration, yields decline, especially for *C. anisata*, which drops to 397.4 kg ha^{-1}, accompanied by a reduced plant height of 54.9 cm. This trend suggests that higher concentrations can hinder growth, signaling a threshold beyond which the extracts may become harmful.

At the highest concentration of 10,000 mg, grain yields decrease for all extracts, with *C. anisata* yielding 410.2 kg ha^{-1} and *C. abyssinica* 426.4 kg ha^{-1}, while *T. vogelii* produces a relatively better yield of 499.7 kg ha^{-1}. These results further support the notion that excessive concentrations may negatively impact both yield and plant height.

Statistical analysis, indicated by the standard error and *p*-values, revealed no significant differences in grain yield ($p = 0.991$) or plant height ($p = 0.225$). This suggests that while trends are observable, they may not be statistically significant, highlighting the need for further investigation into the effects of botanical extracts on plant growth. Overall, these findings emphasized the complexity of plant responses to different concentrations of botanical extracts and the importance of determining optimal levels for agricultural improvement.

4 Discussion

The results of this study emphasized the significant influence of extract concentrations on mung bean productivity, particularly concerning plant height and grain yields. This observation is consistent with earlier research, which has highlighted the importance of nutrient management in optimizing crop growth and yields. For instance, the analysis showed that the highest extract concentration (10,000 mg) resulted in significantly taller plants (62.0 cm) and greater grain yields (572.7 kg ha^{-1}; Table 3). Furthermore, the variations in days to maturity observed, particularly the delay to 60 days at the highest extract concentration, illustrated the effects of environmental factors such as temperature, moisture, and photoperiod on the phenology of mung bean. This finding aligns with the study by Kumar et al. (2020) and Islam et al. (2021), who showed the role of environmental cues in regulating flowering and maturation processes. Understanding these phenological dynamics is vital for optimizing planting schedules and mitigating risks associated with adverse weather, ultimately enhancing crop resilience and stability (Haeften et al., 2023; Prokisch et al., 2024). For example, previous studies have demonstrated that optimizing nitrogen (N), phosphorus (P), and potassium (K) levels can significantly increase mung bean yields (Yin et al., 2018; Bhardwaj et al., 2023; Schreinemachers et al., 2019). In addition, research has shown that utilizing diverse nutrient sources tailored to the specific needs of mung bean can substantially

TABLE 4 Analysis of variance (ANOVA) of some agronomic measured variables as affected by the sites, botanics, and their interactions.

Source of variation	*d.f.*	Germination percent				50% days to maturity				Plant height			
		s.s.	*m.s.*	*v.r.*	*F pr.*	*s.s.*	*m.s.*	*v.r.*	*F pr.*	*s.s.*	*m.s.*	*v.r.*	*F pr.*
Replication	3	14.9	5	0.14		6,791.2	2,264	1.28		850	283.3	0.72	
Sites	1	43.7	43.7	1.2	0.353	86.1	86.1	0.05	0.84	34.2	34.2	0.09	0.787
Residual	3	109.2	36.4	0.88		5,316.2	1,772	3.89		1,177.7	392.6	5.23	
Botanics	3	27.5	9.2	0.22	0.881	980.3	326.8	0.72	0.554	215.4	71.8	0.96	0.435
Sites × botanics	3	34.9	11.6	0.28	0.839	2,430.3	810.1	1.78	0.187	294.1	98	1.3	0.303
Residual	18	747.5	41.5	0.55		8,194.1	455.2	8.03		1,352.3	75.1	1.43	
Rates	3	116.1	38.7	0.51	0.676	1,663.1	554.4	9.78	<0.001	895.7	298.6	5.67	0.002
Sites × rates	3	13.8	4.6	0.06	0.98	22.5	7.5	0.13	0.941	7.5	2.5	0.05	0.986
Botanics × rates	9	89.7	10	0.13	0.999	276.8	30.8	0.54	0.839	763.6	84.8	1.61	0.129
Sites × botanics × rates	9	610	67.8	0.9	0.534	364.3	40.5	0.71	0.694	239	26.6	0.5	0.867
Residual	72	5,449.7	75.7			4,079.7	56.7			3,794.8	52.7		
Total	127	7,257.1				30,204.5				9,624.2			

d.f., degree of freedom; m.s., mean sum of squares; v.r., variance; F pr., F probability.

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TABLE 5 Analysis of variance (ANOVA) of some agronomic measured variables as affected by the sites, botanics, and their interactions.

Source of variation	d.f.	Number of pods/plant				Number of seeds/pot				100-Seed weight				Seed yield per plant				Seed yield per hectare			
		s.s.	*m.s.*	*v.r.*	*F pr.*	*s.s.*	*m.s.*	*v.r.*	*F pr.*	*s.s.*	*m.s.*	*v.r.*	*F pr.*	*s.s.*	*m.s.*	*v.r.*	*F pr.*	*s.s.*	*m.s.*	*v.r.*	*F pr.*
Replication	3	117.3	39.1	0.37		14,452	4,817	0.99		0.2	0.1	0.71		26.3	8.8	2.68		226,226	75,409	3.61	
Sites	1	489.8	489.8	4.61	0.12	4,849	4,849	1	0.391	3.6	3.6	40.5	0.008	2,477.2	2,477.2	756.51	<0.001	7,479,697	7,479,697	358.53	<0.001
Residual	3	318.6	106.2	1.24		14,581	4,860	0.99		0.3	0.1	2.29		9.8	3.3	0.77		62,586	20,862	0.83	
Botanics	3	759	253	2.96	0.06	14,923	4,974	1.01	0.409	2.1	0.7	17.96	<0.001	35.8	11.9	2.82	0.068	379,010	126,337	5.01	0.011
Sites × botanics	3	236.7	78.9	0.92	0.45	14,894	4,965	1.01	0.41	0.2	0.1	1.84	0.176	7.8	2.6	0.61	0.616	18,975	6,325	0.25	0.86
Residual	18	1,537.5	85.4	0.79		88,264	4,904	1		0.7	0	0.37		76.2	4.2	0.46		453,865	25,215	0.96	
Rates	3	63.4	21.1	0.19	0.9	14,532	4,844	0.99	0.402	2	0.7	6.17	<0.001	60.3	20.1	2.21	0.094	294,847	98,282	3.75	0.015
Sites × rates	3	191.8	63.9	0.59	0.62	14,911	4970	1.02	0.39	0.2	0.1	0.65	0.588	38.3	12.8	1.4	0.249	36,254	12,085	0.46	0.71
Botanics × rates	9	1,245.7	138.4	1.28	0.26	44,860	4,984	1.02	0.433	1.5	0.2	1.62	0.127	68.9	7.7	0.84	0.581	183,069	20,341	0.78	0.639
Sites × botanics × rates	9	679.9	75.5	0.7	0.71	43,863	4,874	1	0.45	0.2	0	0.2	0.993	49.5	5.5	0.6	0.79	60,694	6,744	0.26	0.984
Residual	72	7,802.4	108.4			351,848	4,887			7.6	0.1			655.5	9.1			1,886,819	26,206		
Total	127	13,442				621,976				18.6				3,505.7				11,082,044			

d.f., degree of freedom; m.s., mean sum of squares; v.r., variance; F pr., F probability.

TABLE 6 Effects of botanical extract concentrations on grain yield and plant height.

Botanical extracts	Concentration (mg)	Grain yield (kg ha^{-1})	Plant height (cm)
Clausena anisata	0	409.2a	59.88a
Clutia abbsynica	0	502.2a	61.78a
Lobelia giberroa	0	648.8a	65a
Tephrosia vogelii	0	559.1a	58.45a
Clausena anisata	100	522.1a	63.6a
Clutia abbsynica	100	569.8a	64.8a
Lobelia giberroa	100	637.7a	60.0a
Tephrosia vogelii	100	561.3a	59.5a
Clausena anisata	1,000	397.4a	54.9a
Clutia abbsynica	1,000	588a	59.1a
Lobelia giberroa	1,000	614.7a	63.7a
Tephrosia vogelii	1,000	551.3a	53.6a
Clausena anisata	10,000	410.2a	57.6a
Clutia abbsynica	10,000	426.4a	54.8a
Lobelia giberroa	10,000	433.3a	52.7a
Tephrosia vogelii	10,000	499.7a	56.7a
s.e.d.		151.4	3.978
p-value		0.991	0.225

The means along the same column with similar letter (a) do not differ significantly at $p \leq 0.05$.

enhance crop performance (Kaysha et al., 2020; Alam et al., 2024).

The superior performance of *L. gibelloa*—evidenced by its taller plant height (60.3 cm), higher pod count (15.57 pods per plant), and increased grain yield per hectare (583.6 kg; Table 3)—highlights the benefits of diversifying botanical extracts to maximize crop productivity. This supports the findings from the studies by Bangar et al. (2019) and Kumar et al. (2020), which identified plant species with favorable agronomic traits adaptable to specific agro-ecological contexts. By leveraging genetic diversity and employing advanced breeding techniques, breeders can develop mung bean cultivars with enhanced yield potential and stress tolerance, thereby fostering more resilient and sustainable production systems.

Botanical extracts can significantly enhance the growth and yield of mung bean through various mechanisms. These extracts, derived from different plants, contain bioactive compounds that improve nutrient uptake, stimulate root development, and promote beneficial soil microbial activity, which collectively contribute to better plant growth (Punitha et al., 2024; Ng et al., 2024). In addition, extracts from plants such as *C. abyssinica* and *C. anisata* can provide natural pest and disease management solutions, reducing reliance on synthetic pesticides (Escobar-Garcia et al., 2024; Shai et al., 2024). These botanical treatments may also enhance the resilience of plants to environmental stresses, such as drought, by boosting antioxidant activity (Bhowmick et al., 2024; Khshan and Al-Taweel, 2024). The significant differences in seed weight, particularly the heavier seeds from SARI Selian (4.7 g) compared to Miwaleni (4.4 g; Table 3), further highlight the role of botanical extracts in improving crop characteristics. These combined effects result in healthier plants and potentially higher yields, making botanical extracts a sustainable option for mung bean cultivation.

Moreover, the observed differences in grain yield between study sites show the importance of site-specific factors such as soil fertility, moisture availability, and pest pressure in influencing crop productivity. Miwaleni showed a significantly higher seed yield (762 kg ha^{-1}) than SARI Selian (279 kg ha^{-1}; Table 3), highlighting the need for targeted management practices and precision agriculture approaches tailored to local agro-climatic conditions. A study by Islam et al. (2021) demonstrated that site-specific nutrient management strategies can optimize mung bean yield and resource use efficiency, thereby lowering input costs and environmental impacts.

In addition to these agronomic considerations, socio-economic and policy factors play a crucial role in shaping mung bean production systems and market dynamics. A study by Das et al. (2020) emphasizes the importance of market access, price stability, and farmer empowerment in promoting mung bean cultivation and improving rural livelihoods. Strengthening value chains, enhancing market infrastructure, and providing farmers with access to credit, inputs, and extension services are essential steps for creating a favorable environment for mung bean production and trade.

In addition, Table 6 reveals a complex relationship between botanical extracts, their concentrations, and the resultant grain yield and plant height. All extracts support optimal growth, with *L. gibelloa* showing the highest yields and plant height. This indicates that these plants thrive under standard conditions without additional interventions. As concentrations increase to 100 mg, many extracts, particularly *C. abyssinica*, demonstrate improved yields, suggesting that low levels may enhance nutrient availability or stimulate growth (Berihun et al., 2024). However, at 1,000 mg concentration, yields decline significantly for *C. anisata*, indicating its sensitivity to higher levels and highlighting a potential phytotoxic effect (Aidoo, 2023).

The trend continues at 10,000 mg concentration, where all extracts experience further reductions in yield and height, emphasizing a critical threshold beyond which extracts can become detrimental. Despite these trends, statistical analysis revealed no significant differences across treatments, pointing to the complexity of plant responses to these extracts (Chhabra et al., 2024). Further investigation is necessary to understand the underlying mechanisms and optimize extract concentrations for improved

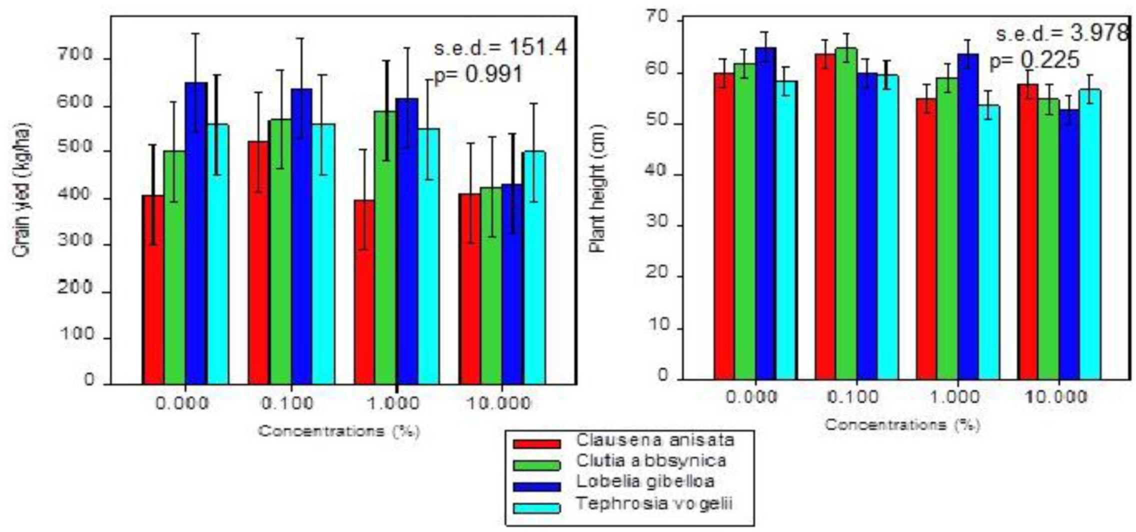

FIGURE 3
Interaction between botanical extracts and concentrations on grain yield and plant height.

agricultural productivity. Overall, the results suggested that while lower concentrations of botanical extracts may enhance growth, higher concentrations could hinder development, highlighting the importance of careful application in agricultural practices (Tirunagaru et al., 2024).

5 Conclusion

The study revealed that site, botanical type, and extract concentrations significantly influence the agronomic performance of mung bean. Notably, the Miwaleni site yielded superior results in terms of plant height and overall grain yield. Among the tested botanicals, *L. gibelloa* exhibited the best performance, achieving the highest values in plant height, number of pods per plant, and grain yield per hectare. The application of plant extracts at a concentration of 10% resulted in the most significant improvements, particularly in plant height and grain yield. These findings provide critical insights for optimizing mung bean cultivation practices. Based on this study, it is recommended that farmers consider using 10% concentrations of *L. gibelloa* extract to maximize mung bean yield and overall productivity. In addition, further research could explore the long-term effects of these extracts on soil health and crop resilience in varying environmental conditions.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

GK: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. AM: Supervision, Validation, Writing – review & editing. PB: Supervision, Writing – review & editing. PN: Supervision, Validation, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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