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Response of Cowpea Growth, Yield, and Organic Acid Secretion in Acidic Soil to Variability in Population and Minus One Element Fertilizer Test

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Abstract

Cowpea is a legume with the potential to serve as an alternative food source to replace soybeans in Indonesia; soybeans are primarily used in traditional foods such as tempeh and tofu. Currently, 70% of Indonesia's soybean demand is met through imports. Cowpea exhibits the ability to thrive in suboptimal soils with low fertility levels. One of the major challenges in Indonesian agriculture is the prevalence of acidic soils, which are typically deficient in essential nutrients. Notably, a lack of phosphorus (P) is a significant limiting factor affecting crop productivity in these acidic soils. To address this issue, a study was conducted to investigate how cowpea can adapt and grow in acidic soil conditions. The first experiment aimed to understand the impact of plant density and fertilization methods on the growth and yield of cowpea. The results indicated that planting one cowpea plant per hole resulted in a higher number of leaves and branches. Additionally, the treatment with complete NPK showed a higher number of pods, although this was not significantly different from the treatment with reduced phosphorus (minus P). These findings suggest that cowpea can thrive in acidic soil even under conditions of phosphorus deficiency. Cowpea has developed an external adaptation mechanism through the secretion of organic acids from its roots to survive in low-phosphorus acidic soils. As a follow-up to these findings, a second experiment was conducted to identify the types of organic acids secreted by cowpea roots under conditions of phosphorus deficiency, using High-Performance Liquid Chromatography (HPLC). The results revealed that the organic acids produced by cowpea root exudates were primarily malic acid and oxalic acid. These research outcomes provide valuable information for growers, indicating that cowpea can be successfully cultivated in acidic soils. Cowpea's ability to produce organic acids allows it to thrive in such environments even when phosphorus levels are low.

Keywords: abiotic stress, malic acid, oxalic acid, P deficiency, root exudates, root morphology

Introduction

Cowpea is a widely recognized leguminous crop in Africa, serving as a significant source of daily protein for over two hundred million people (Mohammed et al., 2020). Its adaptability to high temperatures and low soil fertility has led to its cultivation in tropical regions around the world (Chikoye et al., 2014). In Indonesia, cowpea holds promise as an excellent food ingredient when combined with soybeans. This is particularly relevant given the Indonesian population's strong preference for soy-based products like tempeh and tofu, which make up a substantial 78.44% of all imported soybeans (Ministry of Agriculture, 2020). Cowpeas are also notable for their high vegetable protein content, ranging from 18% to 35% (Goncalves et al., 2016). Utilizing cowpea as an alternative food ingredient to soybeans can potentially reduce Indonesia's reliance on imported soybeans and enhance the country's food security.

One of the obstacles encountered in the development of cowpea includes that cowpeas have not been studied as much as other popular legumes in Indonesia so the productivity of cowpea is still low compared to their potential yield. Therefore, it is necessary to evaluate appropriate farming techniques to increase cowpea yield, including assessment of plant population densities and fertilization. Plants need fertilizer to achieve maximum yield. Nutrients N, P and K are the essential nutrients for the growth of cowpea. However, there is no clear information regarding standard doses of single fertilizer elements

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of N (urea), P (SP-36), and K (KCl) for cowpea and which nutrients have the most effect on cowpea. This research applied minus one element test to reveal the most limiting nutrient among N, P, and K to the growth and yield of cowpea. This method is more useful than testing NPK compound fertilizer where it is not known which element is the limiting factor for plants. The result of Siregar's research (2020) on cowpea with the application of NPK compound fertilizer, it was not known which element had the most effect on cowpea. On the other hand, Tabri's research (2010) by applying the minus one test method in a single fertilizer N, P, K found that the limiting element for hybrid corn production was element N.

High soil acidity is one of the problems limiting crop yield. It is present in around 40% of the world's arable land (Kochian et al., 2004). Low base saturation and exchange capacity, low pH (<5.5), low nutritional content of N, P, and K, and high Al saturation are characteristics of acid soil (Kasno, 2009). Although cowpea can fix appreciable amounts of N, plants find the difficulty to access P in the soil solution compounded by most soils is acid soils (Mohammed et al., 2020). Furthermore, P usually becomes a limiting factor for plant production in acidic soils. Acid-tolerant plants have adaptive mechanisms to survive in acidic soils, one of which is through root exudate. This root exudate maintains a beneficial relationship between plants and microorganisms by regulating the soil microbial community in the rhizosphere (Zhang et al., 2021). Organic acids are compounds in root exudates that play an important role to increase P availability for plants under P deficiency conditions. Phosphate-solubilizing bacteria (PSB) play a crucial part in P cycling and plant P absorption (Estrada-Bonilla et al., 2021). In acid soil, due to external chelation of Al^{3+} and mobilization of Pi, organic acids anion (OAAs), such as malate, citrate and oxalate, have been reported as key components involved in Al detoxification and P acquisition of plants (Lopez-Bucio et al., 2000).

This study is crucial because cowpea still lacks references related to publications on the effect of plant populations and nutrient deficiencies through the minus one element test method on acid soils. In addition, there is no information regarding the adaptation mechanism of cowpea in acid soils under P deficiency conditions in the form of organic acid secretion by roots. Therefore, the purpose of this study was to determine plant density through the number of plants per hole to optimize cowpea productivity and which nutrients N, P, and K act as limiting factors in cowpea production. This study also aims to investigate the type of organic acids secreted by roots as an adaptation mechanism of cowpea to acidic soils.

Materials and Methods

The research implementation consisted of two experiments: 1) the effect of plant density and minus one element fertilizer on the growth and production of cowpea, and 2) the Accumulation of organic acid secretion from cowpea roots under P deficiency conditions. The first research was the field experiment conducted at the Cikabayan Experimental Station, Department of Agronomy and Horticulture, IPB University, Dramaga, Bogor, Indonesia. It is located at an altitude of about 250 meters above sea level. The field experiment was carried out from January until May 2022. Analysis of soil was carried out at the Testing Laboratory, Department of Agronomy and Horticulture, IPB University. Analysis of yield and yield components was carried out at the Post Harvest Laboratory, Department of Agronomy and Horticulture, IPB University. The planting material used was cowpea seeds Uno IPB variety with black seed characteristics. The second experiment was carried out in at Tropical Agriculture Laboratory, Graduate School of Agriculture, Kyoto University, Japan. This second experiment was conducted from July until September 2022. The planting material used was black cowpea gathered from Africa.

Experiment 1: Effects of Plant Density and Minus P Fertilization on Cowpea Growth and Production

The field study used a factorial randomized block design method with two factors and three replications. The data were analyzed using two ways ANOVA. The first factor was plant density with different number of plants per planting hole which consisted of three levels; one plant per sowing hole, two plants per sowing hole, and three plants per sowing hole. The seeds used were gathered from Bogor, West Java, Indonesia. The spacing used was 50 × 20 cm^2. The second factor was the fertilization treatment using minus one test method with four treatment levels; complete NPK fertilization, minus N, minus P, and minus K. Plants are planted in a plot size of 2x3 m^2. Therefore, there are 36 observation plots.

Our study followed a fertilization treatment approach based on the FERADS (Fertilizer Recommendation for Agricultural Development System) method, which determines the appropriate fertilizer dosage through soil analysis. Before planting, soil analysis was conducted using the FERADS program to calculate the nutrient requirements for optimal plant growth. The fundamental principle of fertilization is to supplement soil nutrients that may be deficient, ensuring that the necessary nutrients are available in sufficient quantities for plant growth. In accordance with the FERADS recommendations, our research utilized Urea (N) fertilizer at a rate of 249 kg.ha^{-1}, applied in three stages: 1 week after sowing (WAS), 4 WAS, and 7 WAS. SP-36 (P) fertilizer was applied in its entirety at 1 WAS. KCl (K) fertilizer was applied at a rate of 179 kg.ha^{-1}, distributed across three stages: 1 WAS, 4 WAS, and 7 WAS. For the minus N treatment, no Urea fertilizer was applied, while the minus P treatment involved the omission of SP-36 fertilizer, and the minus K treatment entailed the exclusion of KCl fertilizer (Atmaja, 2017).

External Adaptation Mechanisms and Cowpea Root Organic Acid Secretion

This experiment consisted of two stages, pre-treatment and P-deficient treatment.

In the pre-treatment experiment, black cowpeas were grown hydroponically in the greenhouse under low P concentration (0.25 mM) for two weeks. Every hole was planted one seed of black cowpea. The composition of the hydroponic solution used 7.5 mM NH_4NO_3, 0.25 mM KH_2PO_4, 2 mM $CaCl_2$, 2 mM $MgSO_4$, and 5.75 mM KCl. The nutrient solution was replaced every week. All samples were grown together in a large container with a volume of 40 liters of water. The roots of each sample plant are divided using pipes to prevent them from fusing together. Hoses carrying oxygen were placed inside the container so that the plants could still have good respiration in the water medium.

Figure 1. Cowpeas in the first experiment (A), pre-treatment (B), and P-deficient treatments (C).

In the P-deficient treatment, after two weeks of pre-treatment plants were subjected to P deficiency treatments for three days. Each plant sample was separated in each pot and then given a different treatment. The treatment was given in the form of four concentration levels of phosphorus given in the form of KH_2PO_4: P0 (0 mM), P1 (0.25 mM), P2 (1 mM), P3 (4 mM). After three days, water samples from each pot were collected and analyzed for root-exuded organic acids using high performance liquid chromatography (HPLC) method. The measurement of organic acid method is modified from Tang et al., (2020). The HPLC column in this research used Shodex column type NI-424. The stages in testing organic acids are: (1) Preparation of a mobile phase consisting of 2.1 mM phthalic acid, 2.9 mM aminocaproic acid dan 6 mM phenylboronic acid. (2) Preparation of standard solution. There are 3 organic acids used as standard solutions namely citric acid, oxalic acid, and malic acid. (3) Sample pretreatment. Dilute the samples within the upper limit and put them in a 1 ml sample bottle. Furthermore, filter the samples with a 0.45 μm membrane filter to prevent clogging of the flow path. (4) Measurement of organic acids using HPLC. Put all tube water samples and standard solutions in the HPLC machine. Every sample has five replications. The results of the HPLC measurements are displayed as a chromatogram, which reveals the type and volume of organic acids released by the root. The data were analyzed using one way ANOVA.

Result and Discussion

Experiment 1: Effects of Plant Density and Minus P Fertilization on Cowpea Growth and Production

Climate data in Cikabayan Experimental Station gathered from Bogor Climatology Station show that the rainfall from January to May 2022 is classified as moderate to high with the lowest rainfall in January 2022 of 107 mm per month and the highest of 317 mm per month in April 2022 (BMKG, 2022). The average monthly temperature ranges from 25.76 ºC – 26.49 ºC and the average monthly RH is around 84.44% – 85.03%. Climatic conditions during the study are summarized in Table 1. These climatic conditions generally are favorable for cowpea growth, but continuous water stagnation has the potential to reduce cowpea yield (Adisarwanto 1998). Climate conditions especially during the initiation of the reproductive period (R1) until harvest (R8) from April to May 2022, rainfall was very high with the peak of rainfall occurring in April. The existence of stagnant water due to high rainfall, especially in the R2 phase or full flowering stage, will significantly reduce yields in R8 or harvest time (Olorunwa et al., 2023).

The preliminary soil analysis conducted before the study revealed poor soil fertility characterized by an extremely acidic pH level of 4.3, low organic carbon content, moderate total nitrogen levels, high total phosphorus levels but low availability of phosphorus,

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Table 1. Climate data from January until May 2022 at Cikabayan Experimental Station

Month	T min (ºC)	T max (ºC)	T avg (ºC)	RH (ºC)	Rainfall (mm per month)
January	21.99	31.37	26.03	84.44	107.00
February	22.14	30.66	25.76	85.03	150.00
March	22.12	31.86	26.09	85.03	113.00
April	22.46	32.34	26.37	85.00	317.00
May	22.57	32.34	26.49	84.84	229.00

Note: Data source originated from Bogor Climatology Station (BMKG), January – May 2022. T min: minimum temperature, T max: maximum temperature, T avg: average temperature, RH: relative humidity.

inadequate potassium content (K-dd), and a low Cation Exchange Capacity (CEC), as indicated in Table 2. To address these soil quality issues, corrective measures were taken one week before planting cowpeas. Specifically, two tons per hectare of cow manure and agricultural lime were applied as ameliorants. This intervention aimed to alleviate soil acidity and enhance soil fertility. Very acidic pH levels in the soil can diminish the accessibility of essential nutrients to plants.

It’s noteworthy that while the total phosphorus (P) content in the soil was very high, the actual availability of phosphorus nutrients for plants was remarkably low. This limitation was due to the formation of less soluble compounds involving aluminum (Al), iron (Fe), manganese (Mn), and calcium (Ca), which bound a significant portion of the total phosphorus. Consequently, despite the abundance of total phosphorus in the soil, only a small fraction of it was accessible for plant uptake (referred to as P-available), primarily because of Al metal’s strong affinity for phosphorus in acidic soils.

Plant Growth

Cowpea growth was very good, particularly during the vegetative phase, with plants thriving and showing no apparent signs of nutrient deficiency. The R1 stage signifies that the plant has reached its maximum vegetative growth and is transitioning into the generative phase by initiating flowering. Based on our observations, there were no significant differences observed among the various fertilization treatments (as shown in Table 3). However, the data trends indicated that when it came to the number of leaves, number of branches, plant biomass, and the dry weight of roots, the cowpea plants treated with NPK fertilizer exhibited more leaves compared to those subjected to the minus one fertilizer treatment. These results suggest that cowpea plants can continue to grow well even when facing nutrient deficiencies. Notably, the growth of plants with the minus P treatment yielded the second-highest results, following the complete NPK fertilization treatment, although this difference was not statistically significant

Plant growth with 1 plant per hole showed the highest yield which was significantly different from other treatments on the number of leaves and number of branches (Table 3). Variables of plant biomass and root dry weight were not statistically significant among treatments, but there was a tendency for 1 plant per hole to have a higher dry weight than the other treatments. Treatment of 1 plant per hole produced the lowest plant density so that plants could more freely grow and get resources in the form of water, light, nutrients, etc. While the growth with 3 plants per hole showed the lowest growth because the competition was too high so there were limitations in obtaining resources for plant growth. Applying the right number of seeds per planting hole will provide an

Table 2. The soil chemical properties prior to cowpea planting*

Soil Parameter	Extraction method	Value	Status
pH	pH meter	4.3	Very acidic
C-organik (%)	Spectophotometry	1.63	Very low
N-total (%)	Kjeldahl	0.23	Medium
P-total (me 100 g^{-1})	Spectophotometry	122.24	Very high
P-available (ppm)	Bray	3.70	Very low
K-dd (cmol K.kg^{-1})	AAS	0.27	Low
CEC (cmol.kg^{-1})	Titrimetri	13.36	Low

Note: *Soil chemical properties criteria according to Sulaeman et al., (2005)

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Table 3. Number of leaves, number of branches, plant biomass and root dry weight

Treatments	Number of leaves	Number of branches	Plant biomass (g)	Root dry weight (g)
Number of plants/hole				
1	25.17a	24.00a	15.98a	1.10a
2	19.28b	15.71b	12.98a	0.99a
3	14.59b	12.58c	11.72a	0.79a
Fertilizer				
NPK	22.15a	18.70a	15.12a	1.08a
Minus N	17.78a	15.63a	12.87a	1,05a
Minus P	20.43a	15.74a	14.06a	0.79a
Minus K	19.71a	16.64a	12.19a	0.93a
Plant x Fertilizer	ns	ns	ns	ns

Note: ns: interaction not significant; means within a column followed by the same letter(s) are not significantly different by DMRT at $P < 0.05$.

area for the stems and leaves of the plant to spread and deepen the roots so plant growth and production will be maximized (Arwani et al. 2013).

The treatment with one plant per hole had the highest yield, and these differences were statistically significant, particularly in terms of the number of leaves and branches (Table 3). While variables such as plant biomass and root dry weight did not show significant statistical differences among the treatments, there was a noticeable trend indicating that the one plant per hole treatment tended to have a higher dry weight than the other treatments. The success of the one plant per hole treatment can be attributed to its lower plant density, allowing individual plants to have more access to essential resources such as water, light, and nutrients. In contrast, the treatment with three plants per hole resulted in the lowest growth due to intense competition for these resources. The optimal seeding density per planting hole is crucial as it provides adequate space for the development of stems, leaves, and deepening of roots, ultimately maximizing plant growth and production (Arwani et al., 2013).

Cowpea Yield and Yield Component

The R1 (when about 30% plants had flowered) phase occurs in early April when the rainfall is highest and continues until R8 (harvest) in May. Harvesting was carried out when about 50% of the plants in the experimental plots started to dry and changed color from green to brown or black and was carried out three times per week until the ripe pods were harvested. Data on the number of pods and seed dry weight were obtained in an area of 1x3 m^2 experimental plot, then converted to hectares for productivity. Rainfall is the main controller in cowpea cultivation because it affects growth and yield (Adisarwanto, 1998). The high rainfall during the harvest season causes many root pods to rot and reduce yields. Olorunwa et al. (2023) also mentioned the impact of standing water for 10 consecutive days on cowpea causing stunted root growth.

The yield components were not significantly different for all treatments, both plant density and fertilization except for the number of pods. The number of cowpea pods showed that the complete NPK treatment gave the highest yield, which was significantly different from the minus N and K treatments, but not significantly different from the minus P treatment (table 4). The data from this study reveal that cowpea plants can survive to grow and produce well under conditions of phosphorus deficiency. Plants can maintain yields even under stress conditions, meaning that cowpea is classified as tolerant plant species. Cowpea still grows at very acidic pH with low soil fertility and high rainfall, but its productivity tends to lower, ranging from 0.67 – 0.94 tons. ha^{-1}.

The results of this study indicated that the limiting factors for the yield component of the number of cowpea pods were N and K, where statistically the treatment minus N and K showed the lowest yield on the number of pods which was significantly different from the other treatments (Table 4). Nitrogen can increase the yield of net photosynthesis because it plays a role in forming chlorophyll so it has an impact on increasing growth, plant biomass and increasing seed yields. Based on Gai et al., (2017), the presence of higher nitrogen levels in soybean plants increased soybean seed yields even under flooded and non-irrigated conditions. The role of element K is to

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Table 4. Cowpea number of pods, seed dry weight and productivity at harvest.

Treatments	Number of pods	Seed dry weight (g)	Productivity (ton.ha^{-1})
Number of plants/hole			
1	270.25a	221.25a	0.74a
2	306.67a	247.37a	0.82a
3	293.83a	237.55a	0.79a
Fertilizer			
NPK	342.44a	283.24a	0.94a
Minus N	259.11b	220.68a	0.74a
Minus P	303.67ab	236.03a	0.79a
Minus K	255.78b	201.60a	0.67a
Plant x Fertilizer	ns	ns	ns

Note: ns: interaction not significant; means within a column followed by the same letter(s) are not significantly different by DMRT at $P < 0.05$.

stimulate assimilate translocation from the leaf as a source to the storage organ or sink. In addition, K is also involved in the process of opening and closing stomata which plays an important role in the entry of CO_2 in photosynthesis (Singh et al., 2014). If the process of photosynthesis and assimilate transport is disrupted, the production of the plant will decrease. Although the number of pods was significantly different, dry seed weight and productivity were not significantly different in all treatments. This shows that not all pods contain seeds. High rainfall and low soil fertility lead to imperfect seed formation.

Plants that are tolerant to acid soils such as cowpea generally have a self-defense mechanism so they can maintain their growth even under stress conditions, where sensitive plants cannot grow well. In conditions of P deficiency, cowpea as a tolerant species is more able to absorb nutrients from the growth media even without the addition of P nutrients compared to sensitive species. The results of soil analysis revealed that the total P content was very high, but the available P that could be absorbed by plants was very low. This data shows that not all of the total P can be absorbed by plants. The number of pods in the minus P treatment was not significantly different from the complete NPK fertilization, presumably due to a plant defense mechanism that makes P unavailable to P available to plants. The results of this study are in accordance with Tanaka and Hayawaka (1975) who stated that cowpea is a tolerant plant in cultivation in acid soils with high Al content and low P condition. Indonesia has the most extensive acid soils compared to 35 countries in the world. Indonesia has 107.36 million ha, or 74.31% of Indonesia's total dry land, which is comprised of acid soil highland areas with a pH of 5.5 or lower (Sutriadi et al., 2022). Hence, it is imperative for leguminous crops like cowpea to possess the capability to thrive in acidic soils with phosphorus deficiency. This adaptability allows for the potential expansion of cowpea cultivation in regions characterized by acidic soil conditions.

Experiment 2: External Adaptation Mechanisms and Cowpea Root Organic Acid Secretion

Plant adaptation mechanisms to P deficiency are grouped into two groups, internal and external adaptation. The low availability of soil P due to the ease with which P is fixed by metals such as Al and Fe makes external mechanisms more important. The external mechanism is an avoidance mechanism, namely the ability of plants to avoid actively metabolizing tissues from exposure to stress. On the external mechanism, plants develop nutrient uptake efficiency to make Al-P or Fe-P become available P and increase the ability to absorb P from the soil. Several external mechanisms developed by plants such as changes in rhizosphere pH changes in uptake kinetics under nutrient stress conditions to become high affinity transporters, changes in root morphology, ability to symbiosis with mycorrhiza, produce mucilage, organic acid exudation, and ability to use organic P in the form of phosphatase (Sopandie, 2014).

Alterations in root morphology serve as an adaptation to phosphorus (P) deficiency conditions in acidic soils, manifesting as the development of an increased number of root hairs and proteoid roots compared to the application of NPK fertilizer. This alteration enhances the plant's ability to absorb a higher quantity of nutrients from the soil, thereby improving nutrient uptake efficiency, as illustrated in Figure 2. These changes in root morphology are prompted by low P nutrient stress, resulting in fewer

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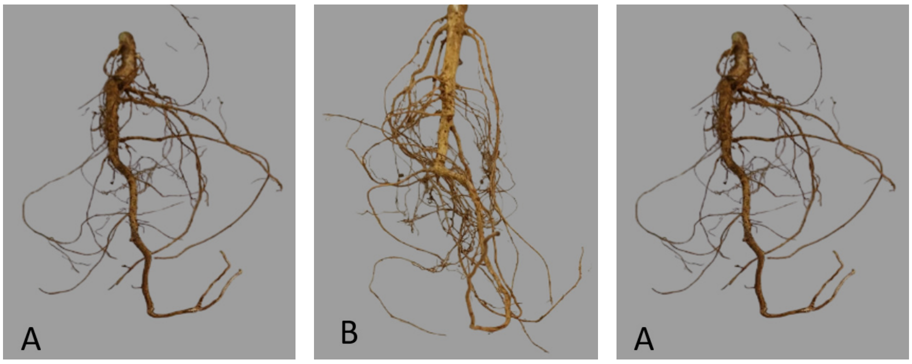

Figure 2. Comparison of root morphology in (A) dry cowpea roots treated with NPK in the first experiment, (B) dry cowpea roots treated with minus P in the first experiment, (C) fresh cowpea roots treated without P (P0) in the second experiment

root hairs when complete NPK treatment is applied. In terms of external mechanisms, these shifts in root morphology are a strategic response by the plant to adapt and draw closer to the nutrients present in the soil. This proximity facilitates the availability of nutrients and their subsequent transport within plant tissues. Alongside these alterations in root morphology, another external mechanism employed under P deficiency conditions is the production of root exudates in the form of organic acids, as described by Adeleke et al. (2017)

The results indicate that cowpea as a tolerant genotype because it produces organic acids as a mechanism for plants to increase the availability of phosphorus. The type of organic acids produced by cowpea was malic acid and oxalic acid. The amount of malic acid is much higher than oxalic acid (Table 5). The malic acid produced in the P0 and P1 treatments was higher which was significantly different from the P2 and P3 treatments. The oxalic acid produced was not significantly different for all treatments, but there was a tendency for the P0 treatment to produce the highest oxalic acid compared to the other treatments. Malic acid together with K^+ plays an important role as a regulator of solute potential in guard cells for the process of opening and closing stomata, and as an intermediate in the process of photosynthesis to be transported to the roots which are useful for root development (Marschner and Marschner, 2012). Observations have confirmed that under conditions of phosphorus deficiency (P1) and when lacking phosphorus nutrients (P0), there is a notable increase in the production of organic acids. This phenomenon occurs as a self-defence mechanism where roots exude organic acids to enhance the availability of phosphorus. It operates through the dissolution of poorly soluble phosphorus compounds (such as Al-P and Fe-P) by raising the pH or promoting P desorption from anion exchange adsorption (as described by Crowley and Reger, 2000). The anions derived from organic acids can form complexes with aluminum (Al) or iron (Fe), either releasing phosphate ions or preventing their interaction with Al or Fe ions. Different plant species deploy varying types and quantities of organic acids in response to phosphorus deficiency conditions in acidic soils. For instance, soybeans and pigeon peas secrete citric acid (Nwoke et al., 2008), chickpeas release oxalic acid and malic acid (Veneklaas et al., 2003), and corn excretes acetic acid and lactic acid (Fischer et al., 2010). This study establishes that cowpea is capable of secreting malic acid and oxalic acid.

In Experiment 1, there were no discernible differences in production between the NPK treatment and the minus P treatment. In Experiment 2, it is evident that cowpea can employ external mechanisms when confronted with phosphorus deficiency, including the secretion of organic acids and alterations in root morphology, characterized by an increase in root hairs and the development of proteoid roots.

Table 5. Malic acid and oxalic acid root secretion after treatment with different concentrations of phosphorus

Phosphorus concentration (mM)	Malic Acid (ppm)	Oxalic Acid (ppm)
0	1213.66a	95.18a
0.25	1271.51a	73.12a
1	418.9b	74.66a
4	456.08b	70.55a

Note: means within a column followed by the same letter(s) are not significantly different by DMRT at $P < 0.05$.

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The outcomes of this study hold significant implications as they provide valuable information about cowpea's adaptability to acidic soils with low phosphorus nutrients. This knowledge is crucial for growers to cultivate cowpea on a larger scale, both in Indonesia and beyond, particularly in regions with similar soil conditions.

Conclusion

Cowpea that were cultivated with one plant per hole demonstrated the most robust growth. In general cowpea productivity was not affected by nutrient availability. However, when considering the production of cowpea pods specifically, the lack of nitrogen and potassium was anticipated to be a limiting factor. Interestingly, there was no significant difference in the yield components of cowpea between the complete NPK fertilizer treatment and the minus phosphorus (P) treatment. In response to phosphorus deficiency conditions in acidic soils, cowpea roots secrete organic acids, specifically malic acid and oxalic acid. This secretion of organic acids serves as an external defence mechanism, enhancing the plant's ability to adapt and obtain essential phosphorus nutrients from the soil.

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