

Impact of potassium fertilization on yield, nutrient use and response efficiency, and antioxidant content of red ginger (*Zingiber officinale* var. *rubrum* Theilade)

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Received: 14 December 2021; Accepted: 1 March 2022; doi:10.4067/S0718-58392022000300380

ABSTRACT

Red ginger (*Zingiber officinale* var. *rubrum* Theilade) is one of the materials used in the functional food and biopharmaceutical industry; it has a low productivity and quality problem and is unable to meet market demand. The present study aimed to evaluate the impact of K fertilization on growth, yield, antioxidant content, and K use and response efficiency in red ginger cultivation. The study was conducted at Agro Techno Park (ATP) Jatikerto, Malang Regency, Indonesia. The field experiment was carried out in two periods, December 2019–August 2020 and January 2021–September 2021. In the first planting season, treatments included 4 K fertilizer rates (100, 200, 300, and 400 kg K ha⁻¹), while eight treatments were applied in the second planting season (0, 60, 120, 180, 240, 300, 360, and 420 kg K ha⁻¹). Measured variables included growth, yield, rhizome quality, and K use and response efficiency. Red ginger growth variables (height, leaf number, and tiller number per clump), yield, plant biomass, K uptake, and soil exchangeable K were strongly affected by K application rates, and the highest effect occurred at 300 kg K ha⁻¹. In addition, the 300 kg K ha⁻¹ rate resulted in the best rhizome morphology quality (rhizome diameter) and antioxidant content (6% to 30% higher than other treatments). Increased K fertilization decreased K use and response efficiency from 43% to 99% and decreased antioxidant content. Therefore, the study suggests that applying K fertilization at approximately 200–300 kg ha⁻¹ improves the yield and quality of red ginger.

Key words: Ginger antioxidant, ginger productivity, ginger quality, potassium fertilization, potassium use efficiency.

INTRODUCTION

The current COVID-19 pandemic requires efforts to increase the resistance of the human body (immunity); one possibility is consuming natural herbal products that contain high antioxidant contents. Antioxidant properties of some chemical compounds can prevent or reduce cell damage caused by free radicals and the effects of reactive oxygen species (ROS), which are continuously formed by the body when using oxygen to process metabolic functions such as respiration and some cell-mediated immune functions (Tohma et al., 2017). Antioxidant components are necessary to protect the human body from oxidative cell damage, which is correlated with some diseases, preserve cell components in a reduced state, and improve health by preventing degenerative diseases (Barbosa and Peteros, 2018).

Antioxidants can be obtained from natural or synthetic materials; however, natural antioxidants are certainly safer for humans because they do not have a toxic effect. Many plants have been studied as sources of natural antioxidants, including ginger. Based on previous studies, approximately 40 antioxidant components have been identified in ginger (Singh and Singh, 2019); this indicates antioxidant activity on lipid oxidation and oxidative stress (Ezez and Tefera, 2021). Antioxidant activity in ginger is produced by various polyphenolic compounds (Stoilova et al., 2007). Polyphenols are secondary metabolites that have a distinctive structure, which consists of several hydroxyl groups (–OH) bonded with benzene rings. These compounds are able to inhibit the initiation or disruption of lipid peroxidation propagation, thus reducing the number of decomposition products (Tohma et al., 2017). The main phenolic compounds contained in ginger rhizome are gingerols and shogaol. The antioxidant activity of gingerol is able to block the activity of enzymes involved in ROS generation, such as xanthine oxidase.

Among the types of ginger, red ginger (*Zingiber officinale* var. *rubrum* Theilade) has a higher gingerol content than others. Gingerol content in red ginger rhizome (5%) is higher than in small white ginger and large white ginger, which contain 1% to 2% gingerol (Azizah et al., 2019). Red ginger also shows promising results as an immunomodulator, antihypertensive, tonic, treatment of Alzheimer's disease, anti-hyperuricemic, and cytotoxic agent. Red ginger oleoresin compounds, which are considered as active compounds, have a tonic effect that is superior to white ginger (Suciwati and Adnyana, 2017). Given its content and qualities (active compound content), red ginger is more widely used as a raw material in products of the biopharmaceutical industry; the quality of red ginger must therefore be considered. However, the quality standard of red ginger as a raw material in the biopharmaceutical industry has not been widely studied, especially related to the cultivation process. Therefore, the quality of red ginger production needs to be improved to meet the requirements of the biopharmaceutical industry.

Red ginger production and quality are influenced by environmental factors, one of which is the availability of soil nutrients, especially potassium (K). Potassium is the main macronutrient most absorbed by ginger (Dinesh et al., 2012). This element is needed by plants for both primary and secondary metabolisms. In the primary metabolism, K is mostly absorbed by plants because of its important role in the photosynthesis and rhizome formation processes. Many physiological and biochemical processes in plants are determined by K, including enzyme activation, regulation of cell osmotic potential, neutralization of soluble and insoluble molecular anions, and stabilization of cell pH (Marschner, 2012). Hepler et al. (2001) stated that K is very important for plant function and development by improving cell growth. This element is essential for the performance of many enzymes, which affect various metabolic functions and have a great effect on growth, photosynthetic transport, and respiratory metabolism (Xizhen et al., 2005). Activation of this enzyme increases carbohydrate translocation and photosynthate translocation to the generative parts of the plant. Photosynthate translocation in ginger plants is maximized for rhizome formation. Potassium affects photosynthesis through its function in stomatal osmoregulation, especially in controlling stomata guard cell turgidity. In most plant species, K⁺ plays a crucial role in changing guard cell turgidity during the stomata movement. Increasing the K⁺ concentration in guard cells increases their osmotic pressure, which increases guard cell turgidity. Under turgid guard cell conditions, the stomata open to ensure smooth CO₂ transport. The accumulation of K⁺ in the cell cytoplasm is induced by sunlight; the stomata open in the morning and close under low light or dark conditions (Hawkesford et al., 2012).

Many researchers have proven that primary metabolites decrease under conditions of K deficiency; however, data are scarce as to the effect of K deficiency on secondary metabolites. Several studies have shown that plant secondary metabolites are also affected by K. In *Sulla carnosa*, a hydroponically grown plant, K⁺ deficiency increased total polyphenol and flavonoid contents by 62.7% and 14.5%, respectively. In addition, total antioxidant activity increased by 33.5% compared with the control plant (Hafsi et al., 2016). This is associated with the role of K, which acts as a coenzyme and activates different precursor enzymes of metabolic pathways; its deficiency has been related to increasing antioxidant enzymes (AOEs) (Ávila-Juárez et al., 2017). Different results were shown in another study that found decreased total phenolic content in blackberries with decreasing K levels. The scopolin content in sunflower was reduced as K levels decreased, and the oxylipin content in *Arabidopsis thaliana* also decreased in K-deficient plants. These results indicate that K plays an important role in regulating the production of plant secondary metabolites (Ibrahim et al., 2012). Thus, K fertilization management is very important in red ginger cultivation.

Potassium fertilization management is important to provide sufficient K for plants because the lack of K disrupts the metabolic process of red ginger plants. This stops growth with small gains and results in shortened internodes, which

then reduce the quality standard of the raw material. Prajapati and Modi (2012) added that the lack of sufficient K uptake affected the stomata opening and closing process that causes a great vapor loss; the plant becomes susceptible to drought and can also suffer stunted growth. Another study showed that the lack of K supply in bulbous or rhizome plants caused impaired crown growth, weak tuber or rhizome development, increased nitrate content in rhizomes, and increased susceptibility to pathogens (Grzebisz et al., 2020). The demand for red ginger continues to increase during the COVID-19 pandemic; therefore, the cultivation process must be improved, especially plant nutrition management to increase its quality. Therefore, the study aimed to evaluate the impact of K fertilization on growth, yield, antioxidant content, and K use and response efficiency in red ginger cultivation.

MATERIALS AND METHODS

Site description

The study was conducted at Agro Techno Park (ATP) Jatikerto (8°07'36" S, 112°31'46" E; 303 m a.s.l.), which is located in the sub-district of Kromengan, Malang Regency-East Java, Indonesia, from December 2019 to August 2020 and from January 2021 to September 2021. Annual rainfall ranged from 1598 to 3540 mm (data for 2006-2015), and relative humidity averaged 77.5% (Wijayanti et al., 2019). Soil type at the study site is Alfisol with loamy clay texture. Soil analysis before the field study showed that soil at the study site had 5.38 to 6.18 pH, 0.58 to 0.82 g 100 g⁻¹ soil organic C, 0.055 g 100 g⁻¹ total N, and 0.41 to 0.48 cmol_c kg⁻¹ soil exchangeable K. Plant quality analysis was performed in the Plant Physiology Laboratory of the Agronomy Department and the Soil Chemistry Laboratory of the Soil Science Department, Faculty of Agriculture, Brawijaya University, Malang City.

Research design and method

The study was conducted over two growing seasons, 2019-2020 and 2021 planting seasons. The study design was a non-factorial randomized block design with four treatments (first season) and eight treatments (second season). The treatments in the first season (December 2019-August 2020) included rates of 100 (K1), 200 (K2), 300 (K3), and 400 kg K ha⁻¹ (K4). Each treatment was repeated 3 times for a total of 12 research plots each measuring 4.5 m × 2.25 m. Meanwhile, the treatments in the second season (January 2021-September 2021) consisted of a control without fertilization (K0) and 60 (K1), 120 (K2), 180 (K3), 240 (K4), 300 (K5), 360 (K6), and 420 kg K ha⁻¹ (K7). Each treatment was repeated 3 times for a total of 24 study plots each measuring 4.5 m × 2.25 m.

The red ginger (*Zingiber officinale* var. *rubrum* Theilade) planting material was rhizome, which was harvested when the plant was 10 mo old, healthy, and fresh. Prior to planting, ginger rhizome seeds were sown so that growth was uniform. Seeds were sown in the shade, dry, not exposed to direct sunlight, and maintained with good air circulation. After shoots germinated, rhizomes were cut that had approximately 2 to 3 internodes (2 to 3 buds) with a weight between 15 and 30 g.

Soil was tilled 2 wk before planting with a plow to loosen the soil to a 30-40 cm depth, followed by a treatment plot. Red ginger rhizome seeds were planted to a 3-4 cm depth, and the shoots were facing upward. In each plot, ginger plants had 35 × 50 cm spacing. The maintenance of red ginger plants included replanting, irrigation, weeding, hoarding, fertilizing, and controlling plant pests and diseases. Replanting was done to replace plants that did not grow or whose growth was abnormal; this was carried out between 1.0 and 1.5 mo after planting. Surface irrigation was performed every 3 d, unless it rained. Manual weeding and hoeing was carried out once a week starting from the seedling stage to the fast growth stage or for 120 d. Hoarding was done after the 4 to 5 tiller growth stage, so that the ginger rhizome was always covered with soil for its optimal development. Inorganic fertilization consisted of N fertilizer at 184 kg N ha⁻¹ and 31 kg P ha⁻¹ (~ 72 kg P₂O₅) as basic fertilizer. Meanwhile, K fertilizer was applied as KCl according to each treatment, the phosphorus (P) fertilizer was applied as SP-36 (total P₂O₅ = 36%), and 200 kg SP-36 ha⁻¹ was applied once at sowing/planting using a localized placement method (especially drilling). In addition, nitrogen (N as urea and K as KCl) were applied three times at 30, 60, and 90 d after planting (DAP), one third of the rate each time. The fertilizer that was applied in this study was a product from the Petrokimia manufacturer, Gresik City, East Java, Indonesia. Pest and disease control was done if needed. The study did not use chemical pesticides for pest and disease control during red ginger cultivation because the level of pests and diseases was tolerable.

Red ginger was harvested 6 mo after planting (for the first growing season) and 8 mo after planting (for the second growing seasons). When the red ginger plant entered the senescence stage or had physiologically matured with the reddish color characteristic of the rhizome, the rhizome appeared on the ground and most of the leaves and stems were dried and decayed. Harvesting was done by carefully removing the ginger rhizome from the ground so as not to damage it and was cleaned.

The measured variables for red ginger included growth, yield, nutrient uptake, and quality. Red ginger growth was observed for plant height, leaf number, and tiller number. Yield consisted of rhizome weight per clump, rhizome length and diameter, and rhizome weight per hectare ($t\ ha^{-1}$), whereas measured variables for ginger quality included antioxidant content by DPPH (1,1-diphenyl-2-picryl-hydrazyl) assay and plant nutrient uptake (K). The N concentration was determined by the Kjeldahl method, while K was extracted by wet ashing using a mixture of concentrated HNO_3 and $HClO_4$ and measured with a flame photometer.

The K use efficiency (KUE) in the fertilization treatment was calculated according to Luo et al. (2021) and White et al. (2021) as:

$$KUE\ (g\ yield\ g^{-1}\ K) = K\ uptake\ (fertilized) - K\ uptake\ (unfertilized) / Applied\ K$$

The K response efficiency (KRE) was calculated according to Keuter et al. (2013) as:

$$KRE\ (g\ biomass\ g^{-1}\ K) = (Plant\ K\ uptake / N\ supply) \times (Biomass\ yield / Plant\ N\ uptake)$$

Statistical analysis

The obtained data were tested for normality, analyzed using ANOVA (5%) if the data were normal. If data were abnormal, data was transformed either using a logarithm or square root. Duncan's multiple range test was applied at the 5% level to assess significant differences between K fertilization rates. The relationships between K uptake, yield, antioxidant content, KUE, and agronomic efficiency were analyzed by averaged replicate plots according to the Pearson correlation coefficient. All statistical analyses were performed with the R statistical software (R Foundation for Statistical Computing, Vienna, Austria).

RESULTS AND DISCUSSION

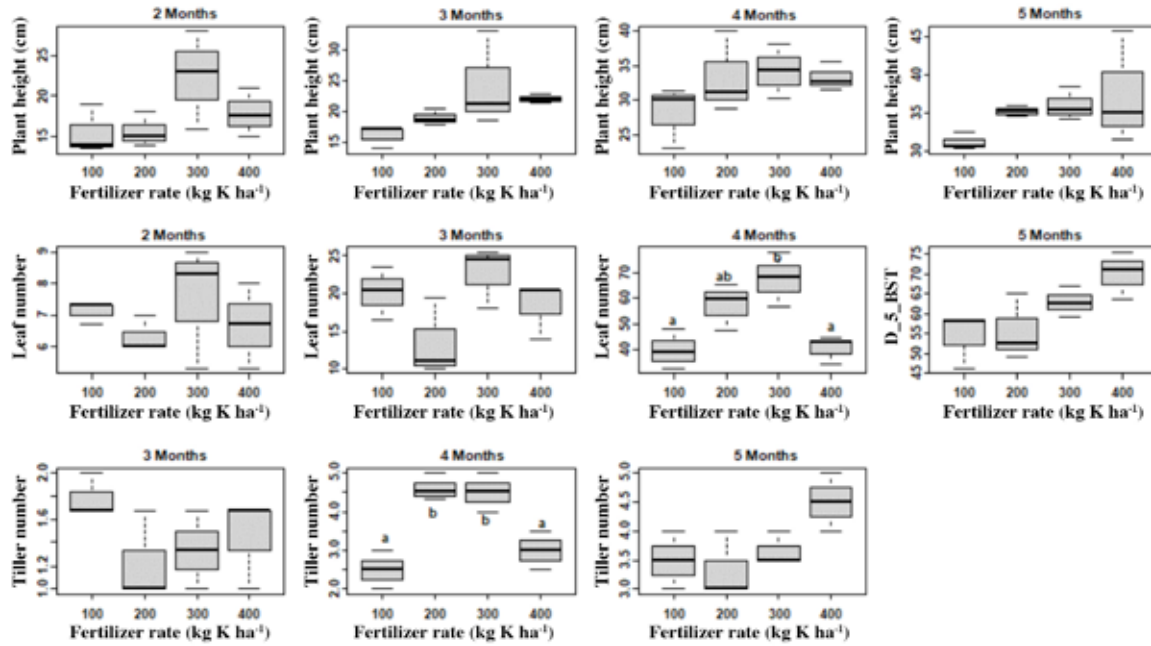
Effect of K fertilizer rate on red ginger growth

The statistical analysis showed that red ginger growth (plant height, leaf number, and tiller number per clump) was significantly different among K fertilizer applications. This mostly occurred in the second season as compared with the first season (Figures 1 and 2). The study was unable to detect significant differences among K fertilizer rates on plant height, leaf number, and tiller number per clump in most measurements during the first season; this was likely because the range of added K in the first season was wider than in the second season. In the first season, differences in added K had an impact on leaf number and tiller number per clump 4 mo after planting (Figure 1). Increases of K up to $400\ kg\ K\ ha^{-1}$ did not significantly increase red ginger growth as compared with the lower rates ($100, 200,$ and $300\ kg\ K\ ha^{-1}$). The $300\ kg\ K\ ha^{-1}$ rate increased leaf number and tiller number per clump by up to 69% and 80%, respectively.

In the second season, different K fertilizer rates strongly affected red ginger growth in all the measurements (Figure 2). Overall, the 300 and $360\ kg\ K\ ha^{-1}$ (P4 and P5) rates resulted in better plant growth compared with the other rates ($0, 60, 120, 180, 240,$ and $420\ kg\ K\ ha^{-1}$) and supported higher plant height, leaf number, and tiller number per clump. The result for the second season concurred with the first season in which the highest red ginger growth occurred at $300\ kg\ K\ ha^{-1}$. At the same K fertilizer rate ($300\ kg\ ha^{-1}$), red ginger growth (plant height, leaf number, and tiller number per clump) was 20% to 140% higher in the second season compared with those in the first season; this was probably due to the differences in planting time. Red ginger was planted in December for the first season and in January for the second season, while the rainy season ended in April; therefore, plants in the second season received more sunlight than those in the first season during the fast-growing stage (especially 3 to 5 mo after planting) and had an impact on the highest growth. Unfortunately, our study was unable to measure light intensity during the first and second seasons.

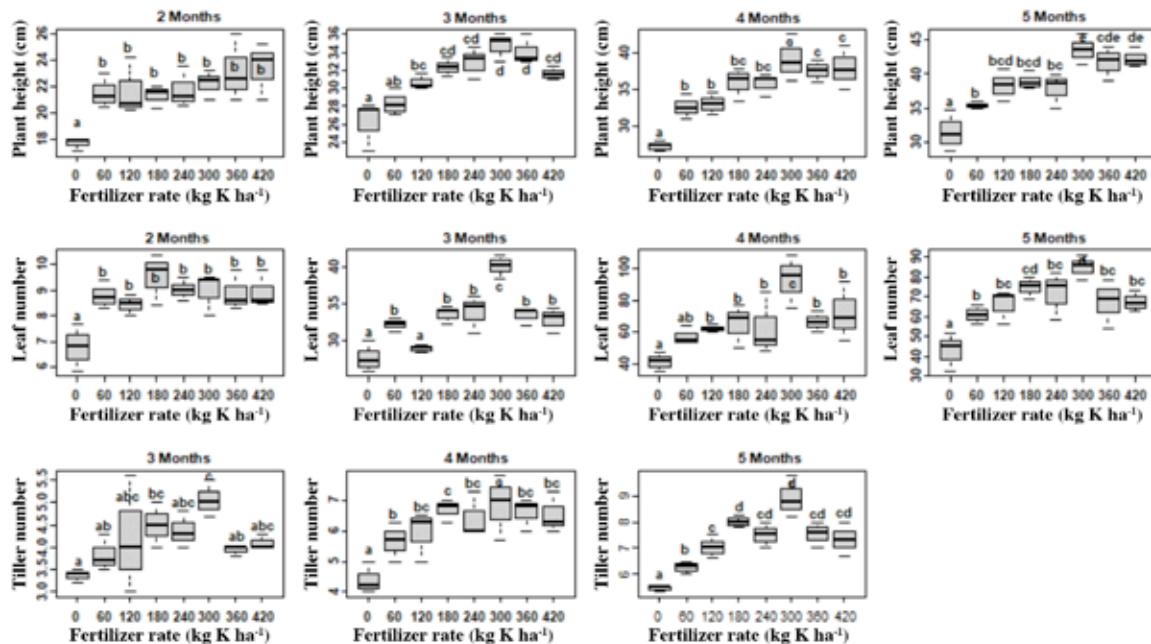
Red ginger plant height during the first and second seasons for all K treatments ranged from 31.1 to 43.4 cm. This was comparable to the previous study conducted by Wagiono et al. (2020), who reported that red ginger plant height 6 mo after planting with 100 to $200\ kg\ KCl\ ha^{-1}$ ranged from 30.6 to 39.2 cm. However, tiller number in the present study for the second season (6.3 to 8.9 tillers per clump) was higher than findings reported by Wagiono et al. (2020) with 100 to $200\ kg\ KCl\ ha^{-1}$, which resulted in 3.2 to 4.4 tillers per clump 6 mo after planting. Differences in red ginger plant

Figure 1. Growth of red ginger for all treatments during the first growing season.



Different letters mean significant differences according to Duncan's multiple range test ($P < 0.05$).

Figure 2. Growth of red ginger for all treatments during the second growing season.



Different letters mean significant differences according to Duncan's multiple range test ($P < 0.05$).

growth was influenced by nutrient availability (e.g., N, K). Lujiu et al. (2004) reported that nutrient uptake by a ginger crop was approximately 400 kg N ha⁻¹, 145 kg P₂O₅ ha⁻¹, and 950 kg K₂O ha⁻¹. The highest ginger plant height in Anhui, China, was reached by applying 300 kg K ha⁻¹, which concurs with our results in the second season. Potassium plays an important role in young growing tissues, especially for cellular elongation and could even affect cell division. Potassium

also promotes photosynthesis and carbohydrate formation in spices and the activation of more than 60 enzyme systems in plants (Sadanandan et al., 2002). Thus, sufficient soil K determined the growth performance of red ginger. During both the first and second seasons, the present study detected that the optimal K fertilizer rates ranged from 300 to 360 kg K ha⁻¹.

Effect of K fertilization on yield and rhizome morphology

The application of various K fertilizer rates had an impact on the physical quality of red ginger, especially rhizome morphology (rhizome diameter) and yield (rhizome weight per plant and yield per ha; Table 1). In the first season, the 300 kg K ha⁻¹ rate had a higher ($P = 0.06 - < 0.01$) rhizome diameter, rhizome weight per plant, and total yield per ha compared with other K fertilizer rates. The 300 kg K ha⁻¹ rate also had the highest yield (per plant and per hectare) compared with other K fertilizer rates (Table 1). This result indicated that the optimal K fertilizer rate for red ginger was 300 kg K ha⁻¹. Nevertheless, the optimal K rate in our study was different from previous results by Pradeepkumar et al. (2001), who reported that the optimal N and K fertilization rates were 144 and 109 kg ha⁻¹, respectively, which was close to the combination of 150 kg N ha⁻¹ and 100 kg K ha⁻¹.

The increases in K from 100 to 300 kg ha⁻¹ enhanced yield by 127% to 153% (3.3 to 5.5 t ha⁻¹) during the first and second seasons; this indicated the important role of K in red ginger yield. Our results concur with the previous findings by Ajithkumar and Jayachandran (2001), who stated that increasing K from 50 to 100 kg ha⁻¹ enhanced fresh rhizome yield. Prajapati and Modi (2012) indicated that K plays an important role in increasing crop yield and quality through photosynthesis, enzyme activation, stomatal activity (water use), sugar, water, and nutrient transport, protein and starch synthesis, and crop quality. However, as for the impact of K in ginger, Sadanandan et al. (2002) reported that ginger removes more K than any other element through harvesting. Therefore, K fertilizer application is needed to maintain soil K sustainability and ginger growth and yield.

At the 300 kg K ha⁻¹ fertilization rate, red ginger yield in the second season (5.9 ± 0.5 t ha⁻¹) was 35% lower compared with the first season. This was probably due to the differences in age at harvest between the first and second seasons. In the first season, harvesting was conducted 6 mo after planting, whereas harvesting in the second season occurred 8 mo after planting. The differences in the age at harvest were expected to affect water content of ginger rhizome and consequently influence its fresh weight.

Table 1. Red ginger yield and morphology during two growing seasons with different K fertilizer applications.

Treatment kg K ha ⁻¹	Yield and physical quality of rhizome			
	Rhizome length	Rhizome diameter	Rhizome weight	Yield
	cm		g plant ⁻¹	t ha ⁻¹
Planting season 1 (December 2019-June 2020)				
100 (P1)	14.8 ± 0.7	4.1 ± 0.2a	63.7 ± 4.7a	3.6 ± 0.3a
200 (P2)	14.4 ± 1.4	4.0 ± 0.1a	99.3 ± 9.7a	5.7 ± 0.6a
300 (P3)	18.4 ± 1.4	5.4 ± 0.8b	159.7 ± 23.2b	9.1 ± 1.3b
400 (P4)	13.8 ± 0.9	4.7 ± 0.6ab	89.0 ± 9.0a	5.1 ± 0.5a
Significance	0.14	0.06	< 0.01**	< 0.01**
Planting season 2 (January 2021-September 2021)				
0 (P0)	12.3 ± 0.9	3.1 ± 0.4	40.5 ± 1.8a	2.5 ± 0.7a
60 (P1)	11.4 ± 2.6	3.2 ± 0.3	50.3 ± 1.2ab	3.3 ± 0.6abc
120 (P2)	12.1 ± 1.3	2.95 ± 0.3	60.8 ± 4.1bcd	2.6 ± 0.5a
180 (P3)	13.4 ± 0.6	3.1 ± 0.1	73.1 ± 3.4d	4.2 ± 0.2b
240 (P4)	10.6 ± 0.4	2.9 ± 0.3	58.0 ± 2.5bc	3.4 ± 0.0ab
300 (P5)	14.1 ± 0.2	3.8 ± 0.4	102.8 ± 9.4e	5.9 ± 0.5c
360 (P6)	12.5 ± 0.3	3.1 ± 0.2	74.8 ± 4.4d	4.3 ± 0.2b
420 (P7)	13.7 ± 0.9	3.1 ± 0.4	72.1 ± 3.7cd	4.1 ± 0.2b
Significance	0.396	0.73	< 0.01**	< 0.01**

*, **Significantly different at 5% and 1%, respectively. ±: Standard error. Different letters mean significant differences according to Duncan's multiple range test ($P < 0.05$).

Impact of different K fertilization rates on antioxidant content, biomass, plant K uptake, and soil exchangeable K in the second growing season of red ginger

Red ginger is a good source of antioxidants because of its gingerols. Kane et al. (1996) stated that antioxidant activity (e.g., catalase) was associated with photo-respiratory detoxification of H₂O₂ through mitochondrial electron transport systems. Potassium also plays an important role in minimizing oxidative stress because it can maintain the level of NADPH oxidase activity, and the photosynthetic electron transport system justifies antioxidant activation by supplying KNO₃ (Cakmak, 2005). Similar to the previous study by Cakmak (2005), our results showed that differences in K fertilization rates significantly ($P = 0.04$) affected antioxidant content in red ginger rhizome (Table 2). The application from 180 to 300 kg K ha⁻¹ had a higher antioxidant content in red ginger rhizome than the control (without K fertilization) during the second season. However, increasing K fertilization rates to 360 and 420 kg K ha⁻¹ showed 6% to 8% lower antioxidant content in red ginger rhizome than from 180 to 300 kg K ha⁻¹ (Table 2). This result indicated that excessive soil K availability did not lead to a high antioxidant content, likely because crop K uptake was based on its capacity or antioxidants were formed under sufficient soil nutrient availability.

The addition of K fertilizer also significantly affected plant biomass, plant K uptake, and soil exchangeable K of red ginger at harvest ($P = 0.002$ to 0.02 ; Table 2). The 300 kg K ha⁻¹ rate significantly increased biomass; it ranged from 49% to 66% compared with the unfertilized control and at 60, 120, and 240 kg K ha⁻¹ rates. Plant K uptake was higher (43% to 73%) at 300 kg K ha⁻¹ than in the control and at 60, 240, and 420 kg K ha⁻¹. However, the highest soil exchangeable K at the end of the present study occurred at 360 kg K ha⁻¹. Kakar et al. (2020) reported that nutrient management technologies using fertilization and mulch increased ginger biomass and soil K availability, but did not significantly affect plant K uptake in ginger cultivation. Potassium uptake by red ginger ranged from 0.31 to 57 g K plant⁻¹ (~ 7.0 to 30.3 kg K ha⁻¹) with various K application rates. This result is lower than K uptake by large ginger, which ranged 80 to 153 kg K ha⁻¹ for 0 to 160 kg K ha⁻¹ application rates (Akhter et al., 2013). The ginger variety studied by Akhter et al. (2013) was different from the variety used in our study, thus indicating the impact of variety on nutrient uptake. This was supported by Sánchez et al. (2021), who reported that nutrient absorption efficiency was influenced by cultivars. The highest biomass and plant K uptake at 300 kg K ha⁻¹ could be due to increased K supply in the soil rooting system. Increasing K fertilizer rates to 420 kg K ha⁻¹ tended to decrease biomass and plant K uptake; this is consistent with Mitscherlich's law of diminishing returns that proposes decreased marginal productivity due to increased levels of the limiting factor (Mengel and Kirkby, 2001; Ferreira et al., 2017).

Potassium use efficiency and its relationship with K response efficiency and antioxidant content

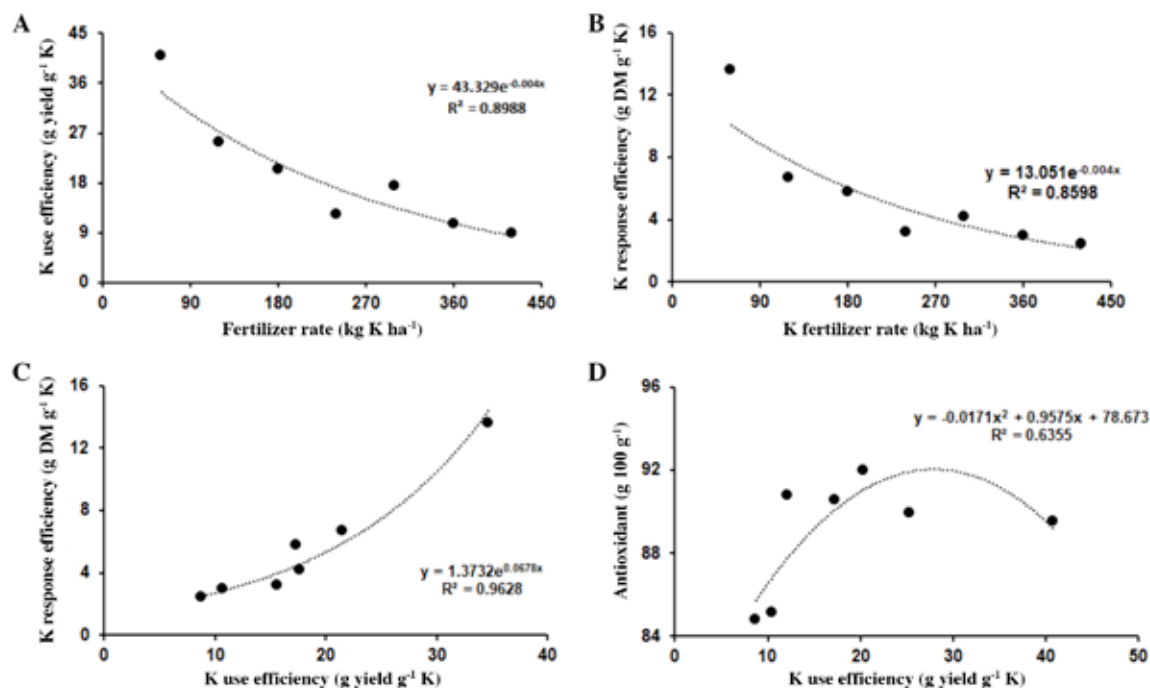
Red ginger roots can gain sufficient K for optimal growth from soil solutions containing micromolar K concentrations. Our results indicated low KUE and KRE with 8.72 to 40.88 g yield g⁻¹ K and 2.38 to 13.59 g DM g⁻¹ K, respectively (Figure 3). This concurs with Dobermann et al. (1996), who stated that KUE is usually very low in agricultural systems, usually less than 20%, and the same trend appeared for KRE. The 180 and 300 kg K ha⁻¹ rates had the highest KUE and KRE compared with other K rates (e.g., 60, 120, 240, 360, and 420 kg K ha⁻¹), indicating that the optimal K fertilization

Table 2. Red ginger antioxidant content, biomass, plant K uptake, and soil exchangeable K for different K fertilization rates in the second growing season.

Treatment	Antioxidant content	Biomass	K uptake	Soil exchangeable K
kg K ha ⁻¹	%	g plant ⁻¹		mmol 100 g ⁻¹
0 (P0)	86.96 ± 0.9a	15.2 ± 1.1a	0.36 ± 0.04a	1.51 ± 0.10a
60 (P1)	89.51 ± 0.8ab	16.7 ± 0.3a	0.38 ± 0.03ab	1.66 ± 0.12ab
120 (P2)	89.94 ± 2.6ab	16.0 ± 1.4a	0.45 ± 0.03abcd	1.74 ± 0.11ab
180 (P3)	91.99 ± 2.1b	20.8 ± 0.9ab	0.50 ± 0.03bcd	2.38 ± 0.18abc
240 (P4)	90.75 ± 1.3b	15.0 ± 1.3a	0.33 ± 0.02a	2.02 ± 0.19abc
300 (P5)	90.56 ± 0.3b	24.9 ± 2.8b	0.57 ± 0.10d	2.48 ± 0.23bc
360 (P6)	85.11 ± 2.2a	19.7 ± 0.5ab	0.53 ± 0.03cd	2.76 ± 0.21c
420 (P7)	84.79 ± 0.6a	18.3 ± 1.5ab	0.40 ± 0.04abc	2.54 ± 0.31bc
Significance	0.04	0.002	0.02	0.003

*, **Significantly different at 5% and 1%, respectively. ±: Standard error. Different letters mean significant differences according to Duncan's multiple range test ($P < 0.05$).

Figure 3. Impact of K fertilization rate on K use efficiency (a) and K response efficiency (b), relationship between K use efficiency and K response efficiency (c) and relationship between K use efficiency and antioxidant content (d) in red ginger.



rate was approximately 200 kg K ha⁻¹ (Figure 2). Our results also showed that KUE and KRE of red ginger decreased when added K exceeded the K requirement, which was shown by the lower KUE and KRE when applying 360 and 420 kg K ha⁻¹. However, the decrease in KUE, and perhaps KRE, was also influenced by environmental factors such as soil compaction, poor soil structure and texture, soil crusting, water holding capacity, water logging, and extreme drying (Baligar et al., 2001). Another study conducted by Sánchez et al. (2021) reported that differences in cultivar were also affected by nutrient use efficiency in the intercropping systems of perennial ryegrass and white clover.

The ability to uptake K from the soil and use K physiologically for vegetative and reproductive growth differs among plants. Our study detected that increases in KUE increased KRE and antioxidant content (Figure 3). The high antioxidant content was found in the optimal K use, which was reflected by K fertilizer application at approximately 180 and 300 kg K ha⁻¹. This result indicated that antioxidant content in red ginger can increase by optimizing the K fertilization rate. Therefore, providing and maintaining K at optimal rates is necessary to increase production and improve quality (Sadanandan et al., 2002).

CONCLUSIONS

Differences in red ginger growth (height, leaf number, and tiller number per clump) was strongly affected by K application rates with optimal rates of 300 and 360 kg K ha⁻¹. In addition, the application of 300 kg K ha⁻¹ also resulted in the highest yield and quality of red ginger and in both morphology (rhizome diameter) and chemical content (e.g., K uptake and antioxidant content). Both K use efficiency and K response efficiency decreased with increasing K fertilizer rates. Therefore, optimizing soil management (e.g., K fertilization) is needed to maintain the sustainability of ginger production and quality in agricultural land.

ACKNOWLEDGEMENTS

The research was funded by the Research and Community services institution through the Non-tax state revenue fund (PNBP) University of Brawijaya through Covid-19 Integrated Research (CIR 1) scheme, according to the Budget Implementation List (DIPA) Number: 023.17.2.677512/2021.

REFERENCES

- Ajithkumar, K., and Jayachandran, B.K. 2001. Effect of major nutrients on yield of ginger (*Zingiber officinale* Rosc.) intercropped in coconut garden. *Journal of Spices and Aromatic Crops* 10(1):17-23.
- Akhter, S., Noor, S., Islam, M., Masud, M., Talukder, M., and Hossain, M. 2013. Effect of potassium fertilization on the yield and quality of ginger (*Zingiber officinale*) grown on a K deficient terrace soil of level Barind Tract (AEZ 25) in Northern Bangladesh. *Research Finding Electronic International Fertilizer Correspondent (e-ifc)* 35:13-18.
- Ávila-Juárez, L., Torres-Pacheco, I., Ocampo-Velázquez, R.V., Feregrino-Pérez, A.A., Cruz Hernández, A., and Guevara-González, G.R. 2017. Integrating plant nutrients and elicitors for production of secondary metabolites, sustainable crop production and human health: A review. *International Journal of Agriculture and Biology* 19(3):391-402. doi:10.17957/IJAB/15.0297.
- Azizah, N., Purnamaningsih, S.L., and Fajriani, S. 2019. Land characteristics impact productivity and quality of ginger (*Zingiber officinale* Rosc) in Java, Indonesia. *Agrivita* 41(3):439-449.
- Baligar, V.C., Fageria, N.K., and He, Z.L. 2001. Nutrient use efficiency in plants. *Communications in Soil Science and Plant Analysis* 32(7&8):921-950.
- Barbosa, G.B., and Peteros, N.P. 2018. DPPH radical scavenging potential of ginger leaves and rhizomes. *Asian Journal of Biological and Life Sciences* 7(3):87-92.
- Cakmak, I. 2005. The role of potassium in alleviating detrimental effects of abiotic stresses in plants. *Journal of Plant Nutrition and Soil Science* 168:521-530.
- Dinesh, R., Srinivasan, V., and Hamza, S. 2012. Nutrition. p. 256-287. In Singh, H.P., Parthasarathy, V.A., Kandiannan, K., and Krishnamurthy, K.S. (eds.) *Zingiberaceae crops: present and future cardamom, ginger, turmeric and others*. Westville Publishing House, New Delhi, India.
- Dobermann, A., Cassman, K.G., Cruz, P.C.S., Adviento, M.A., and Pampolino, M.F. 1996. Fertilizer inputs, nutrient balance, and soil nutrient-supplying power in intensive, irrigated rice systems. II: Effective soil K-supplying capacity. *Nutrient Cycling in Agroecosystem* 46:11-21.
- Eze, D., and Tefera, M. 2021. Effects of solvents on total phenolic content and antioxidant activity of ginger extracts. *Journal of Chemistry* 2021:1-5. doi:10.1155/2021/6635199.
- Ferreira, I.E.P., Zocchi, S.S., and Baron, D. 2017. Reconciling the Mitscherlich's law of diminishing returns with Liebig's law of the minimum. Some results on crop modeling. *Mathematical Biosciences* 293:29-37. doi:10.1016/j.mbs.2017.08.008.
- Grzebisz, W., Szczepaniak, W., and Poznan, J.B. 2020. Potassium fertilization as a driver of sustainable management of nitrogen in potato (*Solanum tuberosum* L.) *Field Crops Research* 254:1-13. doi:10.1016/j.fcr.2020.107824.
- Hafsi, C., Falleh, H., Saada, M., Rabhi, M., Khaoula Mkadmini, K., Ksouri, R., et al. 2016. Effects of potassium supply on growth, gas exchange, phenolic composition, and related antioxidant properties in the forage legume *Sulla carnosa*. *Flora* 223:38-45. doi:10.1016/j.flora.2016.04.012.
- Hawkesford, M., Horst, W., Kichey, T., Lambers, H., Schjoerring, J., Møller, I.S., et al. 2012. Functions of macronutrients. p. 135-189. In Marschner, P. (ed.) *Mineral nutrition of higher plants*. 3rd ed. Academic Press, Cambridge, Massachusetts, USA. doi:10.1016/B978-0-12-384905-2.00006-6.
- Heppler, P.K., Vidali, L., and Cheung, A.Y. 2001. Polarized cell growth in higher plants. *Annual Review of Cell and Development Biology* 17:159-187. doi:10.1146/annurev.cellbio.17.1.159.
- Ibrahim, H.M., Jaafar, H.Z.E., Karimi, E., and Ghasemzadeh, A. 2012. Primary, secondary metabolites, photosynthetic capacity and antioxidant activity of the Malaysian herb Kacip fatimah (*Labisia pumila* Benth) exposed to potassium fertilization under greenhouse conditions. *International Journal of Molecular Sciences* 13:15321-15342. doi:10.3390/ijms131115321
- Kakar, R., Sharma, J.C., Mogta, A., Guleria, A., and Thakur, J. 2020. Assessment of various nutrient management technologies for quality, fertilizer use efficiency, and economics of ginger production under subtropical to subtropical conditions. *Communications in Soil Science and Plant Analysis* 51(22):1-16. doi:10.1080/00103624.2020.1849263.
- Kane, D.O., Gill, V., Boyd, P., and Burdon, R. 1996. Chilling, oxidative stress and antioxidant responses in *Arabidopsis thaliana* callus. *Planta* 198:371-377.
- Keuter, A., Hoeft, I., Veldkamp, E., and Corre, M.D. 2013. Nitrogen response efficiency of a managed and phyto-diverse temperate grassland. *Plant and Soil* 364:193-206. doi:10.1007/s11104-012-1344-y.
- Luju, L.L., Xisheng, G., Jiejun, G., Nan, D., and Lin, Z. 2004. Ginger response to potassium in Anhui province. *Better Crops* 88(1):22-24.

- Luo, T., Zhu, Y., Lu, W., Chen, L., Min, T., Li, J., et al. 2021. Acidic compost tea enhances phosphorus availability and cotton yield in calcareous soils by decreasing soil pH. *Acta Agriculturae Scandinavica, Section B — Soil & Plant Science* 71(8):1-10. doi:10.1080/09064710.2021.1933161.
- Marschner, P. 2012. *Marschner's mineral nutrition of higher plants*. 3rd ed. Academic Press, Cambridge, Massachusetts, USA. doi:10.1016/B978-0-12-384905-2.00006-6.
- Mengel, K., and Kirkby, E.A. 2001. *Principles of plant nutrition*. Springer, Dordrecht, Netherlands. doi:10.1007/978-94-010-1009-2.
- Pradeepkumar, T., Mayadevi, P., Aipe, K.C., Manomohandas, T.P., Giridharan, M.P., Satheesan, K.N., et al. 2001. Optimum dose of nitrogen and potassium for ginger in Wynad, Kerala. *Journal of Spices and Aromatic Crops* 10(1):7-11.
- Prajapati, K., and Modi, H.A. 2012. The importance of potassium plant growth – A review. *Indian Journal of Plant Science* 1:177-186.
- Sadanandan, A.K., Peter, K.V., and Hamza, S. 2002. Role of potassium nutrition in improving yield and quality of spice crops in India. p. 445-454. In Pasricha, N.S., and Bansal, S.K. (eds.) *Potassium for sustainable crop production*. Potash Research Institute of India, Dundahera, International Potash Institute, Zug, Switzerland.
- Sánchez, MP., Acuña, H., Inostroza, L., and Zagal, E. 2021. Nitrogen, phosphorus and potassium efficiency of perennial ryegrass and white clover cultivar mixtures. *Chilean Journal of Agricultural Research* 81:456-466. doi:10.4067/S0718-58392021000300456.
- Singh, R., and Singh, K. 2019. *Zingiber officinale*: a spice with multiple roles. *Research Journal of Life Sciences, Bioinformatics, Pharmaceutical and Chemical Sciences* 5(2):113-125. doi:10.26479/2019.0502.09.
- Stoilova, I., Krastanov, A., Stoyanova, A., Denev, P., and Gargova, S. 2007. Antioxidant activity of a ginger extract (*Zingiber officinale*). *Food Chemistry* 102:764-770. doi:10.1016/j.foodchem.2006.06.023.
- Suciyati, S.W., and Adnyana, I.K. 2017. Red ginger (*Zingiber officinale* Roscoe var *rubrum*): A review. *Pharmacology Online* 2:60-65.
- Tohma, H., Gülçin, I., Bursal, E., Gören, A.C., Alwasel, S.H., and Köksal, E. 2017. Antioxidant activity and phenolic compounds of ginger (*Zingiber officinale* Rosc.) determined by HPLC-MS/MS. *Food Measure* 11:556-566. doi:10.1007/s11694-016-9423-z.
- Wagiono, Sari, D.A., Miledhiya, S.A., Fitria, I.A., Sidabutar, K.V., Kamil, M.I., et al. 2020. Impact of manure and inorganic fertilizer application to growth performance and yields of red ginger (*Zingiber officinale rubrum*) in Majalaya sub district, Karawang district. *Jurnal Agrotek Indonesia* 2(5):41-46.
- White, P.J., Bell, M.J., Djalovic, I., Hinsinger, P., and Rengel, Z. 2021. Potassium use efficiency of plants. p. 119-145. In Murrell, T.S., Mikkelsen, R.L., Sulewski, G., Norton, R., and Thompson, M.L. (eds.) *Improving potassium recommendations for agricultural crops*. Springer, Cham, Switzerland.
- Wijayanti, F., Kurniawan, S., and Suprayogo, D. 2019. Impact of maize conservation agricultural system on nitrogen losses through surface runoff and soil erosion in dryland. *Journal of Degraded and Mining Lands Management* 7(1):1965.
- Xizhen, A., Jinfeng, S., and Xia, X. 2005. Ginger production in Southeast Asia. In Ravindran, P.N., and Babu, K.N. (eds.) *Ginger: The genus Zingiber*. CRC Press, Boca Raton, Florida, USA.