Improving Shallot (*Allium cepa* Aggregatum group) Production in Acidic Soils in West Java, Indonesia

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Abstract

In the West Java region, Indonesia, the wide range of shallot (*Allium cepa*) bulb yields suggests that there is potential for productivity improvements, especially for smallholder farmers. This study, which involved a farmer and soil fertility survey, two field trials and a laboratory incubation study, aimed to improve the shallot productivity of smallholder farmers.

The survey, conducted in four districts of West Java, identified that the Pacet District had the lowest average bulb yield of 5.4 t ha^{-1} and also had a wide range of yields (2.3 to 11.8 t ha^{-1}). The two common soil fertility constraints were very low soil pH and low available soil phosphorus (P). The first field trial aimed to determine the optimal P fertiliser rates, when rates of up to 1 tonne of lime ha^{-1} were applied, for three different farm sites in the Pacet District. These sites had strongly acidic soils with constraining exchangeable Al^{3+} and available soil P levels. The second field trial aimed to determine the response of shallot bulb yield to P fertiliser once exchangeable Al^{3+} had been decreased to a low level using high rates of lime. This field trial used a single farm site with a very low soil pH_{H2O} of 4.1, a high exchangeable Al^{3+} of 1.9 cmol (+) kg^{-1} and a low Bray1-P of 10 mg P kg^{-1}. The incubation experiment assessed the effect of a range of liming materials, as well as rice husk biochar and zeolite, on soil pH, exchangeable Al^{3+} and cation exchange capacity (CEC).

This study quantified the benefits of improved lime and P fertiliser practices and identified constraints to their implementation. Farmers should aim to ensure that soil exchangeable Al^{3+} levels are maintained < 0.5 cmol (+) kg^{-1}, which will be at soil pH levels of approximately > 4.7. Monitoring soil P status through soil testing and achieving Bray1-P levels above 28 kg ha^{-1} also improves the likelihood of achieving high yields. Very good financial returns can be achieved from high yielding shallot crops; however, farmers need better access to the services of agricultural field officers to conduct and interpret soil tests.

Keywords: onion, soil acidity, lime, P fertiliser, aluminium toxicity

This thesis is dedicated to my father

H. Ahmad Supriyadi

Passed away during the covid-19 outbreak, 19 December 2020

‘I am proud to be your daughter. Even though I couldn’t meet you for the last time,

I will always remember you. Thank you, Dad.’

Preface

This basis for this study initially emerged from my responsibility and my passion as a researcher at the Indonesian Vegetable Research Institute. As a researcher, we try to support our farmers in better production to increase their income. However, farmers face different challenges, and their production is not sustained and stable. For example, one of the constraints that shallot farmers face is soil fertility, the acidic soils. This issue reduces shallot bulb yield and decreases farming revenue. How will we solve this issue? My passion is to find out and develop a platform technology that will increase productivity and improve farming revenue through nutrient management using lime and fertiliser.

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Chapter 1

General Introduction and Literature Review

1.1. Introduction

1.1.1. Background

Population growth in many developing countries is increasing the demand for agricultural products. Indonesia's current population is 274 million, making it the fourth-largest national population in the world. By 2050, Indonesia's population is estimated to increase by about 20.4 % to 330 million (Figure.1.1) (Worldometer, 2020). To meet the increasing demand for agricultural products that will result from an increase in population, and a rise in the standard of living over time, substantial growth in crop and livestock production will be needed.

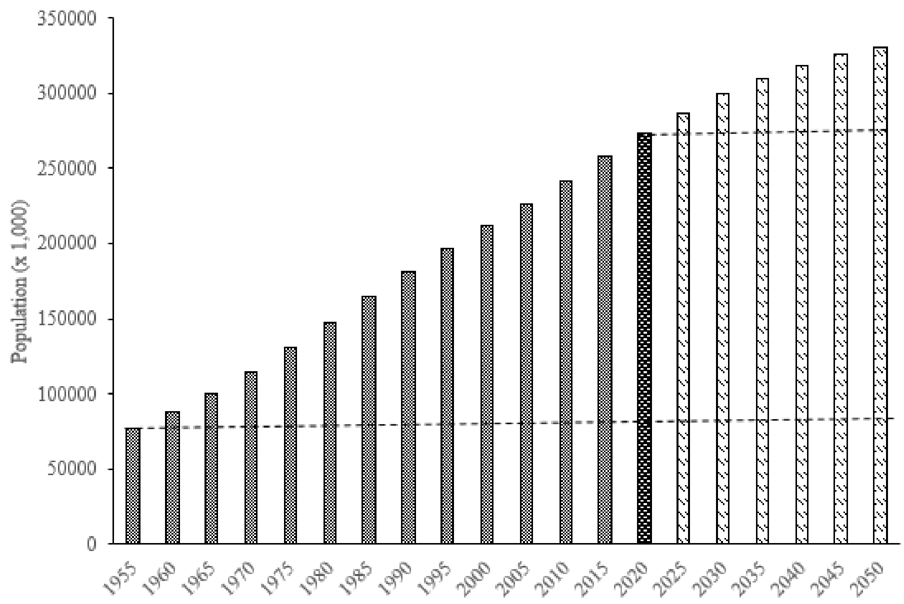

Figure 1.1. Indonesia population from 1955 to 2020 and the estimated population from 2025 to 2050 (Worldometer, 2020).

In developing countries like Indonesia, given the land constraints, it is estimated that approximately 80 % of the increase in agricultural production will need to come from intensification. In comparison, the remaining 20 % could come from land-use change (Lipper et al., 2018). The increasing Indonesian population also accelerates land-use change from agricultural land to the non-agriculture sector, like housing and manufacturing. These changes increase the need for deforestation of marginal land for agricultural production, increasing the risk of soil degradation and contributing to a greater accumulation of atmospheric greenhouse gases.

The availability and productivity of suitable land for agricultural production are also influenced by land degradation and climate change. Land degradation reduces the physical, chemical, and biological properties of soils, decreasing land's productive capacity. Moreover, land degradation and population density might enhance deforestation (Sunderlin & Resosudarmo, 1996). For example, West Java is the most populated island in the world, and deforestation rapidly occurred at an altitude 300 to 1800 m above sea level due to agriculture and non-agricultural land demands (Higginbottom et al., 2019).

More than 24.3 million ha of land in Indonesia is estimated to be degraded due to unsustainable land use, poor soil and water conservation practices, and high soil erosion levels (Republic-of-Indonesia, 2015). Unsustainable land use, for example excessive fertiliser applications, negatively affects the environment, especially water quality, due to eutrophication of rivers and lakes (Qin et al., 1995). In addition, Climate Change is predicted to have a worsening influence on crop productivity (IPCC, 2014), and Indonesia is located within one of the tropical zones that are likely to be affected the most (Lipper et al., 2018). Climate Change raises the threat of extreme climate events, like flooding and drought, which cause a greater risk of crop failure. In areas where Climate Change causes greater amounts and intensity of rainfall and higher temperatures, this can lead to greater erosion, leaching of nutrients, soil acidification and loss of soil organic matter (Fageria & Nascente, 2014). These combined circumstances cause unfavourable conditions for crop growth and lead to a reduction in crop production, accelerating land expansion into more fragile environments such as upland forests and marginal lands such as acidic and peat soils.

Clearing upland forests for agricultural purposes might be the solution for increasing agricultural product yields. However, deforestation leads to environmental destruction that accelerates Climate Change (Lawrence & Vandecar, 2015), loss of biodiversity (Giam, 2017), ecosystem degradation, and has disturbing consequences on local communities, including socio-economic well-being (Amelung, 1993), public health (Garg, 2014) and local culture. Small scale agriculture production was the third largest cause of deforestation in Indonesia (15%) in the period 2001 to 2016, after oil palm plantation (23%) and grassland (20%), which mainly occurred in Java island (Austin et al., 2019). Rather than encouraging deforestation, increasing crop yields from existing farms is necessary to meet the crop demand arising from population growth.

1.1.2. Smallholder farmers in Indonesia

In Indonesia, the most vulnerable entity to Climate Change impacts is the smallholder farmers or "*Petani Gurem*", which refers to growers who have less than 0.5 hectares. Smallholder farmers have limited knowledge and resources to mitigate and adapt to the effects of Climate Change. However, these farmers are also essential for Indonesia's food production because they farm 45 % of the agricultural land (Susilowati & Maulana, 2016).

Smallholder farmers, who usually have low capital, are commonly risk-averse and, therefore, typically aim to minimise their risks rather than maximising yield or profit due to their vulnerability to variations in market prices and climatic conditions (Kahan, 2013). Climate Change is likely to increase the chances of downside risk, such as natural disasters that lead to crop failure, further challenging farmers' livelihoods. The cumulative effect of Climate Change, including the impacts mentioned above on degrading the productive capacity of land over time, is likely to reduce crop productivity or increase the need for inputs, such as fertiliser, lime, and other soil amendments that reduce the incomes of smallholder farmers.

The Indonesian government has undertaken several measures to address climate change impacts, including promoting more sustainable crop production. The strategy involves plans to achieve greater economic resilience within the food system through a sustainable agriculture approach, especially for smallholder farmers, which builds on previous programs. The dissemination of agricultural technology by extension officers is crucial; however, ongoing research also needs to be informed to provide solutions to current and emerging challenges experienced by farmers. Support for smallholder farmers also includes specific incentives for the use of agricultural inputs. For example, there is a maximum price set for subsidised fertilisers.

1.1.3. Shallot production in Indonesia

In Indonesia, shallots (*Allium cepa* Aggregatum group) are an important vegetable crop because they are used as an important flavouring agent in Indonesian cuisine (KEMENTAN-RI, 2020), having been widely grown in the county since the 1950s. Shallots are one of the most popular vegetable crops grown in the country. Between 2013 and 2018, the harvested area increased by 58%, and total shallot production increased by 49%. Over the same period, the average per hectare yield remained relatively stable, being within the range of 9.3 to 10.2 t ha^{-1}. While the potential yield of shallots can be as high as 13 to 19 t ha^{-1}, depending on variety

(Ambarwati & Yudoyono, 2003; Firmansyah et al., 2014), most of the total production increase over this period was due to increases in the harvested area rather than per hectare yield. However, the average per hectare yield values masks the variation between different districts or individual growers (Nurjati et al., 2018; Utami, 2009). By better understanding and improving the per hectare production of districts with lower yields, overall production can be increased without further expanding the harvested area.

Because of shallots importance in Indonesia, government agencies work to maintain the shallot supply throughout the year through programmes like the Policy and Development Program of Horticulture 2020 and the Strategic Plan of Horticulture 2015-2019 (BALITBANGTAN, 2016). To facilitate shallot production, the Indonesian Vegetable Research Institute (IVEGRI) focuses on shallot as one of the main crops for their research and development programs, including a current program to incentivise efficient technology to produce shallots (2020-2024).

Indonesia's West Java region is one of the main shallot production areas, where shallots are grown on lowland and upland areas (PUSDATIN, 2015). Historically, considerable attention has been given to shallot production in lowland areas, while the upland regions have not received the same supported level. However, upland growers have a crucial role in shallot supply during the rainy season, when market availability is usually low. During the rainy season, lowland farmers commonly plant rice as their main crop. Therefore, upland shallot growers' capacity to grow shallot in the rainy season is important to maintain the shallots' supply year-round (Basuki, 2014). Upland areas have different constraints and challenges to crop production compared to lowland areas. These challenges include greater risk of soil erosion, regions of highly weathered acid soils with low natural fertility, poor road access to farm sites and less availability of agriculture support and extension services.

For vegetable production, soil acidity can be a substantial limiting factor that reduces crop growth and affects yield and quality. Soil acidification increases exchangeable aluminium (Al^{3+}) and manganese (Mn^{2+}), which can restrict plant root growth and development (Clarkson, 1965; Wheeler & Follett, 1991) and reduces the availability of key plant growth-limiting nutrients like phosphorus (P) and exchangeable basic cations. Like common onions (*Allium cepa*), shallots have shallow and hairless roots that make them more susceptible to being adversely affected by acidic soil conditions (Abdissa et al., 2011).

Liming is a well-established practice to increase soil pH and improve soil fertility. Liming is typically a low-cost input for vegetable production systems. However, large lime quantities can be required for highly acidic soils to increase soil pH into the range considered optimum for most vegetable crops. For farms in the upland areas of West Java, with poor vehicle access, this can be a major constraint to input use, especially inputs like lime that require large quantities. Therefore, it is essential for shallot growers to have reliable information on the effectiveness of lime and fertiliser use, specific to their soil and climate environments, to evaluate the benefits that can be gained from investing in these inputs. The following literature review summarises the current knowledge relating to understanding the production constraints of shallot growers in West Java's uplands and the role of soil fertility on improving production.

1.2. Literature Review

1.2.1. Shallot production in West Java

Indonesia's country is a major part of the South-East Asian region, concerning its location, population, strategic position, and natural resources. Indonesia is located between two oceans, the Pacific Ocean and the Indian Ocean, and two continents, Asia and Australia. It has the largest population in the South-East Asia region and the fourth largest globally, with about 270 million people. An important province of Indonesia is West Java, the most populated and the nearest region to the capital city, Jakarta. West Java is known as '*lumbung padi nasional*' or the national paddy granary, producing 22% of domestic paddy production and ranked as the fifth region for soybean seed production. The total area of West Java is 35,377 km2, is located on Java Island (5^{o}50'-7^{o}50' South latitude and 104^{o}48'-108^{o}48' East longitude) and is bordered in the North by the Java Sea, in the South by the Indian Ocean, in the West by Banten and Jakarta, and in the East by Central Java (Figure 1.2). A steep mountainous area characterises it in the South (>1,500 m above sea level), gently sloping hillsides in the centre (100-1500 m above sea level) and vast plains in the North (0-10 m above sea level) (BPS-Provinsi-Jawa-Barat, 2017b). The average temperature in 2019 was 26.3 ^{o}C, and humidity was 81%. Precipitation was 3,555 mm per year, and the duration of sunshine was 77 % (BPS-Provinsi-Jawa-Barat, 2020).

Figure 1.2 Map of Indonesia and the West Java (Jawa Barat) province.

The agricultural sector in West Java is the third largest sector, after manufacturing and trading sectors, in terms of the total Gross Regional Domestic Product (GRDP) (NZ$ 3488/year/capita) for the province (BPS-Provinsi-Jawa-Barat, 2017a). The dominant agriculture industry is staple food cropping, followed by horticultural crops, livestock, fishery, and plantation crops (Table 1.1). Horticultural crop production mainly consists of vegetable crops.

Table 1.1. The presentation of Gross Regional Domestic Product of agricultural areas in West Java.

No	The agricultural sectors	2012	2013	2014	2015	2016
				(%)		
1	Staple food crops	48.7	49.5	47.8	48.2	48.2
2	Horticultural crops	18.3	17.6	18.6	18.1	18.5
3	Plantation crops	9.2	8.9	8.4	7.7	7.1
4	Livestock	11.6	11.7	12.2	12.7	12.6
5	Agriculture service and hunting	1.6	1.5	1.5	1.5	1.5
6	Forestry and logging	1.1	1.0	1.0	0.9	0.9
7	Fishery	9.6	9.8	10.6	10.9	10.7

Source: (BPS-Provinsi-Jawa-Barat, 2017a).

Altitude is one of the dominant factors determining the feasibility of crop production in West Java. Based on elevation, agroecological zones of West Java can be a grouped: low-land 0-200 m above sea level, medium land 200-700 m above sea level and upland above 700 m above sea level (Buurma & Basuki, 1991). The typical soil types in the lowlands are Alluvial and Latosol; in the upland regions, the typical soil types are Andisol, Latosol and Inceptisol (Grubben, 1990).

The largest harvested area of vegetable crops in West Java is hot chilli pepper (29,810 ha), followed by shallot (15,705 ha) (BPS-Provinsi-Jawa-Barat, 2020). These crops are well adapted to West Java conditions and produce good yields by about 2,923 vegetable farmers in West Java (BPS-RI, 2013, 2017a). Hot chilli peppers and shallots are grown in both low-land and upland areas of West Java. The shallot is an important crop option for many West Java farmers (BPS-Provinsi-Jawa-Barat, 2017b). The harvested area and the shallot production have increased year on year in recent years. In 2013, shallots' total harvested area was 98,937 ha, producing 1,010,773 tons of fresh bulb yield (Figure 1.3). By 2018 the harvested area had expanded by 58% to 156,779 ha, and production had increased by 49% to 1,503,446 tons. However, from 2013 to 2018, the average per hectare yield remained relatively stable, with 9.3 to 10.2 t ha^{-1}.

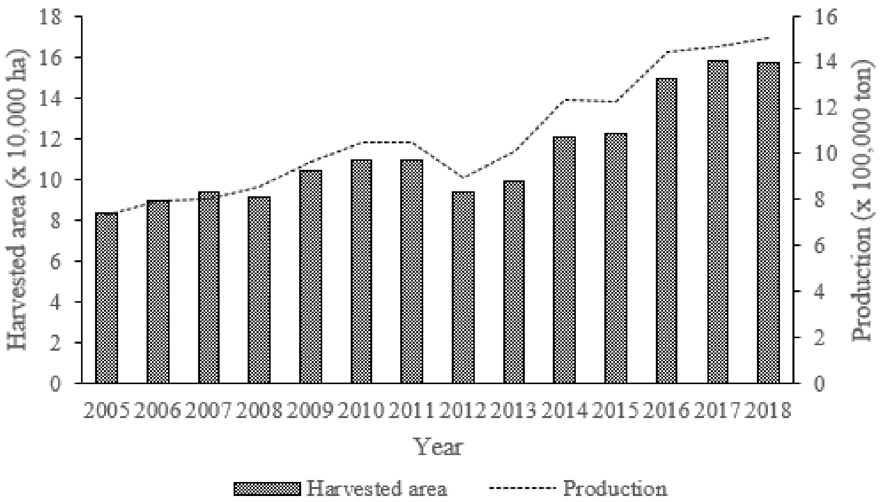

Figure 1.3 Harvested area and production of shallot in Indonesia (2006-2018) (BPS-RI, 2015, 2016, 2017b, 2018, 2019; KEMENTAN-RI, 2011, 2015).

The increase in land area dedicated to shallot production over recent years is causing competition with other crops, and non-agricultural land uses. The land expansion also is expensive and might harm the environment if it involves chopping down the forest to open new farms. Clearing tropical forests and using them as agricultural areas might permit crop production for several years as forest cover will have raised soil pH, base saturation, and soil nutrient status by transferring nutrients from forest vegetation to soils. However, exposing topsoil after forest clearing exposes the soil to solar heat and rain, leading to severe erosion and loss of topsoil that increase nutrient runoff and leaching (Von Uexkull, 1986). After forest clearing, the nutrient cycle and organic matter cycle are broken. Moreover, weathering plus continuous cropping resulted in the decline of organic matter content (organic-C) and altered soil structure that restricts above-ground and below-ground biomass. In tropical regions, approximately 80 years are required to recover above-ground biomass after the first disturbance. A longer period is necessary to recover below-ground biomass if the forest is allowed to regrow (Martin et al., 2013).

West Java has four major central shallot production areas; Cirebon, Majalengka, Garut and Bandung (BPS-Provinsi-Jawa-Barat, 2017b). Cirebon is the largest district for shallot production in West Java (BPS-Kabupaten-Cirebon, 2020), and shallot farms mainly are located in lowland areas close to Central Java. The Cirebon district has similar characteristics to Central Java. In these regions, the typical soil type is Alluvial. Social-geographic and soil-type similarity make to similar crop management practices in those areas. Farmers in those regions mainly grow shallots for 2 to 4 times a year and commonly also have similar harvest times (Wiyatiningsih, 2010; Zuhriyah & Ariyani, 2012). For one cycle, the harvest times of shallot varies on cultivar and location. In the lowland, the harvest time is about 50 to 55 days after planting, while in the upland region, the harvest time is about 75 to 90 days after planting. In the harvest season, significantly, the Indonesian shallot supply increases and reduces shallot prices sharply. Cirebon and Central Java shallots are usually sold fresh shallot bulb yield to other islands like Sulawesi and Borneo (Handayani, 2017; Toiskandar, 2017; Wamad, 2017).

The remaining three shallot production regions in West Java (Majalengka, Garut and Bandung) are in upland areas and focus primarily on the local market. The soil types of those areas commonly are Andisol, associate Andisol-Latosol and Inceptisol (BPS-Kabupaten-Bandung, 2016; BPS-Kabupaten-Garut, 2016; BPS-Kabupaten-Majalengka, 2016; Suriadikusumah, 2018). Those soils are volcanic soils that are typically high in organic matter but low in soil pH. Upland farmers plant shallots in paddy fields during the dry season and plant shallots in dryland during rainy seasons (Rukmana, 1995). Most upland shallot growers own their fields, and they apply organic fertilisers. These characteristics differ from lowland growers, most of whom lease the land, and rarely apply any organic fertilisers (BPS-Kabupaten-Bandung, 2016; BPS-Kabupaten-Cirebon, 2020; BPS-Kabupaten-Garut, 2016; BPS-Kabupaten-Majalengka, 2016). Other differences are the shallot cultivars used and how farmers store and market their shallot bulbs. Many low-land farmers use a ‘Bima’ variety. Bima has unique characteristics (oval bulb shape with a small ring on the bulb neck and light red colour) favoured by the market (BALITSA, 2018). The upland farmers use many local varieties, such as ‘Sumenep’, ‘Tuk-tuk’, ‘Maja’ and ‘Bali Karet’. Lowland farmers commonly sell and store their shallot bulbs with the dry leaves still attached to prevent them from sprouting. Meanwhile, upland farmers usually cut the leaves, leaving about 5 cm to avoid the bulbs from decaying (Rukmana, 1995). The lowland farmers primarily sell their products to other regions requiring a longer shelf life. Upland farmers sell their fresh bulb yield directly to their region's local market.

The differences in shallot bulb yield in different central areas create room for increasing shallot bulb yield per hectare in existing farms rather than increasing pressure to dedicate more land to shallot production.

1.2.2. Shallot cultivation

Shallot, botany, and taxonomy

Shallots are categorised as *Allium cepa*, the same species as common onions. Shallots and the common onions can intercross easily and produce fertile hybrids. Both species have similar cytology and morphology characteristics. The apparent difference is the lateral or multiple bulbs of the shallots. Thus, *Allium cepa* was divided into the common onion and aggregatum groups (synonym: *A. ascalonicum* auct; *A. cepa* var *ascalonicum* Baker) (Krontal et al., 1998).

Shallots have distinct phenotypical characteristics that set them apart from onions; for example, the shallot bulb diameter is small and consist of sets (Figure 1.4). Sets are lateral bulbs that were grown from tillers that came from a mother bulb. The colour of the shallot bulb is commonly red, and shallot pungency is stronger than the mild common onion. Pungency is associated with a high content of sulphides (Mubarak & Kulatilleke, 1990). GC-MS and 'e-tongue' can also be used to distinguish the shallot from onion reliably. Electronic tongue or ‘e-tongue’ is an analytical appliance that consists of an array of cross-sensitive chemical sensors (Auger et al., 2005).

Figure. 1.4. The differences between (a) shallots (*Allium cepa var aggregatum*) and (b) common onions (*Allium cepa*).

Krontal et al. (1998) summarised the main physiological differences between shallots and onions. The physiological age of bulb formation and flower initiation of shallots is earlier than onions. From seed, onions start to branch at a 13-leave physiological age, while shallots branch at three leaves stages. Moreover, onion's floral initiation occurred at 10-14 leaves, while on shallot, it occurs earlier at six leaves.

Another difference is the propagation. Shallots commonly are vegetatively propagated by bulbs or sets, whereas onions are produced from seeds. Creating true shallot seeds (TSS) is a challenge, as the number of flowers and seeds that set is low due to the high temperature and short-day period in the tropics. On the other hand, vegetative propagation via sets is easy and fast. Therefore, producing shallots from seed bulbs is widespread in tropical regions, especially South-East Asian countries.

The Indonesian Government released an identification guideline for shallots and onions (Sugiarto et al., 2017). This guideline helps the border officer in distinguishing common shallot and common onion (Table 1.2).

Table 1.2. The character of shallots versus onions.

Characters	**Shallots** (*Allium cepa var aggregatum*)	**Onions** (*Allium cepa*)
Tillers	Has tillers	Do not have tillers
The ratio of aggregate diameter versus the widest diameter	≥50%	<50%
Bulbs	Cluster bulbs	Single bulb

Adapted and modified from (Sugiarto et al., 2017)

The aggregate diameter and the bulb diameter are measured to distinguish shallots and onions (Figure 1.5). Bulb diameter is d1, and the aggregate diameter is d2. Aggregate diameter is a diameter from the conjunction tillers where the bulb layer does not surround the whole bulb. The bulb is determined as shallot when the ratio between d2: d1 was more than 0.5. In contrast, the bulb is defined as an onion when the ratio of d2: d1 is less than 0.5. However, this manual measurement sometimes leads to a controversial decision, especially for hybrid varieties. Grouping these varieties remains a challenge; genetic measurements could determine the variety; it was more likely to the common onion group or the shallot group. To avoid confusion at the consumer's level and secure shallot's price at the farmer's level, the Indonesian Government prohibited importing small bulb onion varieties (Arieza, 2018).

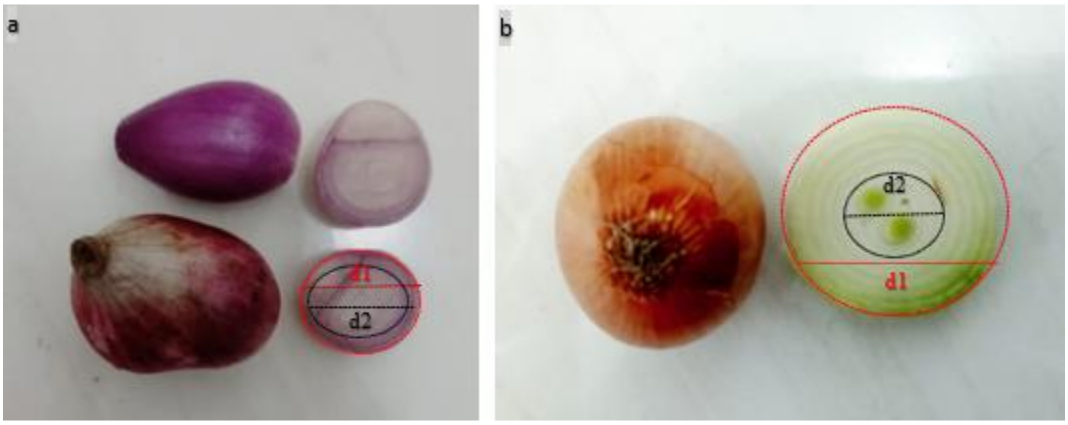

Figure 1.5. (a) Shallot, *Allium cepa* var aggregatum, (b) Onion, *Allium cepa* L d1=bulb diameter, d2=aggregate diameter.

The genetic diversity of shallots in Indonesia has been low (Reflinur et al., 2019). Limited genetic diversity created small room for improving shallot characteristics via conventional breeding. Inter crossing between shallot and onion and the development of true shallot seed were employed to enhance shallot character. Some new varieties with a high potential yield of more than 20 t ha^{-1} are 'Sanren' from East-West company (East-West-Seed, 2020) and

‘Ambassador 1 Agrihorti’ from IVEGRI (BALITSA, 2020). Moreover, some shallot varieties adapt well in particular areas. Natural selection and adaptation promote local variety, and agronomy traits enhanced the shallot bulb yield.

Soil pH

Soil pH is a crucial factor in nutrient availability in the soil. The pH can be considered the critical determinant for nutrient mobilisation since it can influence the surface charge and resulting adsorption of solutes by factor charge soil properties (Bolan et al., 2003). In strongly acidic soils (soil pH < 5.5), the availability of aluminium (Al), iron (Fe), manganese (Mn) significantly increases and the solubility of phosphorus (P) and calcium (Ca) decreases, and typically leads to metal toxicity and nutrient deficiencies (Adams, 1981; Foth & Ellis, 2018).

Shallot is one of *Allium* species that high demand for element nutrients due to shallot roots' morphology. The shallot has shallow roots, low root thickness, and hairless, increasing the requirements for higher nutrient content in soil solution for better nutrient adsorption (Antoniadis et al., 2017).

Shallots grow well in slightly acid to neutral pH (soil pH 5.5 to 7.0) conditions. The percentage of base cations in soil pH more than 5.5 and less than 7.0 is higher than in soil pH less than 5.5. In very strongly acidic conditions with a pH less than 5.0, the exchangeable acidity is high and reduces the base saturation, leading to a low bulb yield. As one of the lowland main shallot production areas, Cirebon has an alluvial soil with a soil pH range from 6.0 to 7.0 (neutral soil). Alluvial-Cirebon soils commonly have a low concentration of carbon and nitrogen, a medium of C:N ratio, medium to very high phosphorus content, medium to very high potassium content, high sulphur content and high cation exchange capacity (CEC) (Gunadi, 2009; Sopha et al., 2015). These soil conditions are ideal for supporting shallot growth and producing optimum yields. However, most West Java upland regions are mainly slight to very acidic soils, Andisol and Inceptisol soils. In summary, Andisol has a high content of carbon levels (8.3-9.7%), a medium of phosphate retention (31-54%), low soil pH (soil pH $\leq$ 4.4-5.0) and a small natural bulk density (0.32-0.65 g/cm^3). West Java’s Inceptisol commonly acidic soils with low pH (soil pH less than 5.0), low of base saturation and high Al^{3+} (more than 1.00 cmol (+) kg^{-1} (Kasno et al., 2006; Sumarni, Rosliani, et al., 2012a; Suriadikusumah, 2018).

Bulb yield reduces strongly with decreasing soil pH. Reid and Morton (2019) suggested that the optimum pH of onion was 6.1, and the bulb production would decrease sharply from soil pH 6.1 to 5.5, about 30%. The same trend occurred in the shallot bulb yield that the bulb yield reduced about 20% from 13.6 t ha^{-1} to 10.9 t ha^{-1} when the soil pH decreased from pH 5.9 to 5.4 (Azri et al., 2016). Sumarni, Rosliani, et al. (2012b) reported the dry bulb yield at a slightly acidic Alluvial (soil pH= 6.3) was 31.20 g/plant, reduced to 18.85/plant grown in strongly acidic Inceptisol (pH=5.5) and sharply decreased to 4.05 g/plant at extremely acidic Ultisol (pH =3.8).

Soil fertility and fertiliser application

Information on soil fertility is essential to tailor specific fertiliser recommendations for particular crops, including shallot. The optimum dose of shallot fertiliser depends on cultivars and soil conditions. For example, in neutral pH, shallot variety ‘Bangkok’, which produces high bulb yields, need more nutrients than shallot variety ‘Bima’ (Table 1.3). The optimum dose ‘Bangkok’ was 170-270 kg N ha^{-1}, 36-52 kg P ha^{-1} and 100-115 kg K ha^{-1}. The optimum level ‘Bima’ was 160-180 kg N ha^{-1}, 39-52 kg P ha^{-1}, and 50-100 kg K ha^{-1} (Sopha et al., 2015; Sumarni, Rosliani, et al., 2012b).

Table 1.3. Nutrient uptake and yield in some cultivars of shallot.

Cultivar	Fresh bulb yield t ha^{-1}	Nutrient uptake (kg ha^{-1}) N	P	K
Indian rose	6.6	30	4	29
Bima	14.6-20.9	97-134	10-15	88-93
Bangkok	15.5-23.4	110-167	13-20	88-114

Source: (Sopha et al., 2015; Vimala & Yeong, 1994)

Phosphorus

Phosphorus (P) is one of the primary nutrients for plant growth and will limit shallot growth if in limited supply. The essential functions of phosphorus are related to energy transfer in metabolic processes, as a structural component of DNA and RNA, cell membranes and essential roles related to cell division, root growth, flowering, fruiting and seed formation (Maathuis, 2009; Taiz et al., 2015). Onions and shallots have a shallow root system. Since P is an immobile nutrient, the adsorption can only occur through direct root interception and diffusion mechanism. Lack of P near the root zone directly leads to P deficiency that interferes with the plant growth and bulb yield (Havlin et al., 2014; Sumiati & Gunawan, 2007).

Phosphorus deficiency symptoms are bulb size and yield decreasing, and delay maturation of onion and shallot bulbs (Brewster, 2008; Sumiati & Gunawan, 2007). Mycorrhizae improve P uptake by extending the P uptake zone. *Glomus fasiculatus* increased the P uptake zone of mycorrhizal onions at least 7 cm from the root surface (Rhodes & Gerdemann, 1975), but this benefit depends on soil pH; *Glomus* requires neutral or alkaline soils (Porter et al., 1987).

In tropical climates, high precipitation instead leads to leaching, accelerating the soil weathering processes. Weathered tropical soils are primarily acidic and have a low plant available-P that a limitation on the crop growth. Moreover, P availability is positively correlated to soil pH. In acidic soil, P is adsorbed by iron (Fe) and aluminium (Al). While, in alkaline soils, forms participate with calcium (Ca). Phosphorus fertiliser is primarily applied to improve the onion growth and yield in low soil available-P status. Even in high soil available-P, P fertiliser application was also beneficial to onion growth; it increased the onion bulb weight in acidic soils (Antoniadis et al., 2017). The possible explanation is P fertiliser application may give a "lime effect" that reduced exchangeable Al^{3+} and increased the concentration of the less-toxic Al-F complex in P-fertilised soil than P-unfertilized soil that decreasing the incidence of aluminium phototoxicity (Manoharan, 1997).

In strongly acidic soil (soil pH 5.5) and very-low soil available-P (Olsen-P 3.2 mg P kg^{-1}), the optimum P rate was 342 kg P ha^{-1}. Meanwhile, in similar soil pH but a higher soil available-P (Olsen-P 12 mg P kg^{-1}), the optimum rate of P fertiliser was 177 kg P ha^{-1} (Chagas et al., 2016). In slightly acidic soil (soil pH 6.5) and medium soil available-P (Olsen-P 16 mg P kg^{-1}), the recommendation rate became smaller, 59 kg P ha^{-1} (George E Boyhan et al., 2007). Another study in India (soil pH 6.2) reported that application 60-80 kg P ha^{-1} increased onion bulb yield by 45-58% from control (Amin et al., 2007). However, Abdissa et al. (2011) reported that the application of P fertiliser by 10-40 kg ha^{-1} did not significantly increase the onion bulb yield in moderately alkaline soil (soil pH 8.0, Olsen-P 16 ppm). Perhaps due to the low rate of P-fertiliser used in the study (0 - 40 kg P ha^{-1}). Despite the soil pH and the availability of P in soil solution, a higher bulb yield target need a higher rate of P-fertilizer than cultivars with a lower bulb yield target (Table 1.4).

Table 1.4. The interpretation of soil available-P status using Bray1 and Olsen and the equation between them in pH < 7.05.

Fertility level	Bray1-P (mg P kg ^{1})	Olsen-P (mg P kg ^{1})	Onion Recommended P (kg P ha^{-1}) *	
			Dry bulb yields 10 t ha^{-1}	Dry bulb yields 6 t ha^{-1}
Low	<20	<10	≤270	≥140
Medium	20–40	10–25	70-200	40-140
High	40–100	25–50	0-70	0-40
Excessive	>100	>50	0	0
Equation	Bray1-P to Olsen-P	0.42Olsen-P = 3.5-(Bray1-P)		
pH < 7.05	Olsen-P to Bray1-P	Bray1-P = 3.5+0.42(Olsen-P)		

Adapted and modified from (Khokhar, 2019; Mallarino, 1995; Reid & Morton, 2019)

There has been little quantitative analysis of optimum P fertiliser rates on very strongly acidic soil (pH <5.0) for either onion or shallots. The application of a high P fertiliser rate without lime did not increase the shallot bulb yield when the soil pH was extremely acid (Sumarni, Rosliani, et al., 2012a). In contrast, the addition of lime increased the soil pH but did not increase the bulb yield when the soil available-P was still low (Dixit & Sharma, 2004). Therefore, it can be seen that bulb yield would still be low if one limiting factor remains, and so a blend of inputs is required to overcome whatever limitations apply to gain a high bulb yield.

Nitrogen

Nitrogen (N) is one of the essential nutrients for plant growth. The prominent plant physiological roles of N are related to supply amino groups as constituents of protein and nucleic acids (Maathuis, 2009; Taiz et al., 2015). Nitrogen also has a vital role in the biochemistry of many non-protein compounds, energy homeostasis, signalling and protein regulation. Severe N deficiency can also lead to complete crop failure. Therefore, targeted N fertiliser application is the most common practice to supply N requirements and support plant growth.

Onions and shallots need sufficient N to produce a high bulb yield and improve the bulb's size. The bulb yield improves linearly in response to N fertiliser application (Abdissa et al., 2011; Aliyu et al., 2008) until the optimal rate (Halvorson et al., 2008). Application of N fertiliser increases leaf numbers, plant height, bulb weight, dry bulb and total soluble solids (Woldetsadik et al., 2003a, 2003b). However, a high bulb N content is also associated with shorter keeping quality and often reduces dry matter content (Blay et al., 2002;

Ruaysoongnern, 1993). Excessive vegetative growth due to excessive N rate (500 kg N ha^{-1}) can often delay maturity and decrease nitrogen use efficiency (NUE) (Hilman et al., 2014). Late application of N fertiliser can delay the harvest time of bulbs (Brewster & Butler, 1989) and may cause undesired thick-necked bulbs (Khokhar, 2017). Over N fertiliser application is undesirable in all cases, with a high risk of N losses through leaching, surface runoff and volatilisation. Low NUE might lead to a high concentration of N in the water, which can impair water quality, negatively impacting human health and the environment (Abdissa et al., 2011).

The response to N fertiliser application also depends on the cultivar. A high potential bulb yield variety requires a higher amount of nitrogen than a low bulb yield variety. For example, the 'Lembah Palu' variety needs 50 kg N ha^{-1} to produce a 13.9 t ha^{-1} bulb yield (Lasmini et al., 2015), while a high-yielding variety, like 'Bangkok', needs 248 kg N ha^{-1} to achieve the potential bulb yield 35.4 t ha^{-1} (Sumarni, Rosliani, & Basuki, 2012).

Potassium

Potassium (K) is another essential macronutrient for shallot production. Potassium is essential for metabolic and enzymatic activity in the cell (Maathuis, 2009; Taiz et al., 2015). Even though K deficiency is rare, plant growth is commonly increased by adding K fertiliser. In soils with a low exchangeable K^+ status (K^+= 0.26-0.51 cmol (+) kg^{-1}), the K fertiliser recommended rate was 105 to 178 K kg ha^{-1}, depending on the cultivar. In soil with medium K^+ status (K^+= 0.51-1.04 cmol (+) kg^{-1}), the recommended rate of K was 141 kg ha^{-1}. Meanwhile, in soils with high K^+ status (≥ 1.05 cmol (+) kg^{-1}), the recommended rate of K was lower, 88 kg K ha^{-1} for shallot cultivar 'Bangkok' and 'Kuning' (Sumarni, Rosliani, et al., 2012b).

Sulphur

Sulphur (S) has a critical role in Allium species, including onions and shallot. Sulphur is the main element of many volatile compounds that produce specific pungent odour and taste characteristics of Alliums (Boyhan, 2008; Havlin et al., 2014). Sulphur fertiliser application significantly affected the volatile compounds in the onion bulb that enhanced the pungency (Boyhan, 2008). As well as increased onion and shallot pungency, S fertiliser application also improved bulb yield when applied to soil with low available S. The application of S-fertiliser plus macronutrients, NPK, increased onion bulb yield in sandy soils (soil pH 5.4 SO_4^- =6.7 ppm) by 24% (from 7.90 t ha^{-1} to 9.80 t ha^{-1}) compared to the plot with NPK fertiliser solely

(Mozumder et al., 2007). Moreover, the application of 120 kg N ha^{-1} + 40 kg S ha^{-1} increased bulb yield in silty loam soil (pH 6.0) by 67% from 10.26 to 17.18 t ha^{-1} compared to the plot N fertiliser only (Nasreen et al., 2008). However, S fertiliser application had no significant effect in dark grey flood plain soils in Bangladesh when the initial S content was high (Rashid, 2010).

Cultivar and plant density

Indonesia has many shallot cultivars with different abilities to adapt to the environment. Shallots cv. 'Probolinggo', 'Parman', 'Kuning', 'Tiron', and 'Biru' are varieties with good adaptation to sandy soil (Ambarwati & Yudono, 2003) potential bulb yield around 13 to 16 t ha^{-1}, respectively. Shallot cv ‘Lokal Napu' have a good yield of about 14 t ha^{-1} in clay soil (Putrasamedja, 2004), and 'Sembrani' is adapted well to peat soils with a fresh bulb yield of about 19 t ha^{-1} (Firmansyah et al., 2014).

The seed bulb diameter also affects the yield. Using a medium-sized seed bulb instead of a larger size bulb would reduce the weight of the seed bulb required to plant a field, reducing the production cost, but this needs to be weighed against the crop's potential yield. Azmi et al. (2016) reported that the optimal size of shallot cv. 'Bima' was 1.4-1.8 cm, 'Maja' was 1.5-2.0 cm, and 'Sumenep' was 1.3-1.6 cm, and the smaller size might reduce dry bulb yield by about 23% across the varieties.

Putrasamedja and Suwandi (1996) reported that the bulb yield of ‘Sumenep’ around 9 to 14 t ha^{-1} (harvested index 70%) in neutral soil pH. Shallot cv 'Sumenep' is a recommended Indonesian cultivar for frying with high soluble solids content 25-27^{o} Brix compare to most other varieties, 15-20^{o} Brix (Siemonsma & Piluek, 1993). 'Sumenep' grows well in the low-land to highland areas (Ansar, 2012), tolerates anthracnose and mild salinity (Permadi, 1994; Yuliani, 2017), is resistant to wilt by *Fusarium oxysporum*, purple blotch by *Alternaria porri*, and has a better economic value (Permadi, 1994).

Most of the shallot varieties that grow from bulbs have a (very) short life cycle, with the harvest time from 53 to 90 days after planting (Figure 1.6). In addition, the flowering and seed development stage in shallot growth might compete for photosynthate and limit bulb yield.

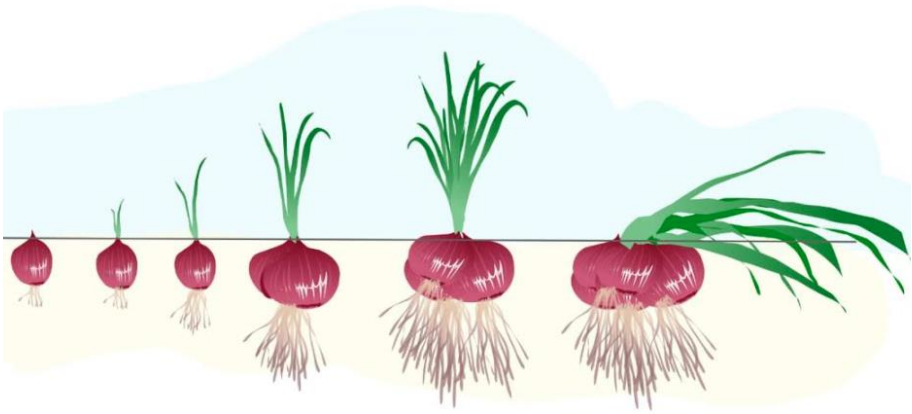

Figure 1.6. Shallot short cycle from bulb seed to bulb yield.

Moreover, plant density contributes to the bulb yield per hectare. Economic returns from the onion and shallots can be increased by optimising crop density (Bleasdale, 1966; Rabinowitch & Brewster, 1990). The higher population would increase the onion and shallot yield due to the higher number of bulbs obtained but would reduce the size and the weight of onion per bulb (Figure 1.7) (Boyhan et al., 2009; Putra, 2010). A higher plant density gave a lower percentage of a large bulb, while the total yield per area was high (Stallen & Hilman, 1991). Small bulbs have a lower price than large bulbs, and the high density would increase the seed cost also. As a result, increasing plant density up to a certain number is not efficient.

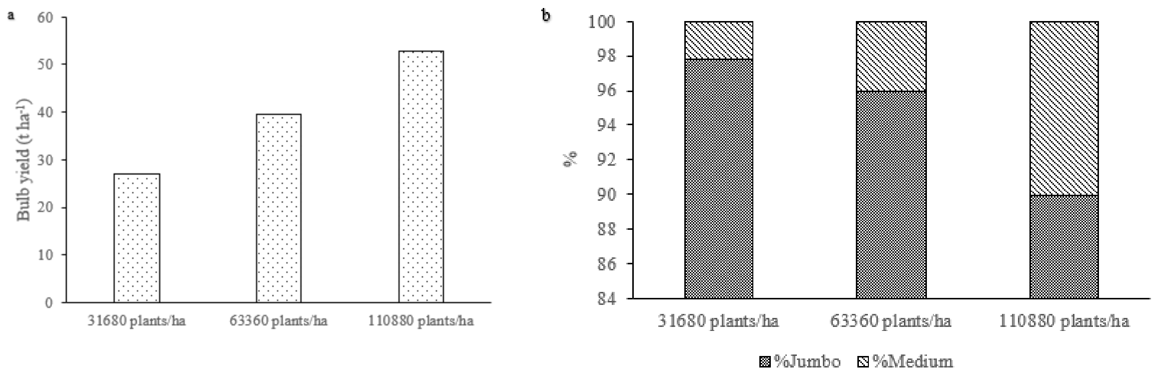

Figure 1.7. (a) Plant density on onion bulb yield cultivar ‘Century’ and (b) the percentage of bulb size. Data is adapted and modified from Boyhan et al. (2009).

Since shallots produce lateral buds or tillers, many tillers would reduce the bulb size. The number of tillers affects shallot bulb yield per hectare as well. Low density increased the number of tillers, but the effect varies among the cultivars and varieties. The optimum plant spacing for shallot ‘86’ was 15 x 20 cm, while there was no significant effect of plant spacing on shallot clones '88' and '52' (Putrasamedja, 1995). The optimum plant spacing for shallot cultivar "Biru Lancor" was 10 x 25 cm (Mahmudi et al., 2017), and for shallot cultivar 'Tuk-Tuk' it was 20x20 cm (Darma et al., 2015).

Water supply

Allium species, including onions and shallots, have high water requirements and often require regular irrigation. Shallot's water requirement per growing period is about 123,8 mm or about 1238 m^3 ha^{-1} per season (Rejekiningrum & Kartiwa, 2018); however, the number varies on soil properties and climate variables. The water supply deficiency inhibits leaf expansion that decreases interception of solar radiation and nutrient uptake due to reduced transpiration rates. Drought-stressed onion or shallot plants exhibit early bulbing, which often generates small-sized bulbs and splitting-bulbs that decrease marketable bulb yields (Woldestadik, 2003).

Onions and shallot have similar growth stages: an early vegetative stage when the plant emerges from bulb seed or seed, a middle stage when the plant starts bulbing or splitting, and the last stage, bulb maturity when leaves were falling, and dry bulb matter is increased. The most critical period for onion and shallot is the early and bulbing stages. In the early and bulbing stage, water deficit reduced the shallot bulb yield by 46 and 52% compared to control without water stress (Woldestadik, 2003). The bulbing period needs the highest water requirement, and water deficiency could significantly reduce yield (Bekele & Tilahun, 2007). Meanwhile, in the last stage (when leaves fall over), irrigation is unnecessary (Abbey & Kanton, 2004). However, continuing the watering until ripening stages could increase the percentage of large-size bulbs compared to irrigation in growth and bulbification stages (Martín de Santa Olalla et al., 2004).

Pests and diseases

Shallots encounter many pests and diseases. One of the main pests in shallot cultivation is *Spodoptera exigua* Hubner or armyworm (Figure 1.8). The incidence of armyworm is usually higher in a dry season than a rainy season (Rauf, 1999) and could significantly reduce yield by about 30% (Hadisoeganda, 2008). A high incidence of armyworm could lead to a shallot yield failure (Supyani et al., 2014). The armyworm can be controlled by insecticides such as '*tebufenozide'* (Jia et al., 2009) and also biologically by predators such as *Podisus maculiventris* (Say) (Hemiptera, Pentatomidae) (Vinuela et al., 2000).

Figure 1.8. The primary shallot pest, armyworm (*Spodoptera exigua),* was caught in the Pacet farmer's field.

The most significant disease in shallot cultivation in Indonesia is purple blotch. Purple blotch, caused by *Alternaria porri,* is widespread and has a severe incidence in hot, humid climates (21-30°C), causing severe crop losses of 50% (Rabinowitch & Brewster, 1990). In the rainy season, purple blotch combined with pest *Spodoptera exigua* could reduce the yield by 72% (Hadisoeganda, 2008). The rainy season with high atmospheric humidity and free water on the leaf surface triggers the sporulation of purple blotch (Everts & Lacy, 1990). The primary infection of purple blotch is usually from leaf debris in the soil (Nolla, 1927). The resistance among shallot cultivars to *Alternaria porri* varies. Some shallot cultivars such as 'Cokol Hijau' and 'Bauji' appear to be more susceptible to the infection of *Alternaria porri* than other types, 'Bima' and 'Sumenep' (Soedomo, 2006; Yulianto, 2012).

Cultural methods that are used to control the disease are rotations with unrelated crops within well-drained soils. Lowering the plant density and sufficient Ca, P, and K fertiliser reduced the incidence (Rabinowitch & Brewster, 1990). In addition, using fungicides such as '*mancozeb*' was adequate to control the diseases in the field (Bock, 1964).

1.2.3. Soil fertility constraints in weathered tropical soils

Weathered tropical soils commonly occur in humid tropics regions, characterized by a warm and frost-free climate with annual precipitation higher than potential evapotranspiration for most of the year. Weathered tropical soils are mostly strongly leached, have low pH (soil pH<

5.2), and have low reserves of elemental nutrients such as Ca, Mg, K and P (Juo & Franzluebbers, 2003). Geographically, this includes all of Indonesia's archipelago. Crops cultivated successively in these areas are the species that need to be well adapted to hot and moist conditions that do not require a prolonged dry season for harvesting.

Soil acidity

Natural processes and human activities can lead to soils becoming more acidic. Acid rain increases this process due to exogenous acid deposition from precipitation that reduces the acid-neutralizing capacity of soils (Wei et al., 2020) and emission of nitric acid and sulphuric acid release H^+ ions when combining with H_2O that reduced soil pH. The N cycle in soils can also have a major influence on sol acidification. Bolan et al. (2003) explained that nitrification is a key process in soils that generates acidy due to production of H^+ that occurs when NH^{4+} is converted to NO^{3-}. However, other process in the N cycle through nitrate leaching or crop removal, reduces the potential for further processes, namely denitrification, plant uptake and urea hydrolysis/ammonification, to neutralise acidity that is generated by nitrification.

The form of N fertiliser can also influence the rate of soil acidification, with ammonium fertilisers being more acidifying than nitrate or urea fertilisers. For example, after urea fertiliser is applied to soil the urea goes through a hydrolysis/ammonification process, which generates alkalinity that helps neutralises some of the acidity that is generated in the subsequent nitrification process. However, N fertilisers effects on soil acidity can vary depending on soil properties, including pH buffering capacity, climate, and crop productivity/ removal. Some fertilisers used by Indonesian farmers are described below (Table 1.5).

Table 1.5. Nutrient content and acidity equivalent of various fertilisers.

Fertilisers	Chemical formula	Nutrient content (% w/w)				Acidity equivalent*
		N	P	K	S	
Ammonium sulphate	$(NH_4)_2SO_4$	21	0	0	24	110
Urea	$CONH_2CO$	46	0	0	0	79
TSP	$Ca(H_2PO_4)_2$	0	18	0	1	15

*Acidity equivalent is the number of parts by weight of pure lime (calcium carbonate) required to neutralize the acidity caused by 100 parts of the fertiliser.

Soil acidity also changes the composition and activity of soil microorganisms. Most beneficial soil microbes prefer a slightly acidic to neutral soil pH (6.0 to 7.0), while most soil fungi prefer a lower soil pH. Thus, acidic soil alters the balanced composition of bacteria and fungi to much more soil fungi. Soil fungi and bacteria have different roles in the decomposition process that may involve essential nutrient immobilisation and slower nutrient release (Rousk et al., 2010). Vesicular arbuscular mycorrhizal fungi have different sensitivity to soil pH. *Glomus* sp grew better in high pH, while *Acaulospora laevis* grew hyphae in acidic soils (Porter et al., 1987).

Nutrient reserve (Phosphorus, basic cations, soil organic matter)

Phosphorus reserves

The P status of cultivated soils is mainly affected by fertiliser application, and shallot's P uptake is commonly low, about 8 to 23% of the total P fertiliser applied, depending on shallot bulb yield (Friesen et al., 1997; Sopha et al., 2015). Moreover, if P is continually added above the plant requirement, it may enhance soluble P in surface, subsoil horizons and groundwater stores (Havlin et al., 2014; Peltovuori et al., 2002) thus causing water pollution.

In acidic soils, P movement and P accumulation are governed by sorption to Al- and Fe- oxides. Application P fertiliser increases P adsorption linearly in soil solution. Every 1000 µg P addition increased adsorbed P by 9.27 µg g^{-1} in acidic Ultisol, soil pH 4.41 (Palanivell et al., 2020). Moreover, soil amendments also increase soil available-P. The lime + biochar and fly ash application increased plant-available-P in Ultisol and Alfisol soils (Hong et al., 2018). Moreover, lime application alone also increases the availability of macronutrients to crops. The application of lime linearly increased P-reserve. Application of 350 kg lime ha^{-1} increased P residue in the soil by 39% than control, from 16.6 to 23.1 kg ha^{-1} in acidic Alfisol (Meena et al., 2019).

Basic cation reserves

Weathered tropical soils, which are highly leached, typically show a low total K status due to high rainfall and temperature. Potassium fertiliser addition will induce a certain reversing to exchangeable-K in soil solution (Havlin et al., 2014) and K addition correlated quadratically with adsorbed K in Ultisol (Palanivell et al., 2020). Moreover, lime addition also improves K reverse. Application 350 kg lime ha^{-1} increased K by 23% from 215.3 kg ha^{-1} to 264 kg ha^{-1-} in an acidic Alfisol (Meena et al., 2019).

In acidic soils, base saturation was low (Havlin et al., 2014). Moreover, N fertiliser addition (ammonium sulphate and urea) reduced exchangeable Ca^{2+} and Mg^{2+} saturation and increased

Al^{3+} saturation linearly due to decreasing soil pH. Application 210 kg N ha^{-1} as ammonium sulphate reduced base saturation by 4.4% and increased Al^{3+} saturation by 4.8%. (Fageria et al., 2010). While lime and dolomite application increased exchangeable Ca^{2+} and Mg^{2+} and reduced exchangeable acidity in tropical acidic soils (Auler et al., 2019; Cahyono et al., 2019).

Organic material reserves

Soil organic materials (SOM) consist of organic constituents in all phases of decomposition, and soil humus is the main component of SOM converted to inorganic forms through mineralisation. However, when there are inadequate nutrients in organic material to meet the microbial demand, the inorganic ions will be immobilised into microbial tissue (Havlin et al., 2014). Thus, mineralisation and immobilisation simultaneously run when organic materials are applied to soils. The process depends on organic material's composition and biotic and abiotic soil properties (Widowati et al., 2012).

Organic materials such as crop residue, organic fertiliser and manures increased organic carbon and released nitrogen upon the mineralisation process. A high amount of manures increased the mineralisation rate (Widowati et al., 2012). Liming materials might reduce or significantly affect organic carbon (Andrade et al., 2002) and might involve an immobilisation process through soil microorganism decomposition.

Aluminium toxicity

The soil acidity in many parts of the Indonesian tropical region is commonly generated by acid rain and leaching (Hemphill, 1987; Prayitno, 2015; Van Lierop et al., 1979). Abundant precipitation depletes base cation adsorbed and these are replaced by particles by H^+ from H_2O, H_2CO_3, or natural acids. The H^+ ions are responsive and take apart the mineral cross sections by responding with structural Al on soil particles. The Al^{3+} atoms from the mineral structure possess some soil cation replaceable sites to exchangeable Al^{3+} (Baquy et al., 2017). Exchangeable Al^{3+} is the main form and the main phytotoxic species harmful to the crops under acid conditions (Delhaize & Ryan, 1995).

The main symptom of Al toxicity is often severe root growth restriction or rhizotoxicity (Wright, 1989). Aluminium also inhibits calcium uptake, displacement of calcium in the apoplast and might disrupt calcium metabolism. Another mechanism is that Al inhibits growth indirectly via signal response pathways involving the root cap, changing hormones, and secondary messengers (Meriño-Gergichevich et al., 2010).

Aluminium has been reported as toxic to onions at a concentration of 100 µM (Clarkson, 1965; Morimura et al., 1978) and 600-1000 µM (Fiskesjö, 1983). So onions are typically sensitive to Al concentration (>20 µM), that increasing the level of Al will reduce the relative root and shoot biomass (Wheeler & Follett, 1991) (Figure. 1.9). The symptoms of Al toxicity are chlorosis of the plant leaves, especially the upper portion, dieback on some tips, the root are stubby, brown with little or no lateral development (Wheeler & Follett, 1991).

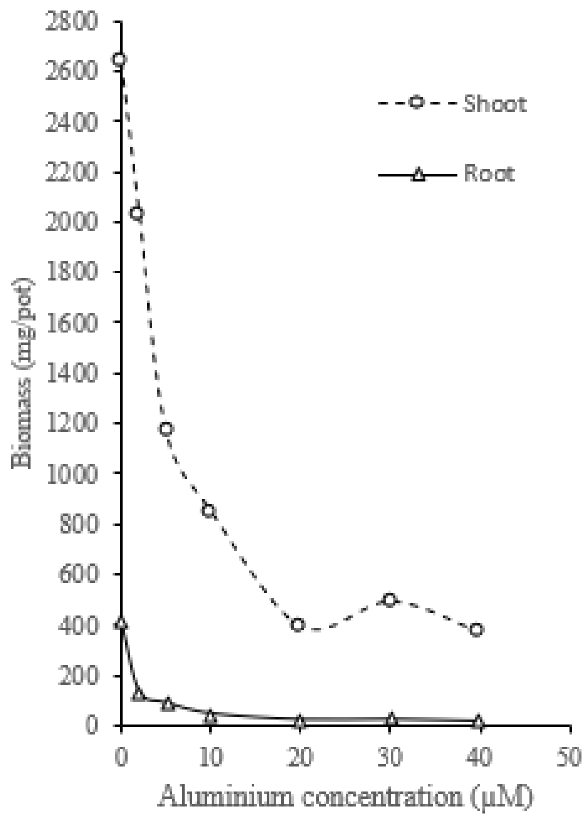

Figure 1.9. Correlation between Al concentration (µM) and biomass (mg/pot) in onion It was adapted and modified Wheeler and Follett (1991).

For some plants, Al toxicity's effect parallels, P deficiency and induced Ca deficiency (Hale et al., 1987). Phosphorus deficiency symptoms are diminishing plant growth, promoting small dark green leaves and slower plant maturation. While curling of the young crop leaves and injured roots are some Ca deficiency symptoms. The reciprocal action between Al and P is acknowledged and studied extensively (Adams, 1981; Havlin et al., 2014; Rengel, 1992).

Manganese toxicity

Another micronutrient that more soluble in the acidic condition is manganese (Mn). A reducing soil pH improves soil redox potential that initiates reducing soil-bound Mn and increasing the exchangeable Mn^{2+}. Excessive exchangeable Mn^{2+} causes Mn toxicity that causes the incidence of brown speckles, interveinal chlorosis, necrosis and yellowing in mature leaves (Faria et al., 2020) and reduces plant growth (Yuan et al., 2019). Furthermore, Mn concentration in the plant tissue is usually triggered by waterlogging for a prolonged period (Sparrow & Uren, 1987). A high concentration of Mn^{2+} in soil solution may cause a severe problem in bulb formatting of *Allium* species, like garlic (*Allium sativum*) (Anderson, Hart, Sullivan, Hulting, et al., 2013).

The symptom of Mn toxicity is like Fe deficiency, chlorosis. The amount of exchangeable Mn in soil solution has a positive correlation with Mn concentration in the tissue leaves (Huang et al., 2016). However, Fiskesjö (1988), who monitored the relative toxicity of metal ions on *Allium cepa* root growth, reported that Mn^{2+} causes lower toxicity than Al^{3+}. Meanwhile, Al^{3+} inhibits the absorption of Mn^{2+} because of similar distribution characteristics (Yuan et al., 2019).

1.2.4. Soil amendments for acidic soils

Liming materials

Liming is a common practice to overcome the acidic limitation in acid soils. Lime improves soil pH, the total number of base cations that enhance the base saturation, and decreases exchangeable acidity, Al^{3+} and Mn^{2+} ions (Fageria & Baligar, 2008) (Cristancho et al., 2014).

Liming gives different responses on plant available-P in soil solution. In the Brazilian Oxisol, plant available-P (Mechlich-1) has a quadratic relationship with increasing soil pH when the soil pH ranges between 5.0 to 6.5. However, at higher pH (> 6.5), the available-P decreases. Incrementally inaccessible P in the pH range between 5.0 to 6.0 was related to discharge from Al and Fe oxides, which were liable for P fixation (Fageria & Barbosa Filho, 2008). At higher pH (> 6.5), the decrease of soluble P was related to precipitation P as Ca phosphate (Naidu et al., 1990). Liming also raised the nutrient use efficiency of P, Zn, Co, Fe and Mn for rice plants in tropical acidic soil. Although liming decreases the availability of Fe, Mn and Zn, the increased plant growth from liming may have resulted in a larger root system and, thus, improves the ability to take up trace elements from the soil. The improvement was related to diminishing soil acidity, improving their accessibility and root system (Fageria & Breseghello, 2004).

The effectiveness of liming to increase pH and crop yield could vary depending on the type of lime materials, liming method, lime rate and crop species. Anderson, Hart, Sullivan, Horneck, et al. (2013) used a lime score to determine the effectiveness of lime that was a combination between the neutralizing value of lime or calcium carbonate equivalent (CCE), moisture and fineness or particle size of the materials. Calcium carbonate equivalent is the acid-neutralizing capacity of lime materials that are presented as a weight percentage of $CaCO_3$. For example, in Oregon, the CCE of limestone was 90-100%, dolomite was 95-110%, hydrated lime was about 120-135 %, and burnt lime was 150-175% (Anderson, Hart, Sullivan, Horneck, et al., 2013). In tropical regions, agricultural limestone has 95-109% CCE; Calcite lime has 100% CCE; dolomite lime has 100-120% CCE; burned lime has 179% CCE (Fageria & Baligar, 2008). Fine materials improve the soil pH more rapidly than coarser materials. However, the coarser materials can last longer and maintain the soil pH.

The solubility of Al depends on the soil pH. The concentration of exchangeable Al^{3+} reduces while the soil pH increases (Moir & Moot, 2010). Aluminium may present different forms, and soil characteristics possibly give a different critical concentration for Al toxicity. The application of lime increases the concentration of Ca^{2+} and simultaneously reduces Al:Ca ratio. The Al:Ca ratio was proposed as a more reliable indicator for evaluating the Al toxicity rather than Al^{3+} solely (Vanguelova et al., 2007), which is commonly used to measure Al toxicity for forest trees. Since Al:Ca ratio and the concentration of Al in crops vary with crop species and soil types, there is still a lack of information about Al toxicity in onion and shallot in tropical acidic soils.

In oil palm, the ratio of Ca^{2+}+Mg^{2+}/Al^{3+}+Mn^{2+} (r= 0.79) had a better correlation than Al^{3+} total (r= 0.69) on interpreting the stress of exchangeable acidity in acidic soil that expressed in the reduction of the root dry weight (Cristancho et al., 2014). Increasing exchangeable Ca^{2+} and Mg^{2+} concentration in soil solutions alleviate the toxic effect of Al on root development (Cristancho et al., 2014). Application of dolomite and magnesium carbonate ($MgCO_3$) increased linearly soil pH, Mg^{2+} and nitrate (NO_3^-) concentrations that reduced the exchangeable Al and Mn. The high level of Al^{3+}, Al_2SO_4, AlF and Mn decreased the root dry weight of oil palm.

The recent studies about lime on onion and shallot bulb yield are limited. A pot study found that onions failed to bulb when soil pH was < 3.0, and the application of agricultural lime at a rate of 12 t ha^{-1} increased the soil pH (from 3.4 to 5.1) and increased the onion bulb yield from 90 g pot^{-1} to 160 g pot^{-1} (Van Lierop et al., 1979). Mathur and Levesque (1983) showed that onion bulb yield increased linearly, increasing pH value from pH 3.0 to 5.8. In a field trial in less acidic soil conditions in Oregon, the United States, Hemphill (1987) reported that an application of 14.8 t ha^{-1} agricultural limestone (95% $CaCO_3$ equivalent) increased soil pH from 5.5 to 6.6 and enhanced the onion bulb yield from 4.0 t ha^{-1} to 30.4 t ha^{-1}. However, there are limited field study investigations into the effects of liming on onion yield in very acid soil (pH < 5.0).

Biochar and zeolite

Biochar comprises condensed aromatic organic carbon with a high C content that confers its persistence and soil stability (Wang et al., 2016). In addition, the biochar structure is porous with a high surface area that increases the water-holding and sorption capability (Sohi et al., 2010). Improving nutrient availability through biochar application can be explained as increasing pH in acid soils due to the oxide content on biochar (Biederman & Harpole, 2013; Liu et al., 2013), CEC (Liang et al., 2006) and soil pH buffering capacity (Shi et al., 2017). In addition, a specific amount of nutrients (K, Ca, Mg and Si) might be added by biochar ash and increase soil pH (Glaser et al., 2002).

Different types of biochar feedstock have different capabilities in alleviating Al toxicity. For example, corn stover biochar increased pH and reduced exchangeable acidity more significantly than switchgrass biochar when applied at the same rate to similar clay loam soils (Chintala et al., 2014).

Moreover, the effect of biochar application on soil fertility could diversely depend on soil chemical characteristics. For example, in Gleysols (soil pH 6.5), rice husk biochar application increased total organic carbon, C:N ratio, exchangeable K^+ and exchangeable Ca^{2+}. Meanwhile, in Acrisols (soil pH 4.8), rice husk biochar application improved exchangeable Ca^{2+} significantly, but not the rest (Haefele et al., 2011).

Crop response to biochar application varies. For example, Jeffery et al. (2011) reviewed 16 different studies (1994-2010), and the overall effect of biochar on crop production was small (10%). Furthermore, Liu et al. (2013) studied 100 published works and showed that the impact of biochar on the rice yield had the same magnitude - the increasing grain yield was 11%. However, the most significant effect was in legumes and vegetables, showing a significant increase in 30 and 29% yield, respectively. In addition, there was a strong tendency for the beneficial effect of biochar to be greater in acid soil (soil pH< 5) than near neutral soils. In this condition, 10 t ha^{-1} rice husk biochar enhanced total rice biomass 257% (Masulili et al., 2010), and eucalyptus biochar dose 50 t ha^{-1} increased maize yield up to 157% (Raboin et al., 2016).

Zeolite can increase soil pH through increasing NUE and reduce nitrification process, increase CEC, and can remove toxic cations, inhibiting cadmium's leaching from soil and uptake of cadmium by crops. Zeolites reversibly bind ammonium to be an excellent slow release-N source for plants but reduce 50% of the soluble P (Lefcourt & Meisinger, 2001). The zeolite 5 t ha^{-1} + TSP 150 kg ha^{-1} increased pH from 4.60 to 5.46 and reduced H^+ from 0.73 to 0.29 (Aainaa et al., 2018) and application of 600 mg zeolite -clinoptilolite kg^{-1} soil + 100 mg P kg^{-1} soil increased base saturation by 7% above the control without zeolite + P (Badora, 2016).

1.2.5. Summary

Improving shallot production in the existing production areas is necessary to meet the crop demand increased by population growth; however, various factors influence the shallot bulb yield. A wide gap of bulb yield at the farmer's level compared to possible yields creates room for shallot practice improvement. Appropriate soil pH and nutrient availability are important to support plant growth and produce a high bulb yield. Over the years, some research efforts have been made, including shallot fertiliser application and pest and disease control in many central shallot production areas. However, much less research has been done under acidic soil conditions (low pH, high exchangeable Al^{3+}), which prevail in midland and upland communities. This research addresses the gap and will help farmers achieve better yields in acidic soils. The consequences of the investigation can be utilized in other zones with similar issues of soil acidity.

1.3. Research Question and the Objectives

Various factors contributed to the shallot bulb yields in acidic soils, including pest and diseases and soil fertility. The most apparent solution for pests and diseases that could reduce harvestable bulb yield is by improving the effective spraying regimes while respecting withholding periods; however, that is not be investigated in this thesis. At the same time, there is no single effective solution for increasing shallot bulb yield based on improving nutrition and soil properties. Therefore, this study's exploration question is **"How to manage soil acidity and alleviate acidic toxicity to support shallot growth in acidic soil in West Java?"** Specific research questions are:

- What are the potential soil fertility limitations that cause low shallot yields in the upland regions of West Java?
- What is the effect of lime and P fertiliser application in strongly acidic soils in West Java?
- What is the soil pH and Bray1-P target levels and the threshold for exchangeable Al^{3+} level that allow optimum shallot growth bulb yields?
- What is the specific fertiliser and lime recommendations for growing shallots in strongly acidic soils?

This investigation's general theme is improving soil fertility, supporting shallot growth and promoting sustainable shallot production in West Java's acidic mid- and upland soils. The specific objectives of this thesis are:

- To identify potential causes of low shallot yields in areas of West Java.
- To understand the effect of lime and fertilisers on shallot growth and bulb yield in strongly acidic soils.
- To determine the efficacy and cost-effectiveness of soil amendments on alleviating Al toxicity.
- To create specific recommendations for improving shallot bulb yield in these acidic soils.

1.4. Structure

This thesis comprises seven chapters, and the structure of this thesis is schematically presented in Figure 1.15. Following this general introduction and literature review **(Chapter 1). Chapter 2** describes the general methodology for plant and soil analysis that was used in this study.

Chapter 3 defines the crop management practices at the farmer's level, also the correlation between soil fertility and shallot yield. Field trials were conducted to evaluate different lime and P fertiliser application rates on the yield response of shallot growth in three different acidic soils are discussed in **Chapter 4**. **Chapter 5** describes incubation treatments with separate soil amendments to increase soil pH and reduce exchangeable Al. Alleviating Al toxicity using lime materials under field conditions and the shallot growth and yield are studied in **Chapter 6.** **Chapter 7** consists of a general discussion of the results and conclusions, and lastly **Chapter 8** consist of limitations of the study and suggestions for future research.

Chapter 2

General Methodology: Plant and Soil Analyses

This chapter consist of the plant and soil analyses used in this study. While the other specific methods are described in the related chapters. The method for the socio-economic survey is described in Chapter 3, the agro-pedo-climatic information is provided in Chapters 4 and 6, and methods for the incubation study are described in Chapter 5.

2.1. Plant Analysis

All plant and soil analysis were conducted in the Indonesian Vegetable Research Institute (IVEGRI) Laboratory at Lembang, Bandung Barat Regency, West Java, Indonesia (ISO/IEC 17025:2017; LP-798-IDN). Five plant samples were taken out from each plot in Field Trials 1 and 2. Fresh, clean plant samples were cut into the above and below ground components and dried in an oven at a temperature of 70^{o}C. Once dried, the roots, bulbs and leaves were ground and sub-sampled. Oven-dried samples were sieved by < 2mm and < 0.5 mm mesh screen size (Eviati & Sulaeman, 2009; Jones Jr, 2001).

For Field Trial 1, the concentrations of N, P and K for the above-ground (leaves and stems) and below-ground (bulbs and roots) components for each treatment and replication were analysed separately. For Field Trial 2, the concentration of N, P, K, Ca and Al for the above-ground section (leaves and stems) and below ground (roots and bulbs) for each treatment were compositely analysed and followed by separate analysis Ca-roots, Al-roots and Mn-leaves for specific treatments and each replicate.

2.1.1. Total nitrogen

The digestion procedure for total N was adapted from the standard Kjeldahl digestion method Jones Jr (2001), using the modification of Eviati and Sulaeman (2009). A 0.25 g sample of herbage was put in to a 250 ml digestion tube, then 1 g of a mixture of 1.55 g $CuSO_4$ anhydrite, 86.9 g Na_2SO_4 anhydrite and 1.55 g selenium was added and then 2.5 ml of concentrated (97%) H_2SO_4 was added. The digestion tube was left to stand overnight, approximately 12 hours. The tube was heated at 350 for hours until white steam released, and the solution in the tube was clear. Afterwards, the digestion tube was cooled to room temperature and distilled water up to

50 ml and the solution mixed until homogenous. The solution was left overnight and the used to measure the total N.

Nitrogen in the solutions was determined using the direct distillation of the solution and the NH_3 titration method (Bradstreet, 1965; Eviati & Sulaeman, 2009). A 10 ml sample was pipetted into a 250 ml boiling flask. About 3 to 4 boiling stones and H_2O were added to a half volume of the boiling flask. A 10 ml aliquot of 1% boric acid and two drops of Conway indicator (red colour) were placed into a 100 ml Erlenmeyer flask to collect NH_3. The Erlenmeyer flasks were connected to a distillation machine, and 10 ml of 40% NaOH was added and covered. The distillation process occurred until Erlenmeyer's volume was about 50-75 ml and green. The distillate was titrated by 0.05 N H_2SO_4 until the solution had a pink colour. The titration volume of sample extract and blank extract were recorded.

2.2.2. Macro and micronutrients analysis with HNO_3 and $HClO_4$

To estimate the concentration of nutrients, other than N, in plant tissues in this study, a nitric and perchloric acid digestion method was used (Eviati & Sulaeman, 2009; Jones Jr, 2001; Zasoski & Burau, 1977). A 0.5 g herbage sample was added to a digestion tube long with 5 ml 65% HNO_3 (nitric acid) and 0.5 ml 60% of $HClO_4$ (perchloric acid). The tube was covered and let stand overnight. The tube was heated to 100°C for 1.5 hours, then the temperature increased to 150°C for 2.5 hours until yellow fumes from $HClO_4$ disappeared. It was then heated up again to 200°C for 1 hour until a white fume was formed. The destruction process was completed when white sediment was formed, and about 0.5 ml of clear solution remained. The tube was then cooled to room temperature, then it was made up to a volume 50 ml with water. The solution was mixed until homogenous and left overnight. The extract was used to measure the concentrations of P, K, Ca, Al, and Mn.

Phosphorus measurement

Phosphorus was determined by colourimetry (blue molybdophosphoric acid method) (Eviati and Sulaeman, 2009). A 1 ml extract of sample was pipetted into the test tube and 9 ml of distilled water was added and mixed. 1 ml solution was transferred into a test tube and 10 ml P colouring regent was added and mixed until homogenous. The solution was left for 30 minutes. The concentration of P in the solution was measured by spectrophotometer at wavelength 889 nm.

The P colouring regent was made from a concentrated P regent, which was made from 12 g $(NH_4)_6Mo_7O_{24}$. $4H_2O$ was diluted into 100 ml distilled water and 140 ml concentrated H_2SO_4 and 0.227 g K (SbO) $C_4H_4O_6$.$0.5H_2O$ was added. Then the solution was then made up to 1 L with distilled water. The P colouring regent was made from 1.06 g ascorbic acid plus 100 ml concentrated P regent mixed and made up to 1 L with distilled water.

Potassium, calcium, aluminium, and manganese analysis

Every 1 ml sample and standard series have been taken into the test tube separately, add 9 ml 0.25% La and mixed until homogenous. 0.25% La was made from 44.14 g $LaCl_3$ was diluted by H_2O up to 1 L and diluted ten times again. The solution was mixed until homogenous and was measured by AAS (Atomic Absorption Spectrophotometer). Al and Mn were measured directly from the sample extract with AAS.

2.2. Soil Analysis

Bulk soil samples (0-20 cm depth) of approximately 1 kg for each sample were taken from 100 farms from four different locations in Survey Activity (Chapter 3). Soil samples from all treatments and replications in Field Trial 1 (Chapter 4) and Field Trial 2 (Chapter 6) also were taken with the same depth and volume. Each bulk sample was cleaned from the roots, plants, rocks, and other derbies then oven dried at 40°C until dry, approximately 2 to 3 days. Soil samples were lightly crushed and sieved through a 2 mm and 0.5 mm sieve.

Soil pH, plant available-P (Olsen-P and Bray1-P), basic cations (Ca^{2+}, Mg^{2+}, K^+, Na^+), cation exchange capacity (CEC), base saturation (BS), exchangeable sulphate (SO_4^-) and phosphate retention were analysed in the Survey Activity. Soil pH, KCl-titratable acidity (Al^{3+}, H^+), basic cations, Bray1-P), organic-C, Kjeldhal-N and C: N ratio were analysed in Field Trial 1. Soil pH, KCl-titratable acidity and basic cations were measured in the Incubation Experiment (Chapter 5). Soil pH, KCl-titratable acidity, basic cations, BS, Bray1-P and exchangeable Mn^{2+} were analysed in Field Trial 2**.**

Soil pH_{H2O} was measured using a HANNA pH meter (HI 2550) with a soil: water ratio of 1:5 (Miller & Kissel, 2010) while pH_{KCl} was measured using a KCl solution . An index of available P in soils was calculated by Olsen-P and Bray-1-P method. Olsen-P was measured by extraction with 0.5 M sodium bicarbonate pH 8.4 (Olsen, 1954), and Bray-1-P method was determined

Bray-1 phosphorus-free reagents (Bray & Kurtz, 1945). Phosphorus retention (%) was measured by the method of Saunders (1965) using a P concentration of 1000 ppm P. Soil organic carbon was determined by wet combustion technique (Nelson & Sommers, 1983), and total N was determined by Kjeldhal wet digestion followed by distillation (Bremner, 1960).

Basic cations were extracted in 1 M ammonium acetate (NH_4AO_c) at pH 7. The concentration of exchangeable Ca^{2+} and Mg^{2+} were measured by AAS, and the concentration of exchangeable K^+ and Na^+ were measured by flame emission spectroscopy. Cation exchange capacity (CEC) was determined by colorimeter (indophenol blue) (Anderson & Ingram, 1989). KCl-titratable acidity (Al^{3+} + H^+) was determined by 1 M KCl and was titrated with 0.1 M NaOH (Thomas, 1983).

2.2.1. KCl-titratable acidity (Al^{3+} and H^+)

KCl-titratable acidity (Al^{3+} and H^+) was evaluated by a titrimetric method, according to Eviati and Sulaeman (2009). A 5 g sample of air-dried soil was placed in a centrifuge tube, and 50 ml of 1 M KCl was added then was shaken for 30 minutes. The extract was filtered (Whatman No 40 or equivalent) into a plastic bottle. To obtain exchangeable acidity, 10 ml of the extract was pipetted into a 50 ml Erlenmeyer flask, then 4 or 5 drops of 0.1% phenolphthalein was added. The extract was titrated with 0.02M NaOH to the first permanent pink endpoint.

To determine exchangeable Al^{3+}, one drop of 1M HCl was added at a time to the soil extract until a pink colour disappeared. Then 2 ml of 4% NaF was added to the extract, which produced a red colour. The extract was then titrated with 0.05 M HCl until the red colour disappeared.

2.2.2. Soil available- P

The plant-available soil phosphorus in the soil determined using both the Olsen and Bray1 methods (Bray & Kurtz, 1945; Olsen, 1954; Van Reeuwijk, 2002). Olsen-P was used in the survey activity when the soil pH > 5.5. For the Olsen-P method, 1 g soil was weighed sample and then 20 ml 0.5M $NaHCO_3$ (pH 8.5) was added and shake in an end-over-end for 30 minutes. The extract was filtered until clear then pipetted 2 ml to test tube and was added 10 ml of P colouring regent (made from 1.06 g ascorbate acid and 100 ml P regent and added by 25 ml of H_2SO_4N), centrifuges and left for 30 minutes. The extract was measured by spectrophotometer at a wavelength of 889 nm.

The Bray1-P method involved adding a 2.5 g sample of air-dried soil to 25 ml Bray and Kurts-I extractant into centrifuge tube, then shaking or centrifuge for 5 minutes. The Bray and Kurts-I extract made from 1.11 g NH_4F that was diluted by 600 ml H_2, adding 5 ml 5N HCl and making up to 1 L with distilled water. After the shaking, the sample was filtered by Whatman no 42 to 100 ml volumetric tube and made up to 100 ml by distilled water. About 2 ml of the filtrate was transferred to be measured with a spectrophotometer at a wavelength of 889 nm.

2.2.3. Basic cations

The exchangeable basic cations (Ca^{2+}, Mg^{2+}, K^+ and Na^+) were extracted from soil with NH_4^+ using 1 M ammonium acetate (NH_4OH) (pH 7) extractant (Eviati & Sulaeman, 2009; Hendershot & Lalande, 2008). The method involved adding 2.5 g of air-dried soil samples into centrifuge tube and added 40 ml 1 M NH_4OAc and shaking for 5 minutes. Tubes from shaker were removed and let stand overnight. The solution was shaken again for 15 minutes and was filtered using Whatman No 42. filter paper and then placed in 500 ml filtering flasks. Contents of the tubes were transferred to the funnel with suction applied. The tube and the stopper were washed with 1 M NH_4OH from a wash bottle. Soil was washed in the funnel with four 30 ml portions of 1 M NH_4OA. Each portion was drain completely before adding the next. The leachate was transferred to a 250 ml volumetric flask and the filtering flask was rinsed and makeup to volume with 1 M NH_4OA. The extract was mixed well and saved for Al, Ca, Mg, K and Na analysis.

For total exchange capacity (CEC), the funnels containing the ammonium-saturated soil were replaced onto the filtering flask. The residual NH_4OA from the soil was removed by washing the soil in the funnel with three 40 ml portions of isopropanol, the isopropanol was discarded. Then the soil was washed by four 50 ml of 1 M KCl, and letting each portion drain completely before adding the next. The leachate was transferred to a 250 ml volumetric flask. The filtering flask was rinsed into the volumetric flask with 1 M KCl and make up to volume with 1 M KCl and mixed well. The exchangeable ammonium was measured by Spectro-colorimetry using a light wavelength of 636 nm (Eviati & Sulaeman, 2009).

For measuring base cations (Ca^{2+}, Mg^{2+}, K^+ and Na^+), about 1 ml of the filtrate was combined with 9 ml of 0.25% Lanthanum chloride, $LaCl_3$. 2.5% Lanthanum chloride was made from 44.14 g $LaCl_3$ was made up to 1 L with distilled water. Than to obtain 0.25% La, the 2.5% La was diluted by distilled water for ten times. Then the solution was mixed well until homogenised. Cations, Ca^{2+} and Mg^{2+} were determined by using Atomic Absorption Spectroscopy (AAS). While K^+ and Na^+ were measured by flame emission.

2.2.4. Organic-C and Kjeldhal-N

To measure organic-C, a 0.5 g soil sample was put in a 100 ml test tube. The 5 ml of 1 N $K_2Cr_2O_7$ was added and mixed well. The 7.5 ml of 98% H_2SO_4 was added and agitated for 30 s before inserting into a preheated (135°C) digestion block. The tubes were removed from the block after 30 minutes and cooled. Then 100 ml of distilled was added water and left overnight. The clear solution is measured by spectrophotometer at a wavelength of 561 nm (Eviati & Sulaeman, 2009; Skjemstad & Baldock, 2008).

To measure Kjeldhal-N, a 0.5 g soil sample is placed to digest tube. About 1 g selenium and 3 ml of H_2SO_4 and digested at 350°C (about 3 to 4 hours). The digestion process was completed when the white steam release and the solution is clear. The followed instruction is similar to Nitrogen analysis for the herbage's samples.

Chapter 3

Shallot Production Systems in West Java, Indonesia; Survey of Current Farmer Practice

3.1. Introduction

West Java is Indonesia's fourth-largest shallot producer. In 2018, West Java had 15,404 ha of harvested shallot (9.8% of the total domestic harvested area) with an average yield of 10.9 t ha^{-1} (BPS-RI, 2019). Around 57% of the shallot cultivated area is in mountainous upland regions, while the remaining is lowland. Most West Java farmers operate small-scale farms, with approximately 90% of farmers owning less than 1 hectare (BPS-RI, 2013). The small farm size limits farm income and often restricts the ability of farmers to invest and implement more efficient farming practices (i.e., mechanisation). In 2013, the Growth Domestic Product (GDP) of small-scale farmers per capita in Indonesia was NZ$ 1,276 per year, less than half the average national GDP per capita of around NZ$ 3,488 per year (PUSDATIN, 2014). Therefore, improved crop management practices that increase crop yields consistently would enable farmers to increase their incomes.

The Cirebon Regency is the largest shallot production area in West Java, followed by Majalengka, Garut and Bandung Regencies (Figure 1.1) (BPS-Provinsi-Jawa-Barat, 2017b). Many areas of the Cirebon Regency have an elevation of less than 1 m above sea level. Therefore, Cirebon farmers grow shallots in flat lowland areas following paddy or sugarcane crops. Lowland farmers grow shallots on raised soil beds (approximately 1.2 m wide) with irrigation water between beds, where the production system is called “surjan” or furrow irrigation (Figure 3.2). A typical cropping pattern is a yearly rice-shallot-shallot-shallot or rice-shallot-capsicum-pepper rotation (Siemonsma & Piluek, 1993).

Figure 3.1. The central shallot production regions in West Java, Indonesia.

Figure 3.2. The shallot production system in lowland Cirebon with paddy system.

Meanwhile, the central shallot productions in Majalengka, Garut and Bandung Regencies are in upland areas. Upland farmers grow shallot after harvesting rice in paddy fields during the dry season and then use the dry land or "tegalan" for shallots again in the rainy season (Figure 3.3). Unlike paddy field systems, the dry land system is rainfed with no additional irrigation applied to crops. Therefore, growing shallots in the rainy seasons is more challenging than in the dry season, which results in shallot yields typically being lower in the rainy season.

Figure 3.3. The shallot production system in upland Bandung within the dryland system.

In West Java, the regional average shallot yields range from 8.9 to 12.5 t ha^{-1} (BPS-Provinsi-Jawa-Barat, 2017b). However, the regional averages conceal much wider underlying variability at the individual farm level. For example, Utami (2009) reported that the average shallot bulb yield for the farmer in Brebes Regency, Central Java Province was 10.1 t ha^{-1}, with a 20% coefficient of variation (CV). While Nurjati et al. (2018) reported that the average shallot bulb yield in Pati Regency, Central Java Province was 4.4 t ha^{-1} with 105% CV, indicating a considerable variation amongst the farms in this region. Various local factors influence the individual farm yield variation; soil fertility and fertiliser use, water availability, soil tillage practices, planting materials and cultivars, plant densities, and pest and disease management (Grubben, 1994). Yield variation can also occur between seasons on the same farm. For example, higher rainfall during the rainy season increases plant micro-climate humidity, which increases disease incidence causing higher fungicide costs or reduces shallot bulb yields (Rabinowitch & Brewster, 1990). Higher rainfall can also reduce soil fertility by increasing the likelihood of nitrogen and potassium leaching (Campo et al., 1998; Fang et al., 2009; Tanaka & Navasero, 1964).

It can be more challenging to maintain adequate soil fertility to achieve high yielding vegetable crops in weathered tropical soils. Phosphorus availability and pH are often limiting factors as soil pH is frequently well below optimum (Campo et al., 1998). Furthermore, shallots have coarse and shallow root structures, often with a characteristic low root/shoot ratio, making them less efficient at accessing P in the soil (Föhse et al., 1991). In addition, high soil acidity negatively affects root growth, further reducing the plant uptake of phosphorus and other essential nutrients (Högberg et al., 2007).

There is limited information on the variation in farmer shallot yields and the relationship between soil fertility and bulb yields in West Java. Moreover, soil testing is not being widely used by farmers, which is likely to be due, in part, to the small-scale nature of these farming systems. Therefore, this study aimed to design a farmer survey and soil testing results to characterise the current shallot production systems and identify potential shallot yield-limiting factors, especially related to any soil fertility issues, in the main shallot producing districts of West Java.

3.2. Materials and Methods

3.2.1. Sampling strategy

A face-to-face survey in West Java was undertaken to assess current agronomic practices and soil chemical properties and quantify shallot production levels resulting from these practices. Four shallot production areas from three regencies were chosen based on altitude and production, two lowland areas (Cirebon Regency) and two upland areas (Garut and Bandung Regencies) (Figure 3.4.b to 3.4.d). From the selected three regencies, the survey was conducted in four different districts or *Kecamatan*. They were the Babakan and Losari Districts from the Cirebon Regency, Bayongbong District from the Garut Regency, and the Pacet District from the Bandung Regency (Figure 3.4.e to 3.4.g), representing the main areas of shallot production for each Regency.

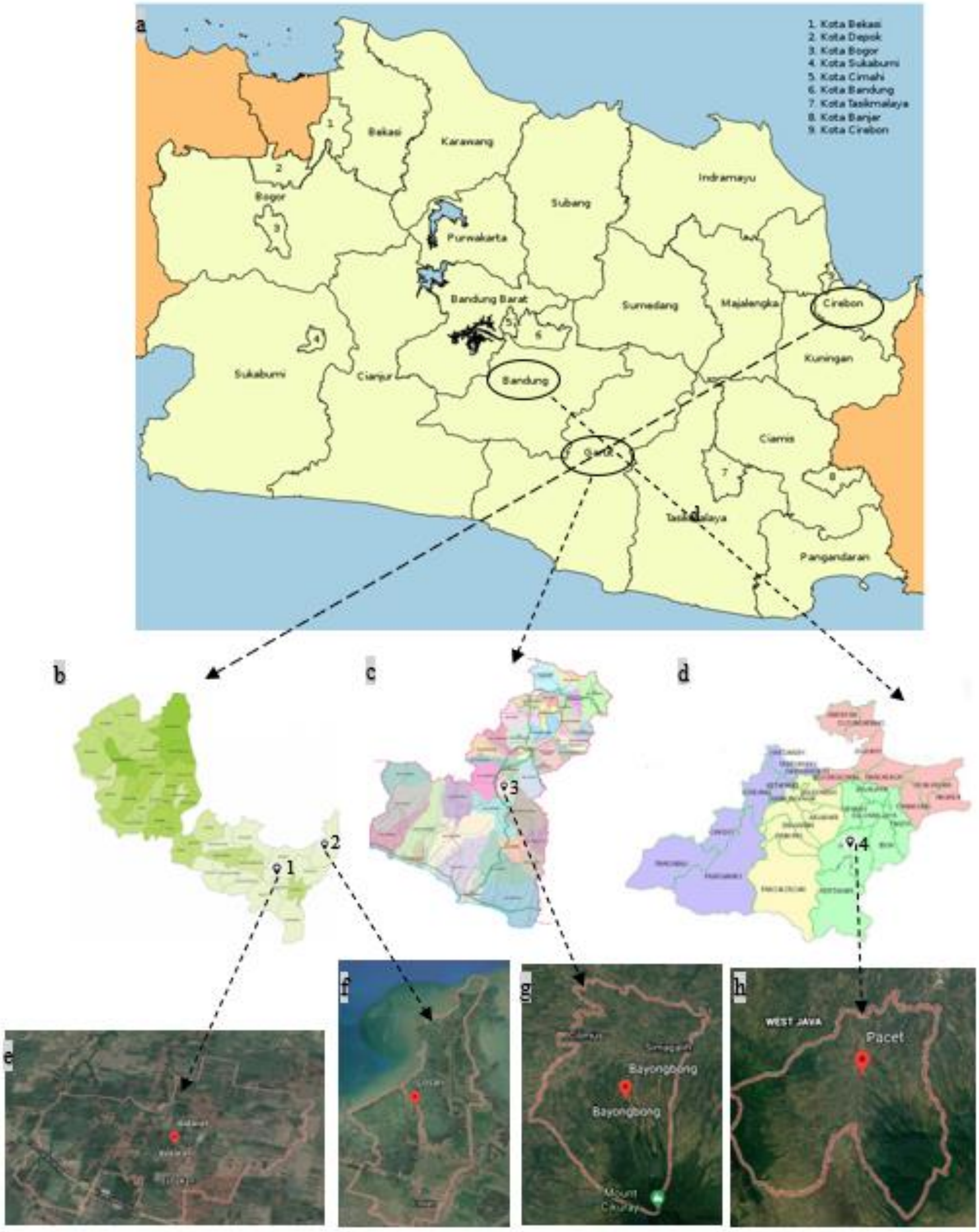

Figure 3.4. The locations of survey activity, (a) West Java Province, (b) Cirebon Regency, (c) Garut Regency, (d) Bandung Regency, (e) Babakan District, (f) Losari District, (g) Bayongbong District and (h) Pacet District.

A hundred farmers were selected and surveyed within these four districts (ca. 25 farmers per district) using semi-structured interviews at each farmer's farm. Each farmer respondent was chosen typically based on the following criteria they are a small-scale farmer with a harvested area of between 0.25 to 1 ha; they have grown shallot for at least 5 years, they grew shallot in both the dry and rainy seasons in 2015 to 2016, their farm site is accessible by foot, and they are literate. The survey was conducted from December 2017 to February 2018. All farmers managed their own fields, and the planting technique was performed traditionally without machinery. Information of a socio-economic nature was not collected in this survey because this survey focused on collecting information relevant for determining the agronomic aspects, such as soil fertility and farm management practices, that might limit shallot growth and bulb yield. Site characteristics are described in Table 3.1.

Table 3.1. An overview of the site characteristics in the survey experiment.

	District 1. Babakan (Cirebon Regency) Main soil type: Alluvial Village: Karangwangun and Babakan Altitude: 0-32 m above sea level Period of the survey: 2-7 February 2018 Predominant shallot cultivar: Bima Annual rainfall: 1800 mm/year (Regency average) T min: 22.5ºC T max: 35.5ºC
	District 2. Losari (Cirebon Regency) Main soil type: Alluvial Village: Losari Lor and Mulyasari Altitude: 0-20 m above sea level Period of the survey: 8-12 February 2018 Predominant shallot cultivar: Bima Average rainfall: 1800 mm/year (Regency average) T min: 22.5ºC T max: 35.5ºC
	District 3. Bayongbong (Garut Regency) Main soil type: Andisol Village: Sukamanah and Karyajaya Altitude: 1100-1250 m above sea level Period of the survey: 3-7 January 2018 Predominant shallot cultivar: Tuk-tuk Average rainfall: 2589 mm/year (Regency average) T min: 24.0ºC T max: 27.0ºC

	District 4. Pacet (Bandung Regency) Main soil type: Inceptisol and Andisol Village: Sukarame and Mandalahaji Altitude: 1000-1150 m above sea level Period of the survey: 10-15 December 2017 Predominant shallot cultivar: Sumenep Average rainfall: 2000 mm/year (Regency average) T min: 21.0^{o}C T max: 28.0^{o}C

3.2.2. Soil analysis

Soil samples were also collected from the farmers' fields who were participating in the survey activity and from areas that had been used to grow shallots approximately within the last year. The sampling technique used a corer to collect 16 soil cores (0-20 cm depth) randomly from each farmer's field, bulked together to provide a single soil sample per participating farmer. In total, 100 soil samples were collected from the farmers' fields. Soil samples were analysed for pH, plant available-phosphorus (P) (Bray1-P), exchangeable basic cations and sulphate. The method of soil analysis is provided in Chapter 2.

3.2.3. Questionnaire

A questionnaire-based study was designed to explore the association between crop management practices and shallot bulb yield complied with Massey University's Code of Ethical Conduct (Application number: 4000018614). This survey discussed many crop management elements: fertiliser application, pest and disease control, shallot varieties used, and agronomic practices, like plant spacing, achieved bulb yields, and other factors. Initially, the questionnaire was tested with five shallot farmers in the Bandung Regency, and the structure was adapted based on their feedback. The questionnaire was written in Bahasa Indonesian and sometimes translated into *Bahasa Sunda,* the regional language in West Java. Photos of common pests and diseases symptoms were used to help the identification of pest and disease incidence (Appendix 3.1). The full English version of the questionnaire is in Appendix 3.2.

3.2.4. Data analysis

Data from the survey activity was recorded and analysed using Microsoft Excel and Minitab 18. Box plot was used to determine the differences between districts. The correlation coefficient (r) and regression (R^2) were used to identify variables that appear to affect shallot productivity significantly. While a correlation does not confirm a cause of observation, it assists in identifying possible factors that warrant further investigation.

3.3. Results and Discussion

3.3.1. Site overview

The yield results showed a wide variation in the average shallot fresh bulb yields for these four districts, ranging from 5.4 to 12.2 t ha^{-1}. The Babakan District had the highest average yield (average fresh bulb yields 12.2 t ha^{-1}), and the Pacet District had the lowest average yield (average fresh bulb yields were 5.4 t ha^{-1}, Figure 3.5). In comparison, the average bulb yield for Indonesia is 10.0 t ha^{-1}. Within each district, there was also a wide variation in yields between individual farmers. For example, in the Bayongbong District (average fresh bulb yields 7.65), the yield ranged from 3.5 to 14.7 t ha$^{-1,}$ potentially due to local differences in crop soil fertility and management. The wide variation in the district might also be affected by environmental conditions and shallot cultivar differences. Pacet farmers planted the Sumenep variety, Bayongbong farmers planted the Tuk-tuk variety, Babakan and Losari farmers planted the Bima variety. They choose the variety based on tradition, adaptation and market demand that is specific for each area. The differences between and within districts are discussed in the following sections.

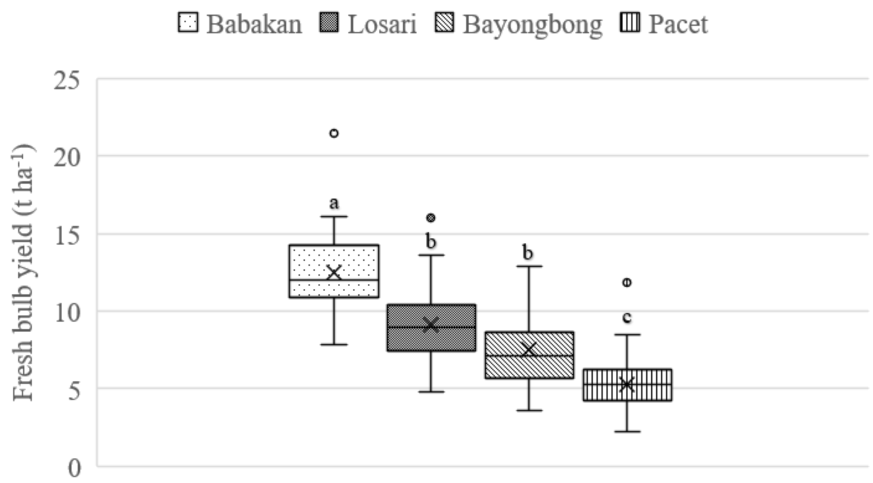

Figure 3.5. Summary of the fresh bulb yields (t ha^{-1}) from farms survey in each of the four districts. The lower and upper box lines indicate lower (Q1=25%) and upper (Q3=75%) quartile of data, respectively, and the centre line provides the median value for each box plot: the wide box, IQR=Q3-Q1. The lower whisker indicates the minimum value (Q1-1.5IQR), and the upper whisker indicates the maximum value (Q3+1.5IQR). The ‘x' marks the mean value. The circles show outlier values (<Q1-1.5IQR or >Q3+1.5IQR). Tukey’s method for means comparison; means presenting the same letters in the same column are not significantly different at α= 5%.

3.3.2. Soil analysis

Soil samples were collected during survey activity up to a year after shallot crops were grown, from which the yield data was obtained. The time gap between these activities can potentially affect the relationship between the soil analysis results and shallot bulb yield. However, the purpose of this survey is to identify the possible causes of the low yield rather than develop the direct relationship between soil fertility and bulb yield.

Soil pH

There was wide variation in the soil pH averages, ranging from 4.9 to 6.8 amongst the four districts. The Losari District had the highest average soil pH, and the Pacet District had the lowest average soil pH (Figure 3.6). Both the Pacet and Bayongbong Districts had average pH values that were strongly acidic and below the optimum level, 5.5 (Hemphill and McReynolds (1987). There was also a wide variation of soil pH value within each district. For example, the soil pH values for the Pacet District ranged from 4.1 to 6.1, but the majority of the farms assessed in this district had soil pH values below 5.5. The soil pH ranged from 5.6 to 7.8 in the Losari District, above the minimum optimum soil pH. All the farms assessed in the Babakan District also had soil pH values above 5.5 because the soils are mostly alluvial and commonly neutral. Alluvial soils in West Java have high natural fertility because their parent materials are derived from recent river deposits (Edelman & Van der Voorde, 1963).

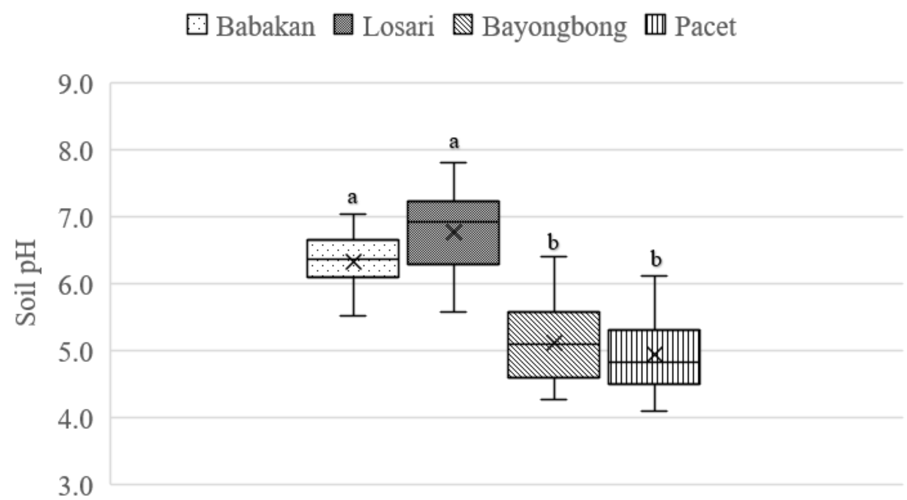

Figure 3.6. Summary of the soil pH_{H2O} values of farms surveyed in each of the four districts. Tukey's method for means comparison; means presenting the same letters in the same column are not significantly different at $\alpha = 5\%$.

There is a general trend of lower fresh shallot bulb yields at low-pH soil sites, with most of the farms with soil pH values of below 5.5 also having low yields of below 10 t ha^{-1}, which were all farms from the Pacet and Bayongbong Districts (Figure 3.7). Van Lierop et al. (1980) reported that when soil pH was below 5.5, onion plants produced a smaller bulb yield. Ilham et al. (2019) reported that shallot failed to bulb in extremely acidic conditions, and the bulb yield of shallot increased from 0.0 to 5.5 t ha^{-1} when the soil pH increased from 3.69 to 4.76. Sumarni, Rosliani, et al. (2012b) also reported that shallot bulb yield in alluvial (soil pH 6.3) soils were higher than Inceptisol (soil pH 5.5) and Ultisol (soil pH 4.3), which had bulb yields of 10.2, 6.0 and 1.4 t ha^{-1}, respectively. Soil acidity (soil pH < 5.5) has also been determined as a limiting factor on onions production (Sullivan et al., 2001). However, most of the Losari District farms also had yields below 10 t ha^{-1} even though all soil pH values were above 5.5. The low yields potentially indicate that there are likely other factors (e.g. soil fertility and/or environment) that are more limiting than soil pH at most of the farms surveyed in this region. Only in the Babakan District did most of the farms have soil pH values above 5.5 and yields above 10 t ha^{-1}.

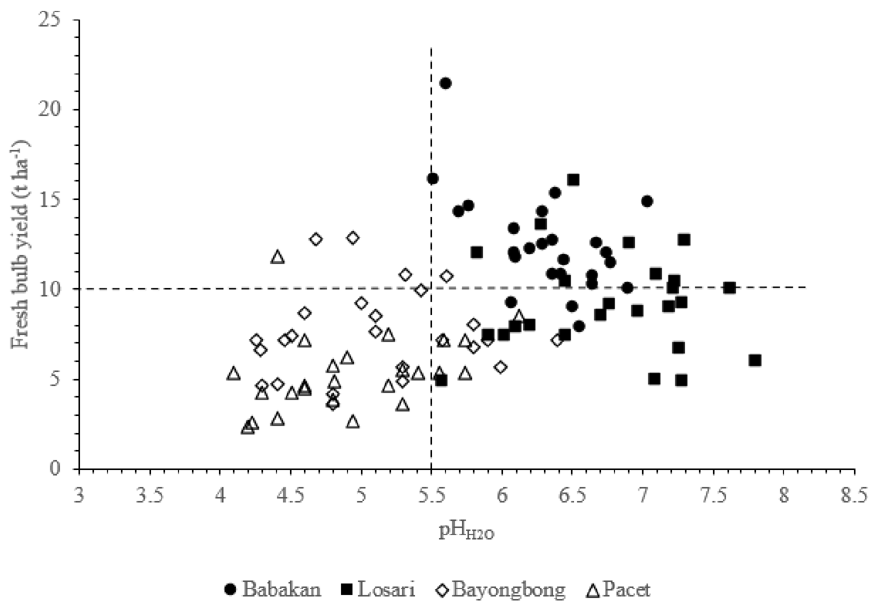

Figure 3.7. Fresh bulb yield (t ha^{-1}) in relation to soil pH_{H2O} across the districts, n= 100.

Soil available-P

There was a wide range in the district average soil plant-available P concentrations, as measured by the Bray1-P test (Figure 3.8). The highest district average was for the Babakan District of 96 mg P kg$^{-1,}$ and the lowest average was for the Pacet District, 15 mg P kg^{-1}. Losari and Bayongbong Districts also have high average values of 70 and 75 mg P kg^{-1}. Shallot bulb yield is not expected to appreciably be influenced by further increases in P availability when the soil P availability was high (Bray1-P > 40 mg P kg^{-1}). At the same time, it would have a significant effect when the soil P availability was low (Bray1-P< 20 mg P kg^{-1}) (Khokhar, 2019). Only the farm's survey in the Pacet District had an average value lower than 20 mg P kg^{-1}. There was also a very wide range in Bray1-P values for individual farms within each district. In the Bayongbong District, the variation in values was extremely high and was not distributed normally, ranging from 7 to 137 mg P kg^{-1}.

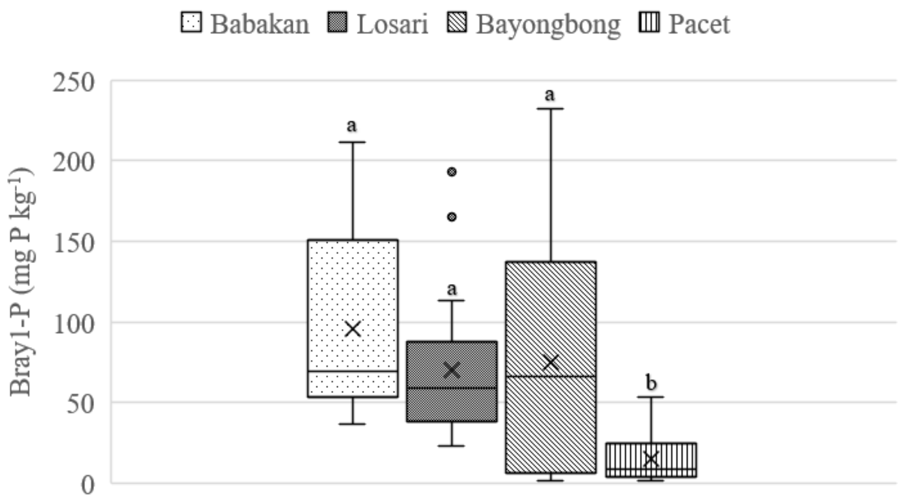

Figure 3.8. An average of plant available-P (Bray1-P) (mg P kg^{-1}) in each district. Tukey's method for means comparison; means presenting the same letters in the same column are not significantly different at α= 5%. Therefore, the five values higher than 400 mg P kg^{-1} were excluded from the Bayongbong data set. In addition, two values higher than 85 mg P kg-1 were excluded from the Pacet data set because the values were an extreme outlier.

Figure 3.9 shows that almost all farms with Bray1-P values below 20 mg P kg^{-1} had low bulb yields below 10 t ha^{-1}, mostly farms in the Pacet District. For farms with Bray1-P values above 20 mg P kg^{-1}, a little under half still had yielded less than 10 t ha^{-1} in the Losari, Bayongbong and Pacet Districts. Therefore, other factors are more limiting to bulb yield for many farms than soil P availability. However, more than half of the farms with Bray1-P values above 40 mg P kg^{-1} had high bulb yields above 10 t ha^{-1}. Overall, these results indicate a very low likelihood of a farm having a high shallot yield when Bray1-P values are below 40 mg P kg^{-1}. Above this level of available P, the possibility of high yields increases to greater than 50%. These results support the routine use of the Bray1-P soil test, with a value below 20 mg P kg^{-1}

that might indicate P is likely to be a limiting yield and soil available P target is expected in the range between 20 to 40 mg P kg^{-1}.

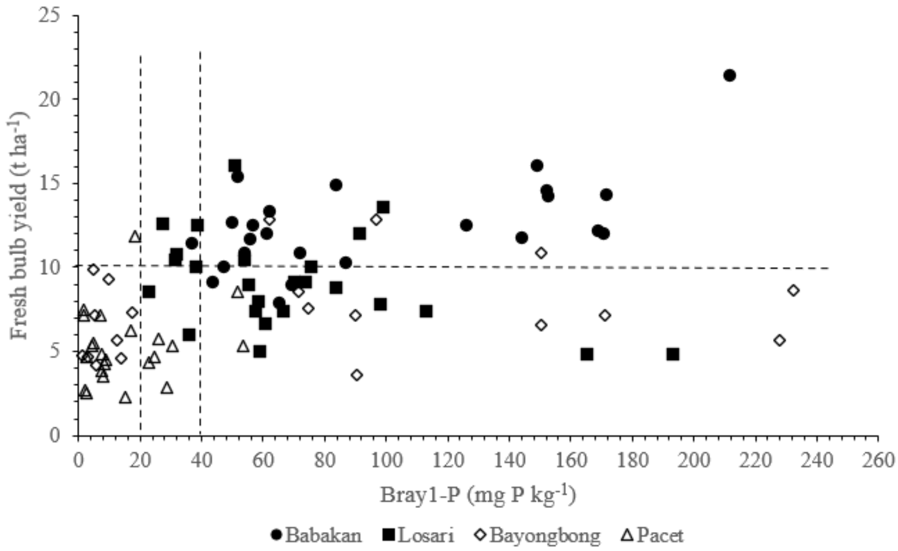

Figure 3.9. Fresh bulb yield (t ha^{-1}) in relation to Bray1-P (mg P kg^{-1}) across the districts, n= 93. Five values higher than 400 mg P kg^{-1} were excluded from the Bayongbong data set, and two values were higher than 85 mg P kg^{-1} was excluded from the Pacet data set because the values were extreme outliers.

Basic Cations, CEC, and Base Saturation

According to the concentration of exchangeable Ca^{2+}, there were two groupings for the four districts, high and low concentrations of exchangeable Ca^{2+} (Figure 3.10). Both Babakan and Losari Districts had high exchangeable Ca^{2+} (an average exchangeable Ca^{2+} of 29.9 and 30.5 cmol (+) kg^{-1-}, respectively). In comparison, Bayongbong and Pacet Districts had low exchangeable Ca^{2+} (an average exchangeable Ca^{2+} 7.8 and 5.5 cmol (+) kg^{-1}, respectively). The Losari District had the highest average concentration of $Ca^{2+,}$ and Pacet District had the lowest average concentration of exchangeable Ca^{2+}. The concentration of exchangeable Ca^{2+} in soil solution is strongly influenced by soil pH and lime application. Babakan and Losari Districts are neutral or alkaline soil pH. Therefore, Ca^{2+} dominates the CEC in this soil type, with high exchangeable Ca^{2+} in soil solution. On the other hand, Bayongbong and Babakan are acidic soils, where Al^{3+} dominates the CEC (Havlin et al., 2014). In acidic soils, the high concentration of exchangeable acidity can induce Ca deficiency and reduce Ca uptake (Sumner et al., 1988).

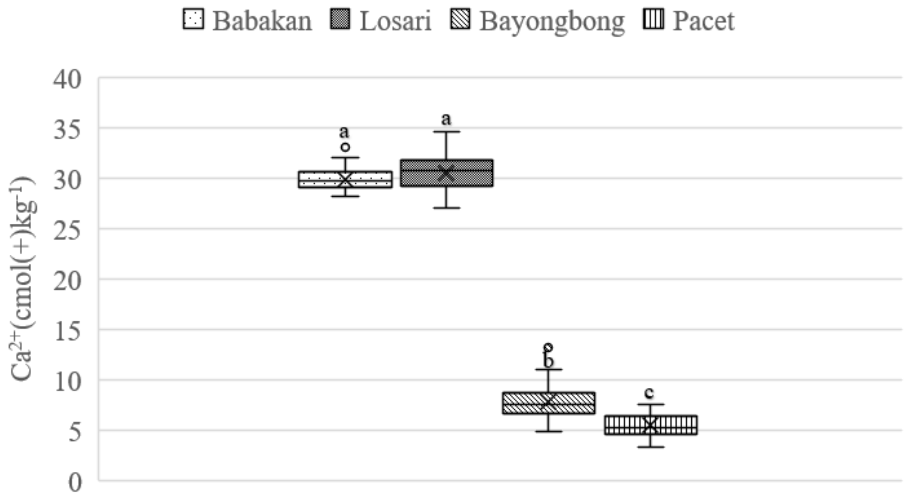

Figure 3.10. An average of exchangeable Ca^{2+} (cmol (+) kg^{-1}) in each district. Tukey's method for means comparison; means presenting the same letters in the same column are not significantly different at α= 5%.

There was wide variation in the average exchangeable Mg^{2+} in Bayongbong and Pacet Districts but not in Babakan and Losari Districts (Figure 3.11). The Pacet District had the highest average of exchangeable Mg^{2+}, and Babakan District had the lowest average of exchangeable Mg^{2+}. The Bayongbong and Pacet Districts had average exchangeable Mg^{2+} above 1.5 cmol (+) kg^{-1}, while Babakan and Losari Districts had average exchangeable Mg^{2+} below 1.5 cmol (+) kg^{-1}.

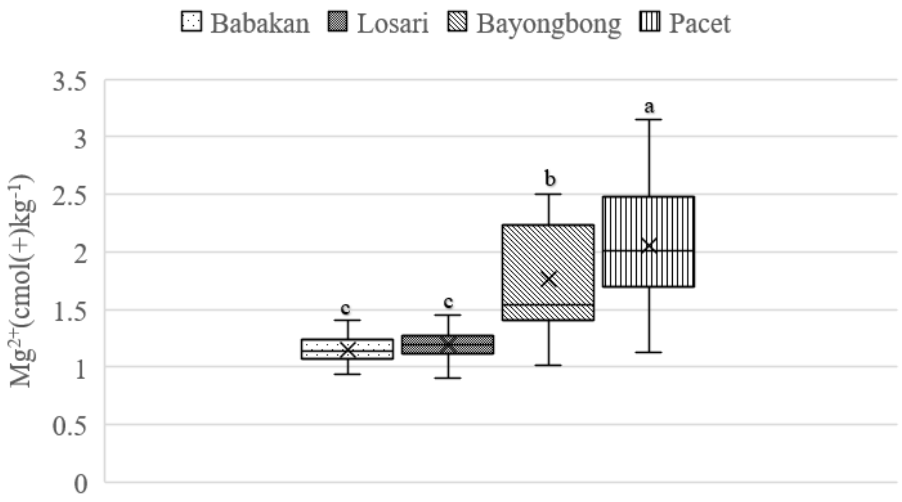

Figure 3.11. An average of exchangeable Mg^{2+} (cmol (+) kg^{-1}) in each district. Tukey's method for means comparison; means presenting the same letters in the same column are not significantly different at α= 5%.

Generally, Mg deficiency symptoms occur when the concentration of Mg^{2+} is less than 25-50 ppm or about 2.1-4.2 cmol (+) kg^{-1} (Havlin et al., 2014). However, the response varied on plant species and soil types. For example, the concentration of exchangeable Mg^{2+} in Babakan and Losari Districts was lower than 2.10 cmol (+) kg^{-1}. In contrast, more than half of Bayongbong farms had a low concentration of exchangeable Mg^{2+} as well.

The concentration of exchangeable Mg^{2+} has a negative correlation to Ca^{2+}. The high concentration of exchangeable Ca^{2+} in Babakan and Losari Districts resulted in a low concentration of exchangeable Mg^{2+} in those districts, which increased the Ca:Mg ratio (Figure 3.12). Increasing exchangeable Ca^{2+} in soil solution also reduced the plant uptake of Mg^{2+} (Fageria, 2001). Commonly, in many crops and soil types, magnesium deficiency symptoms occur when the Ca:Mg ratio is higher than 15 (Havlin et al., 2014). In this study, Babakan and Losari Districts had a higher proportion of neutral or alkaline soils with a high concentration of Ca^{2+} that increased the Ca:Mg ratio (Ca:Mg >15). While Bayongbong and Pacet Districts are acidic soils with a low concentration of Ca^{2+} and low Ca: Mg ratio (Ca:Mg < 10). Therefore, a low Ca:Mg ratio may indicate calcium deficiency problems, while a high Ca:Mg ratio may indicate magnesium deficiency.

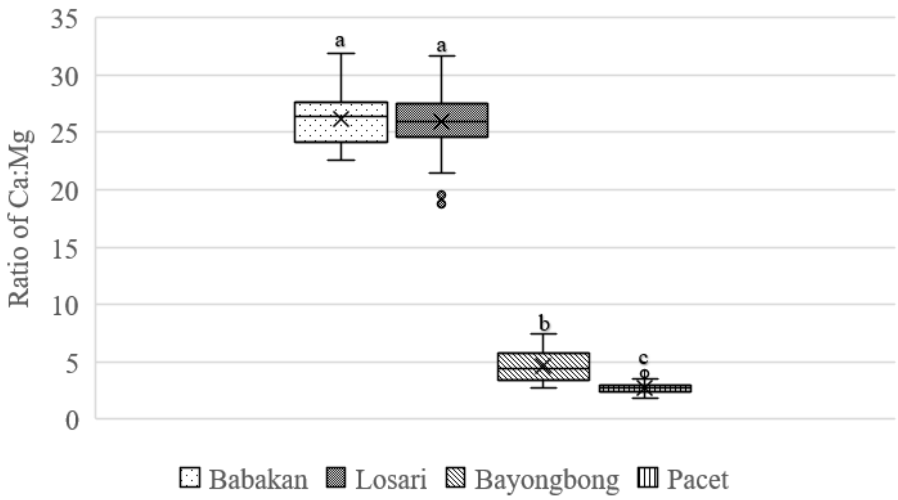

Figure 3.12. An average Ca:Mg ratio in each district. Tukey's method for means comparison; means presenting the same letters in the same column are not significantly different at α= 5%.

There is no general trend of exchangeable Ca^{2+} concentration and bulb yield (Figure 3.13). Babakan and Losari Districts had a high concentration of exchangeable Ca^{2+} (from 27 to 34.6 cmol (+) kg^{-1}), however, the bulb yield varied widely in those soils (from 4.8 to 21.4 t ha^{-1}). Bayongbong and Pacet Districts had a low concentration of exchangeable Ca^{2+} (from 3.3 to 13.2 cmol (+) kg^{-1}) but also had a high variation in bulb yield (from 2.3 to 12.9 t ha^{-1}).

Generally, most crops grow well in soils with 15 ppm or about 0.75 cmol (+) kg^{-1} of Ca^{2+} (Havlin et al., 2014). In this survey, all the areas had a Ca^{2+} concentration above 0.75 cmol (+) kg^{-1}, which would suggest that Ca^{2+} availability may not have a limited shallot yield at any of the farm sites. However, at low soil pH, the high exchangeable Al^{3+} levels may contribute to Ca^{2+} deficiency. One of the Ca deficiency symptoms is dieback or tip burn of leaves (Figure 3.14). This symptom was found in upland regions, especially Pacet. Further investigation is needed to understand the limitation of Ca^{2+} on shallot growth and bulb yield.

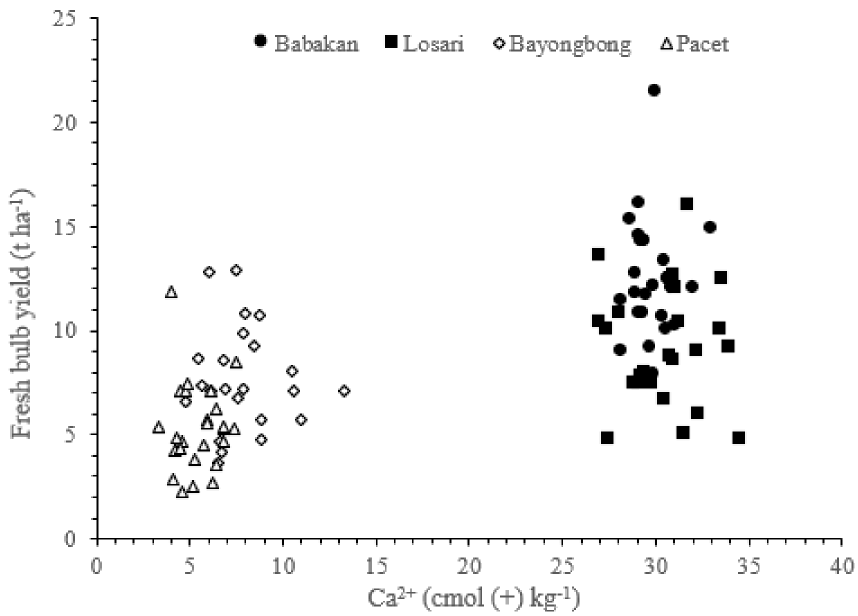

Figure 3.13. Fresh bulb yield (t ha^{-1}) in relation to exchangeable Ca^{2+} (cmol (+) kg^{-1}) in all districts, n= 100.

Figure 3.14. Tip burn is a typical Ca deficiency symptom in shallot. The picture was taken from the farmer's field in Pacet regions during survey activity.

There is no general trend of exchangeable Mg^{2+} and bulb yield in all districts (Figure 3.15). However, farms with exchangeable Mg^{2+} concentrations less than 1.5 cmol (+) kg^{-1} generally had better bulb yields than farms with exchangeable Mg^{2+} more than 1.5 cmol (+) kg^{-1}. Khokhar (2019) summarised that the medium range for exchangeable Mg^{2+} was about 0.49 to 0.82 cmol (+) $kg^{-1,}$ and exchangeable Mg^{2+} more than 2.50 could be categorised as a high or excessive. The high level of Mg^{2+} reduces the Ca:Mg ratio that might lessen the calcium uptake.

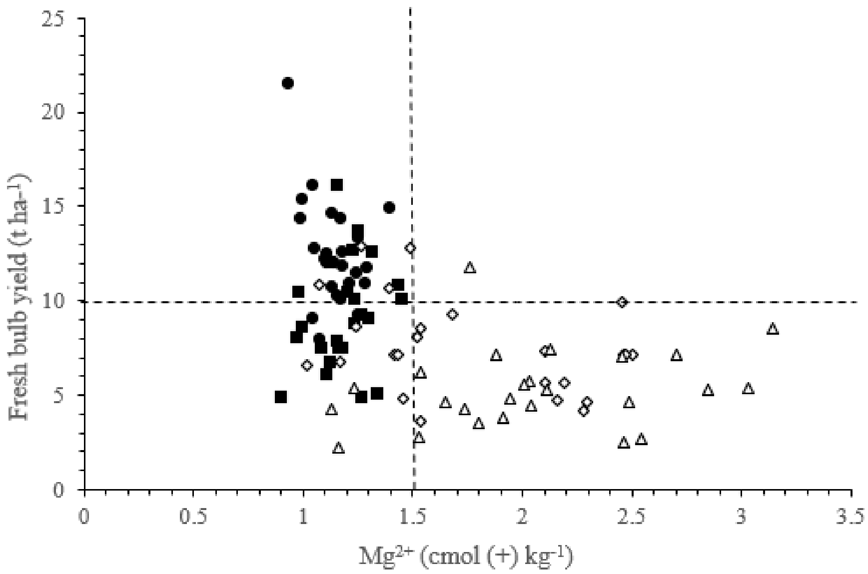

Figure 3.15. Fresh bulb yield (t ha^{-1}) in relation to exchangeable Mg^{2+} (cmol (+) kg^{-1}) in all districts, n= 100.

While the ratio was quite variable, it did not appear to limit bulb yield strongly (Figure 3.16), consistent with another author that onion bulb yield significantly reduced when the Ca:Mg ratio was lower than 0.5 (Van Lierop et al., 1979). However, in this survey, the Ca:Mg ratio was above 0.5 in all districts; therefore, it is unlikely that the Ca:Mg ratio was a limiting factor for bulb yield.

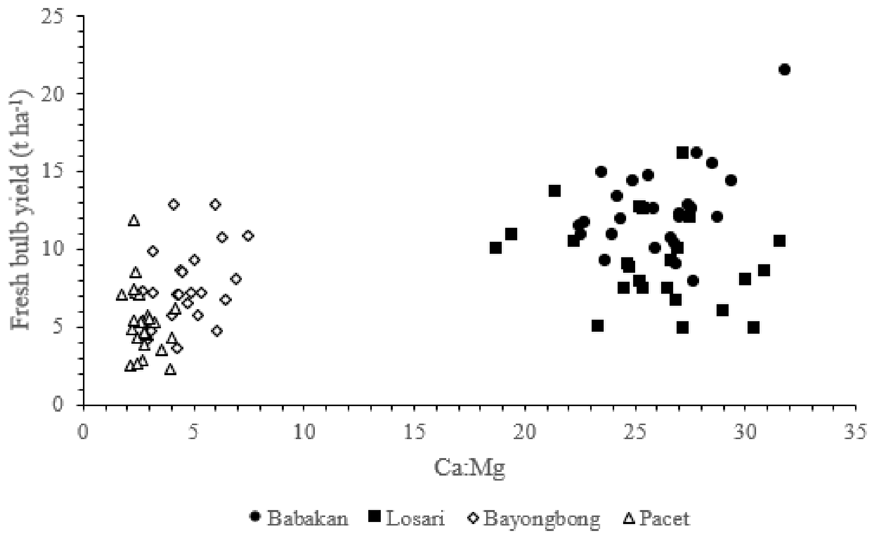

Figure 3.16. Fresh bulb yield (t ha^{-1}) in relation to Ca:Mg ratio across the districts, n= 100.

The Bayongbong District had the highest average concentration of exchangeable K^+ (1.29 cmol (+) kg^{-1}), and the Pacet District had the lowest average concentration of exchangeable K^+ (0.61 cmol (+) kg^{-1}; Figure 3.17). While the district averages are considered medium to high, there were individual farms with soil K status that was low (< 0.5 cmol (+) kg^{-1}). Most of the farms with low soil exchangeable K^+ levels were in the Pacet District. About 25% of farms in this district had low soil K.

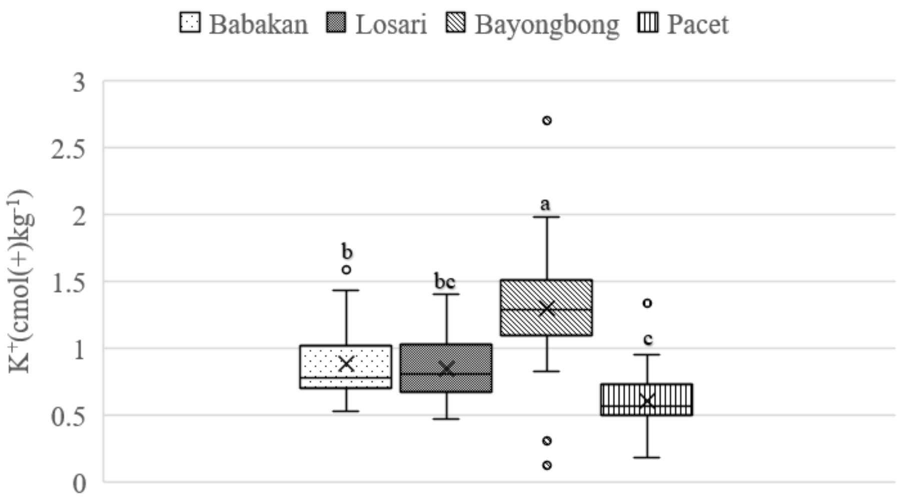

Figure 3.17. An average of exchangeable K^+ (cmol (+) kg^{-1}) in each district. Tukey's method for means comparison; means presenting the same letters in the same column are not significantly different at α= 5%.

There was no correlation between exchangeable K^+ status and shallot bulb yield in all districts (Figure 3.18). Potassium availability did not appear to be a primary key factor influencing bulb yield, which is expected for the farms surveyed in the Babakan, Losari and Bayongbong Districts because soil exchangeable K^+ levels were either medium or high. However, there was no evidence of a relationship between exchangeable K^+ and shallot bulb yield in the Pacet District, even though five farms surveyed had low soil K status, possibly due to other factors being more limiting than K in this district. Most of the farmlands with medium and high soil K status in this district also had low yields. Potassium fertiliser addition responses have been observed in other studies, where K was a primary crop growth-limiting factor. G. E Boyhan et al. (2007) reported that K fertiliser recommendations for low K (exchangeable $K^+ < 0.5$ cmol (+) kg^{-1}) was 112 kg K ha^{-1}. In another study, the application 50-150 kg K ha^{-1} improved shallot bulb yield when the initial K concentration was low (exchangeable $K^+ = 0.44$ cmol (+) kg^{-1}) (Amin et al., 2007). Aftab et al. (2017) observed that K fertiliser's application increased shallot growth, bulb diameter, and bulb weight. Potassium involves NO_3^- uptake as an accompanying cation. A high concentration of exchangeable K^+ can decrease Ca, Mg and P uptake (Fageria, 2001). Those farms in the Pacet District with low soil K status would likely benefit from K fertiliser addition. However, correcting other limiting factors first, such as soil pH and soil P and N availability, will increase the bulb yield. There is no general trend of bulb yield and the concentration of exchangeable Na^+ in all districts.

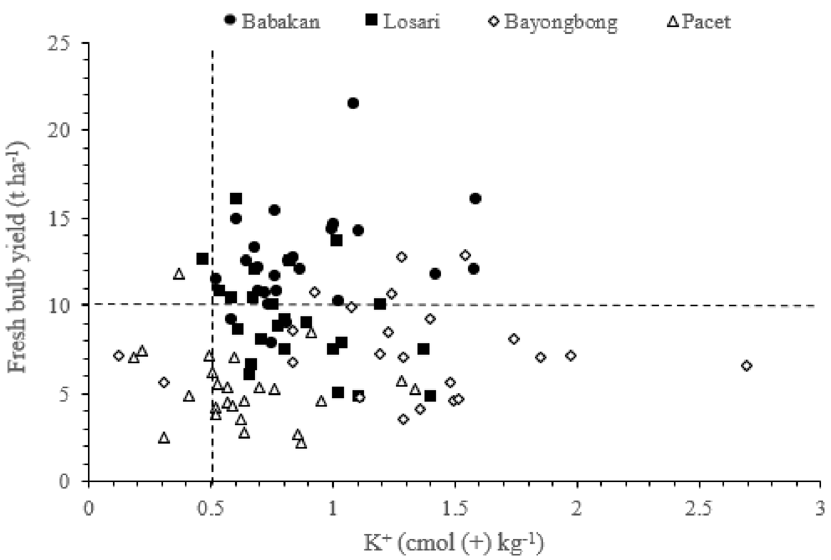

Figure 3.18. Fresh bulb yield (t ha^{-1}) in relation to the concentration of exchangeable K^+ (cmol (+) kg^{-1}) across the districts, n = 100.

Losari District had the highest average concentration of exchangeable Na^+, with the widest variation in values. In contrast, Pacet District had the lowest average concentration of exchangeable Na^+, with the slightest variation in values (Figure 3.19). The Bayongbong District had an average exchangeable Na^+ similar to that of the Pacet District and had a minor concentration value variation. A high exchangeable Na^+ concentration in Losari District is likely due to the district's location near the coast. Sodium can be supplied in precipitation, and Na concentrations in rainfall increase with closer proximity to the coast because the sea provides a source of Na. In contrast, the Pacet and Bayongbong Districts are situated in mountain areas, further away from the coast. Therefore, Na^+ leaches intensively in upland areas due to a high weathering degree (Guicharnaud & Paton, 2006).

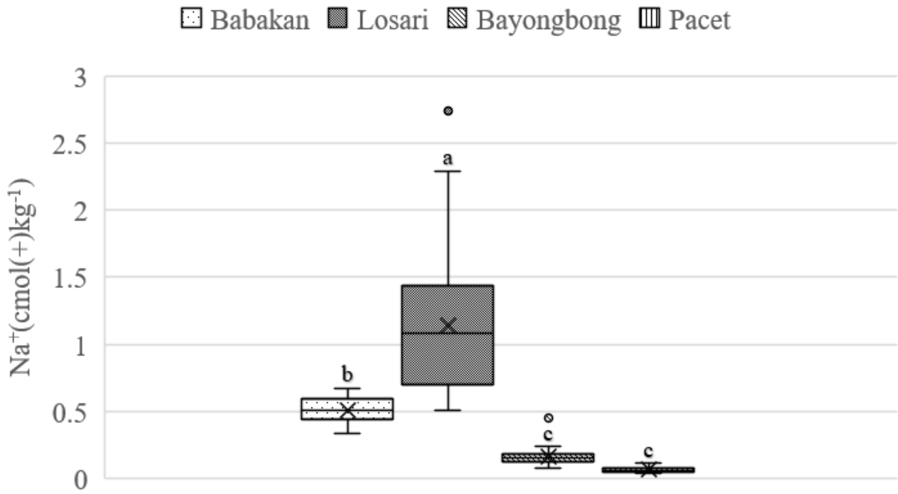

Figure 3.19. An average of exchangeable Na^+ (cmol (+) kg^{-1}) in each district. Tukey's method for means comparison; means presenting the same letters in the same column are not significantly different at α= 5%.

Pacet and Bayongbong Districts had a lower cation exchange capacity (CEC) and base saturation (BS) than Babakan and Losari Districts (Figure 3.20). Soil CEC is strongly affected by soil texture and organic material content. Soils with clay texture and high organic matter have higher CEC than sandy soils with low organic matter concentration (Havlin et al., 2014). Babakan and Losari Districts had a high percentage of clay (71 and 72%, respectively). In comparison, Pacet and Bayongbong Districts had a lower clay concentration, about 60 and 40%, respectively.

Soils with high CEC tend to be more fertile than those with low CEC due to the soil capacity to hold basic cations as essential nutrients. However, many crops can grow well in low CEC soils. The average CEC for Babakan and Losari Districts was 45.7 and cmol 45.1 cmol (+) kg^{-1}, while the average CEC for Bayongbong and Pacet Districts was 18 and 14 cmol (+) kg^{-1}. Onions have grown and produced well in Inceptisol soils in Brazil with an initial CEC of 13 cmol (+) kg^{-1} (Oliveira et al., 2016). Therefore, it seems that the CEC was not a limiting factor of shallot growth in surveyed areas. The average base saturation in Babakan and Losari Districts was 71 and 75%, significantly higher than Bayongbong and Pacet Districts, about 61 and 58%, respectively, influenced by soil pH. In general, base saturation increases when the soil pH increases.

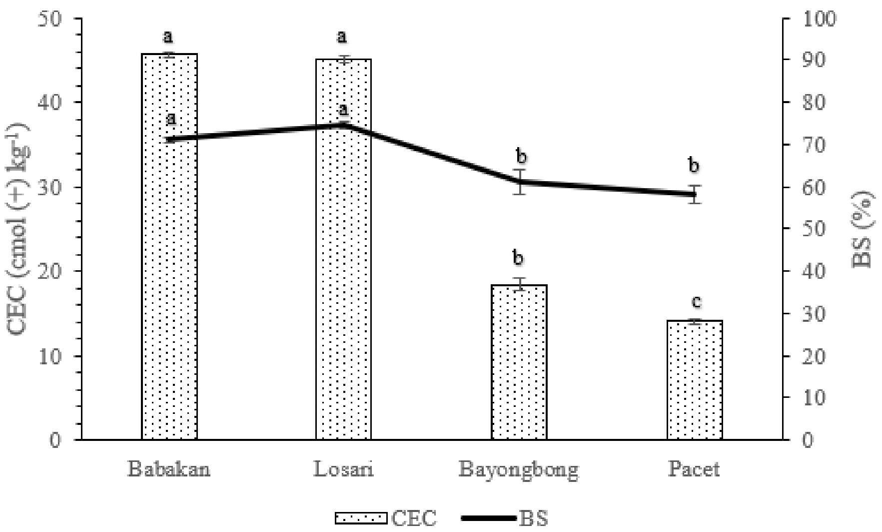

Figure 3.20. An average of CEC (cmol (+) kg^{-1}) and base saturation (%) in each district. Tukey's method for means comparison; means presenting the same letters in the same column are not significantly different at α= 5%.

Soil pH is positively correlated to base saturation in all districts (Figure 3.21). Acidic farmlands (soil pH < 6.0) had a low percentage of base saturation (%), which were primarily farms in the Bayongbong and Pacet Districts. Acidic soils commonly had a low base cation saturation because of the high concentration of acidic cations, such as aluminium (Al^{3+}) and manganese (Mn^{2+}), while the basic cations: calcium (Ca^{2+}), magnesium (Mg^{2+}), potassium (K^{+}) and sodium (Na^{+}), are in a low concentration. In more acidic conditions (soil pH < 5.5), base saturation increased linearly with increasing soil pH. However, above pH 5.5, a diminishing marginal increase was diminished, with minimal to slight changes above pH 6.5 (Babakan and Losari Districts). This observation follows the general relationship between soil pH and base saturation previously established (Sumner et al., 1991; Thomas, 1996).

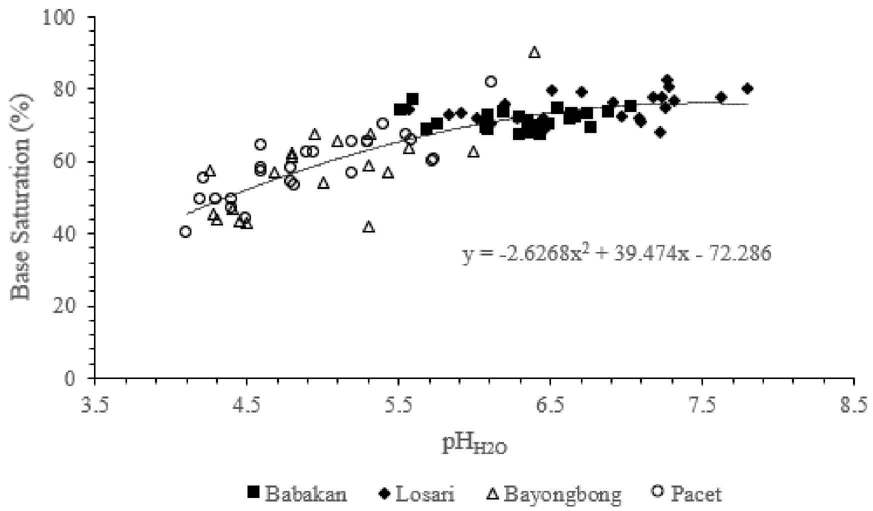

Figure 3.21. Base saturation (%) in relation to soil pH across the districts, R^2= 0.73, n= 100.

Sulphate-S

The district average for soil sulphate-S ranged from 18 to 52 ppm (Figure 3.22). The Bayongbong District had the highest average of sulphate S, and the Babakan District had the lowest value. Bayongbong District also had the largest variation in sulphate-S values compared to the other districts (range from 3 to 135 ppm). The high concentration of soil sulphate-S in the Bayongbong District may be due to a combination of high soil organic matter, ammonium sulphate fertiliser and high anion retention (as assessed by the P retention test). Also, acidic soils tend to have higher anion retention (Metson & Blakemore, 1978).

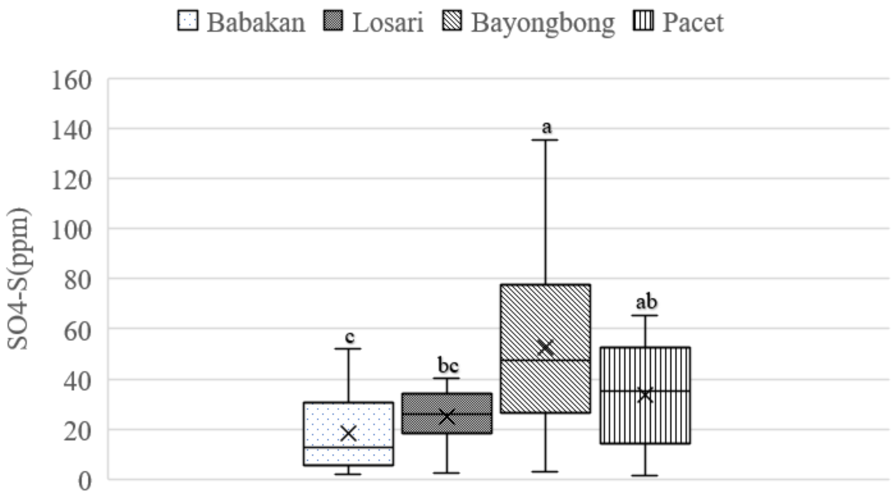

Figure 3.22. An average of sulphate-S (ppm) in each district. Tukey's method for means comparison; means presenting the same letters in the same column are not significantly different at α= 5%. Two values higher than 76 ppm were excluded from the Losari data set because the values were outside the range of the other samples (extreme outliers, more than Q3+3IQR).

There was no clear relationship between soil sulphate levels and shallot bulb yield (Figure 3.23). However, there was a large proportion of farms with high sulphate-S levels (> 10 ppm S), which had low bulb yields (< 10 t ha-^{1}). The relationship indicates that other factors are likely more yield-limiting than soil sulphate supply at these sites. However, a higher sulphate value may be preferred to increase bulb storage life and pungency, an essential quality characteristic for Indonesia's shallots (Reid & Morton, 2019). While increasing pungency in shallot is a desired characterised, this contrasts with growing in NZ, where the preference is to reduce the pungency of onions to produce a sweeter taste.

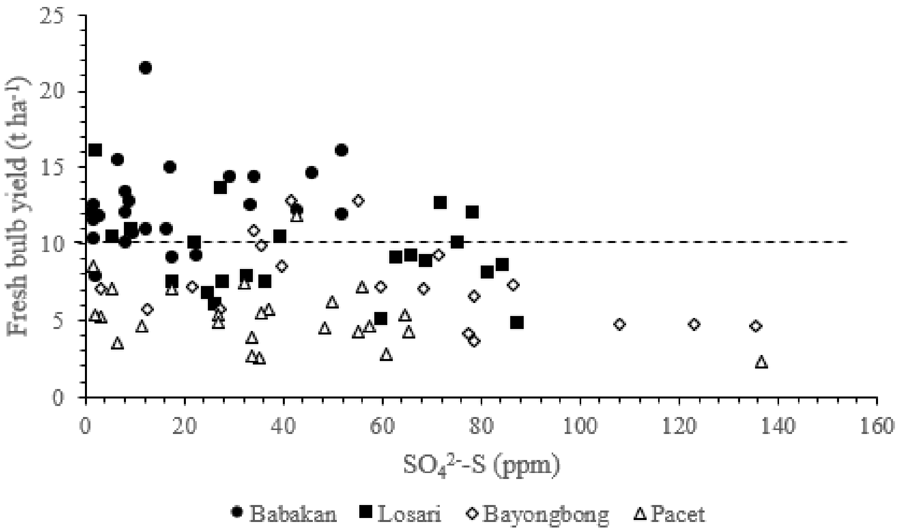

Figure 3.23. Fresh bulb yield (t ha^{-1}) in relation to sulphate-S (ppm) across the districts, n= 98.

3.3.3. Crop management practices

Lime use

The farmer's survey recorded that less than 50% of farmers applied lime before shallot cultivation in all districts (Figure 3.24). However, lowland farmers who used lime were higher than highland farmers. For example, about seven from 25 surveyed Babakan farmers used lime, followed by six farmers at Losari, two farmers at Bayongbong and one farmer at Pacet Districts.

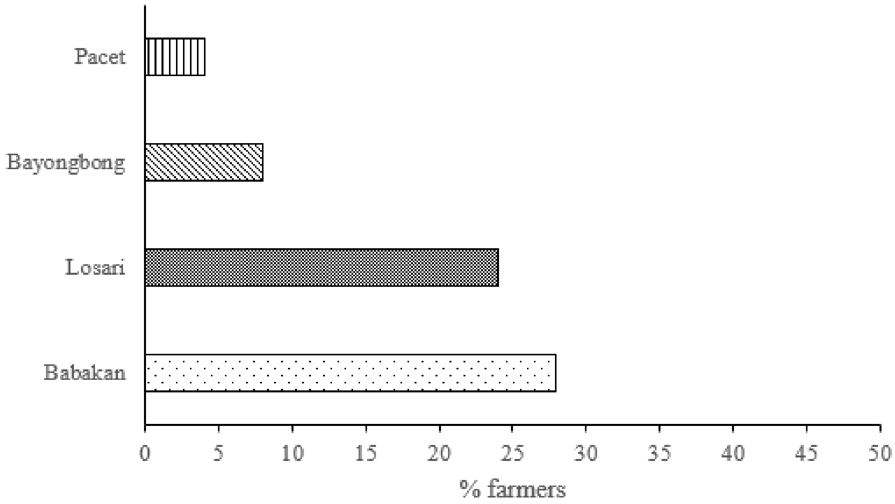

Figure 3.24. The percentage of farmers who used lime in each area.

On average, Bayongbong farmers used the highest rate of lime, 1.4 t ha^{-1}, followed by Losari (1.05 t lime ha^{-1}), Babakan (0.71 t lime ha^{-1}), and Pacet (0.6 t lime ha^{-1} lime). Pacet farmers used a low rate of lime due to the weight of the lime, where most of the farmlands are located on the hill, and minimum transportation access limits them to carry more lime. Moreover, an apparent lack of knowledge regarding the importance of soil pH on crop production contributes to the farmer's decision. Pacet farmers never analysed their soil properties, and they determined soil fertility based on visual cues, like soil colour, soil texture and weeds grown on the farm fields. For example, one of the Pacet farmers said that "The soil is less fertile if the colour was red or yellow, hard to plough (compact), and there was a lot of '*Alang-Alang*' (*Imperata cylindrica*) grown on the field. While the fertile soil is black, porous, easy to plough, and many broad leafy weeds were grown in the field".

Nitrogen fertiliser use

Generally, Losari, Bayongbong and Pacet farmers applied a high rate of nitrogen (N) fertiliser. A general recommendation for N fertiliser on shallots is 150 to 200 kg N ha^{-1} (Sumarni & Hidayat, 2005). On the other hand, the Babakan farmers applied the lowest N fertiliser at 120 kg N ha^{-1}. On average, Losari farmers used 182 kg N ha^{-1}, Bayongbong farmers about 235 kg N ha^{-1}, and Pacet farmers about 258 kg N ha^{-1} (Figure 3.25). Nitrogen was applied as ammonium sulphate, urea, and compound fertilisers (NPK).

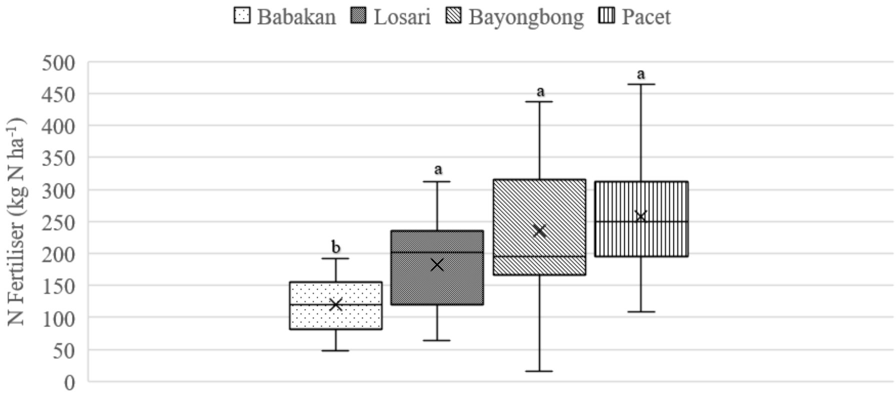

Figure 3.25. Nitrogen fertiliser use (kg N ha $^{-1}$) for surveyed farmers in each district. Tukey's method for means comparison; means presenting the same letters in the same column are not significantly different at α=5%. Two values higher than 585 were excluded from the Losari data set. One value higher than 762 kg N ha-1 was excluded from the Bayongbong data set, and two values more than 661 were excluded from the Pacet data set. The values were extremely outlier, more than Q3+3IQR.

All surveyed farmers split N fertiliser application into several applications. The majority of Losari and Pacet farmers split N fertiliser three applications; Pacet farmers applied N fertiliser split over a base fertiliser application and two additional fertilisers (the first and second supplementary fertiliser application). In contrast, Losari farmers used N fertiliser as additional fertiliser, the first, second and third supplemental fertiliser application. Babakan and Bayongbong farmers split N fertiliser application two times at first and second supplementary fertiliser application (Figure 3.26). Moreover, more than 40% of Pacet farmers also gave N in the third additional fertiliser application.

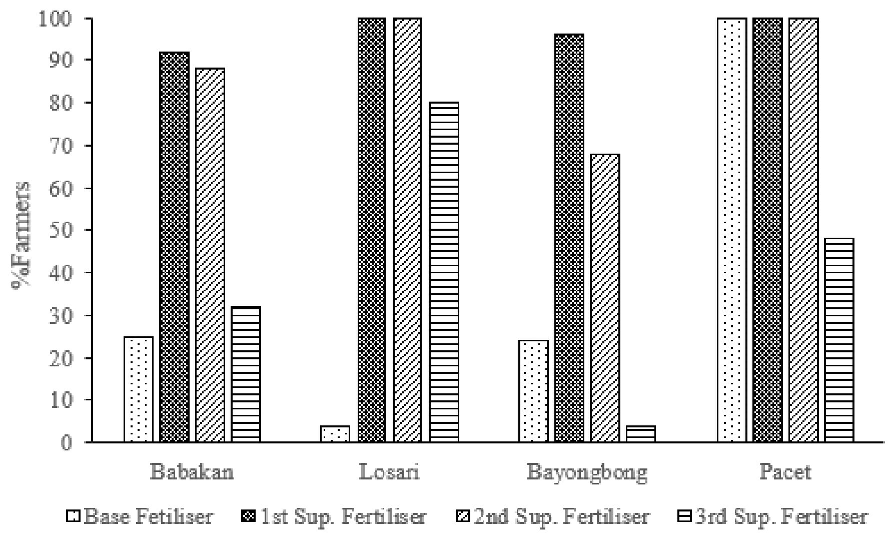

Figure 3.26. Percentage of surveyed farmers who used N fertiliser in each district and how these fertiliser applications were split.

On average, the Babakan and Bayongbong farmers applied base fertiliser three days before planting, Losari farmers applied five days before planting, and Pacet farmers applied base fertiliser at the time of planting. The first supplementary fertiliser application was applied ten days after planting for Babakan and Losari farmers, 17 days for Bayongbong farmers and 21 days for Pacet farmers. The second supplemental fertiliser application was given at 23, 22, 31 and 45 days after planting for Babakan, Losari, Bayongbong and Pacet farmers, respectively. The last (third) supplemental fertiliser application was given at 28, 30, 45 and 67 days for Babakan, Losari, Bayongbong and Pacet farmers, respectively. Pacet farmers applied the additional fertiliser quite later than other districts due to the physiology age of the Pacet farmers' variety. Sumenep has a longer physiology age than Bima and Tuk-tuk used in Babakan, Losari, and Bayongbong. The last supplementary fertiliser usually was applied in the bulbing stage of development about 14 to 20 days before the harvesting time.

Most of the surveyed farmers in all districts applied high N fertiliser rates in the first and second supplementary fertiliser applications (Figure 3.27). Thus, the farmer's application appears to be in line with the general recommendation suggesting applying N fertiliser two times, the first 10-15 days after planting and the second at 30 days after planting, each a half dose (Sumarni & Hidayat, 2005).

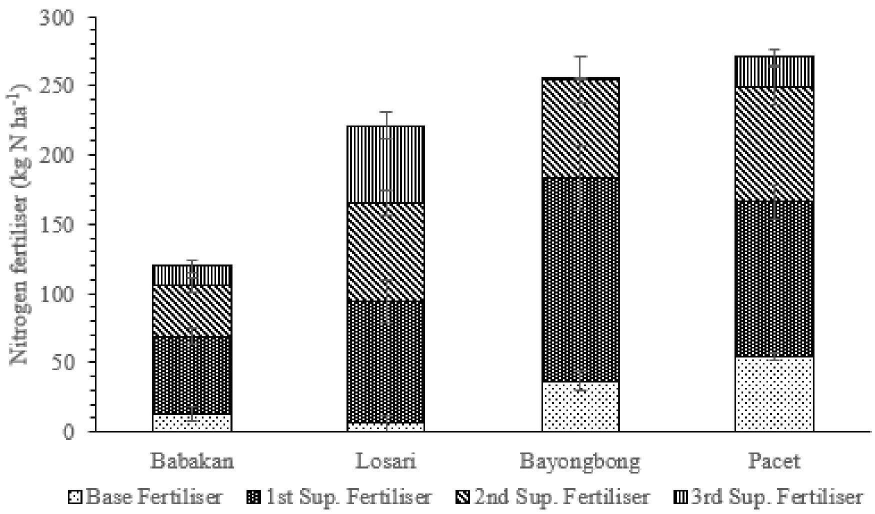

Figure 3.27. Nitrogen fertiliser rate (kg N ha $^{-1}$) per application of surveyed farmers in each district. Error bars are standard errors.

There was an apparent weak negative correlation between yield and N fertiliser use that when the N fertiliser was more than 200 kg N ha^{-1} a low bulb yield was more likely (Figure 3.28). A typical N fertiliser recommendation for onion bulb production was 125 to 200 kg N ha^{-1} (G. E Boyhan et al., 2007). Reduced yields in response to high N fertiliser have only previously been reported when excessive N fertiliser amounts were applied (> 390 kg N ha^{-1}) (Maier et al., 1990). Therefore, a more likely explanation here is that farmers who experienced low yields were adding more N in the hope of raising those yields, not realising that this strategy is effectively just a waste of their money. They need to identify and remove other limits to growth, such as low soil pH status.

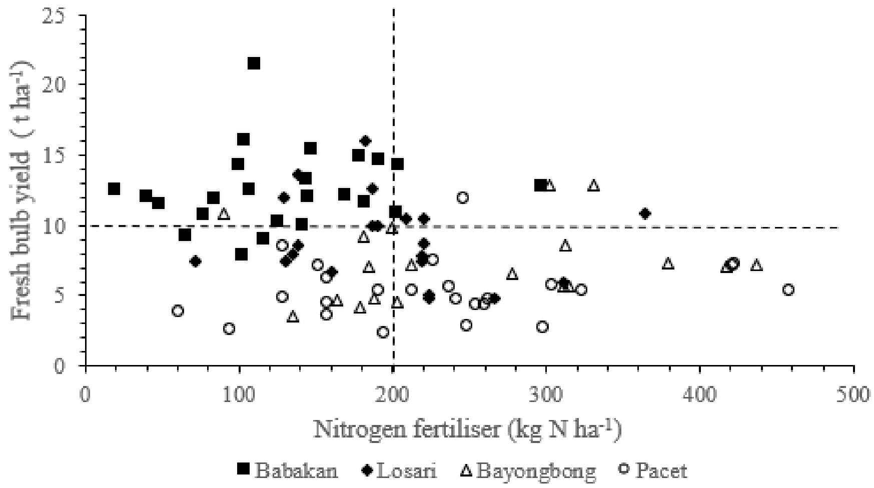

Figure 3.28. Fresh bulb yield (t ha^{-1}) in relation to N fertiliser rates (kg N ha $^{-1}$) across the districts, n = 95.

Phosphorus fertiliser use

Pacet farmers applied the highest amount of phosphorus (P) fertiliser compared to other districts (Figure 3.28). On average, Pacet farmers used 135 kg P ha^{-1}, followed by Bayongbong farmers by 90 kg P ha^{-1}, and Babakan farmers by 87 kg P ha^{-1} and Losari farmers by 71 kg P ha^{-1}. The general recommendation Phosphorus fertiliser rate on shallots is about 30 to 40 kg P ha^{-1} (Sumarni & Hidayat, 2005). It seems that most farmers in all districts applied a high rate of P fertiliser in comparison to the recommended level to remove growth limits and achieve the high bulb yield. However, this strategy seems ineffective to increase the shallot bulb yield. Phosphorus was applied as triple superphosphate (TSP), diammonium phosphate (DAP), single superphosphate (SSP), and compound fertilisers (NPK). A further investigation was needed to determine the optimal rate of P for shallot bulb yield.

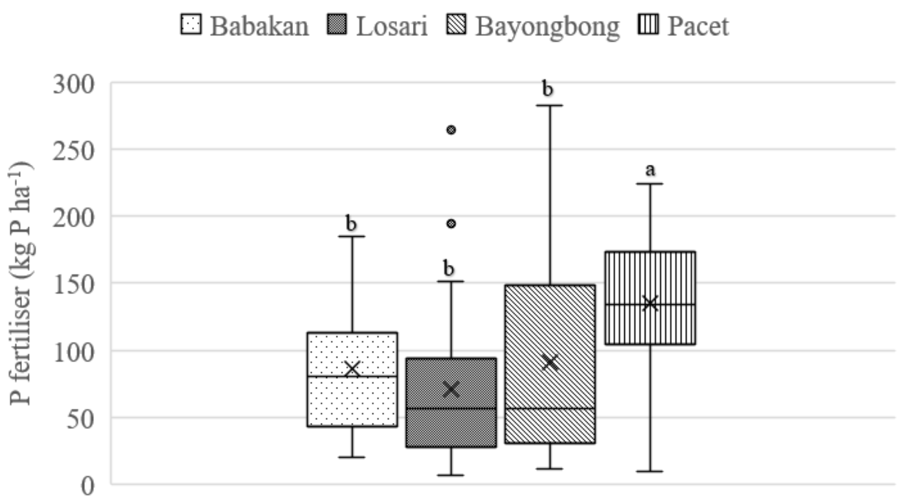

Figure 3.29. Phosphorus fertiliser use (kg P ha^{-1}) for surveyed farmers in each district. Tukey's method for means comparison is; means presenting the same letters in the same column are not significantly different at α= 5%.

Even though Pacet farmers applied high P fertiliser rates, the Pacet District had the lowest Bray1-P compared to the other districts (Figure 3.7). The factors that influence plant available-P include soil minerals, soil pH, cation and anion capacity, organic material, time, temperature, flooding and phosphate retention (Havlin et al., 2014). The Pacet District also had the lowest soil pH. Therefore, a high concentration of exchangeable acidity may involve the changing of plant available-P in soil solution. Moreover, phosphate retention in Pacet District might be higher than in other districts. On average, the phosphate retention in Pacet District was 52% (P retention 40—60%), which is considered a medium level of P retention.

Another possibility of the low soil available-P of Pacet District is Pacet's topography. Pacet District has a steep contour with a high slope of about 30^0 to 60^o that contribute to surface flow. Pacet farmers pressed the soil with wood sticks and put manure and P fertiliser as base fertiliser into the hole (Figure 3.30) one day before planting time. This practice is common in Indonesian upland growers and is called the '*tugal*' practice. The practice of creating shallow depression around the planting site was developed to avoid surface runoff and minimise the loss of applied fertiliser. However, farmers planted seed bulbs directly beside the fertiliser that might create local toxicity problems and interfere with the high salt concentration near the bulb. This practice also is very likely to involve the soil P sampling results due to P immobilisation. Nevertheless, this practice could be good to retain and positively impact if the fertiliser was applied at a low rate and incorporated with liming or other soil amendments that might remove the growth limits.

Figure 3.30. Phosphorus fertiliser mixed with manure beside the seed bulb at Pacet farms.

More than 50% of Babakan, Losari and Bayongbong farmers applied P fertiliser as additional fertiliser (Figure 3.31). Babakan and Bayongbong farmers split the application two times, while Losari farmers split the application three times. More than 50% of Pacet farmers also applied P fertiliser as a base fertiliser despite additional fertiliser. While the general recommendation for growing shallot, P fertiliser should be used only as a base fertiliser applied at 2 or 3 days before planting time (Sumarni & Hidayat, 2005).

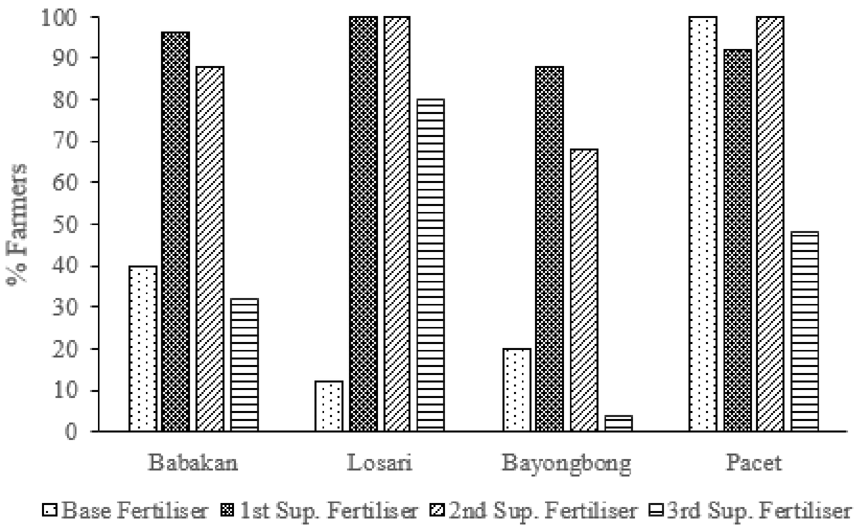

Figure 3.31. Percentage of surveyed farmers who used P fertiliser in each district.

The rate of P fertiliser application differed for each district. For example, Bayongbong, Babakan and Losari farmers applied a high P fertiliser rate in the first supplementary fertiliser application. In contrast, Pacet farmers used a high P in the base, before or during planting time and last supplemental fertiliser applications (Figure 3.32).

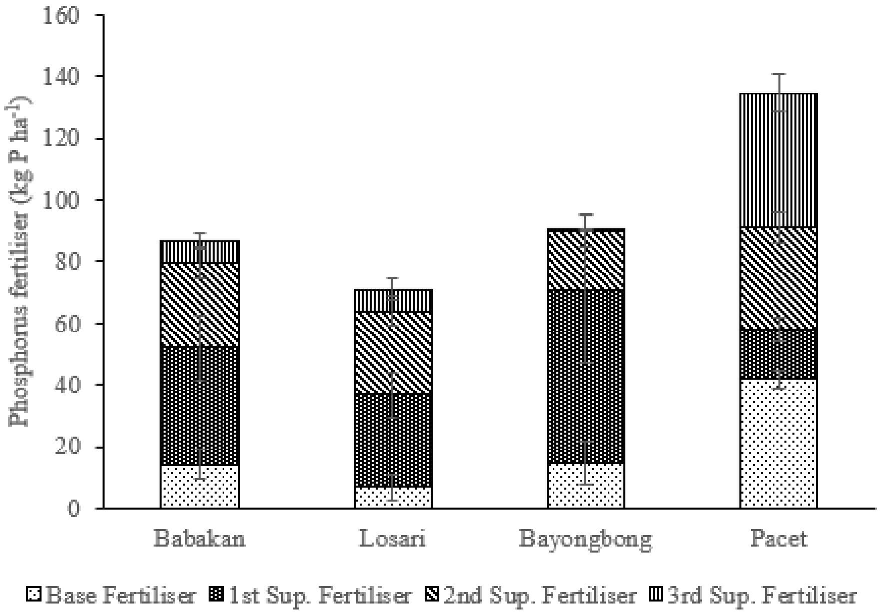

Figure 3.32. Phosphorus fertiliser rate (kg P ha^{-1}) per application used by surveyed farmers in each district.

There was no general trend between the P fertiliser rate and the fresh bulb yield for each district (Figure 3.33). While most farmers applied a high P fertiliser rate, there was a high variation in fresh bulb yield. Phosphorus fertiliser application will be significantly beneficial to soils with low soil available-P status, but not when the initial soil available-P was high. (Sopha et al., 2015) reported no significant effect on shallot bulb yield when the P fertiliser rate was 22 to 65 kg P ha^{-1} and the initial soil available-P was high. However, when the initial soil-available P was very low (Bray1-P < 20 mg P kg^{-1}), there was a linear relationship between the rate of P fertiliser application and bulb yield (Sumarni, Rosliani, et al., 2012a). In this survey, there was no apparent effect of P fertiliser use on bulb yield. In the Pacet District, for most farms with low soil P, high P fertiliser was used. There must be other soil factors limiting bulb yield. The soil samples were collected up to about a year after the shallot crop was grown, affecting the ability to establish a clear relationship between P fertiliser application and bulb yield.

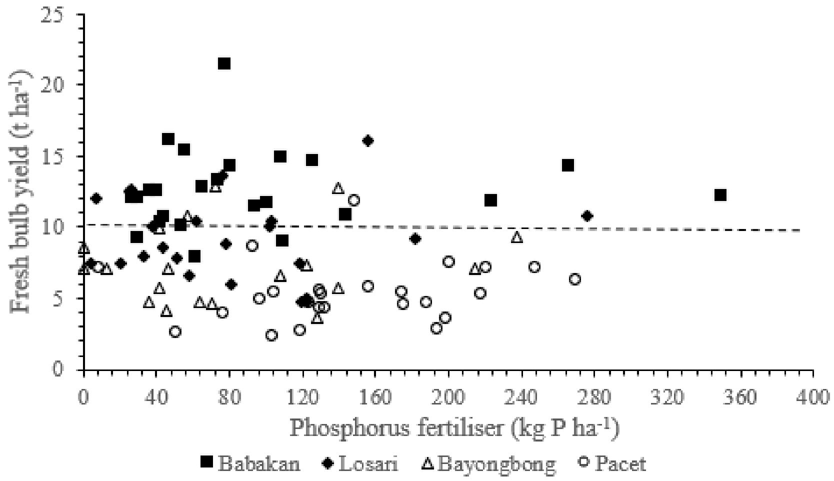

Figure 3.33. Fresh bulb yield (t ha^{-1}) in relation to P fertiliser rates (kg P ha^{-1}) across the districts, n= 100.

Potassium fertiliser use

The Losari district farmers applied the highest potassium (K) fertiliser, averaging 132 kg K ha^{-1}, compared with 120 kg K ha^{-1}, 117 kg K ha^{-1}, 77 kg K ha^{-1}for the Pacet, Babakan and Bayongbong districts, respectively. The general recommendation for applying K fertiliser for shallots is about 40 to 125 kg K ha^{-1} (Sumarni & Hidayat, 2005) (Figure 3.33). Most of the farmers surveyed in the Babakan and Bayongbong districts applied the K fertiliser rate within the recommended range. In contrast, most farmers in the Losari and Pacet districts applied the K fertiliser above this range. Potassium was applied as potassium chloride (KCl) and compound fertilisers (NPK, KNO_3).

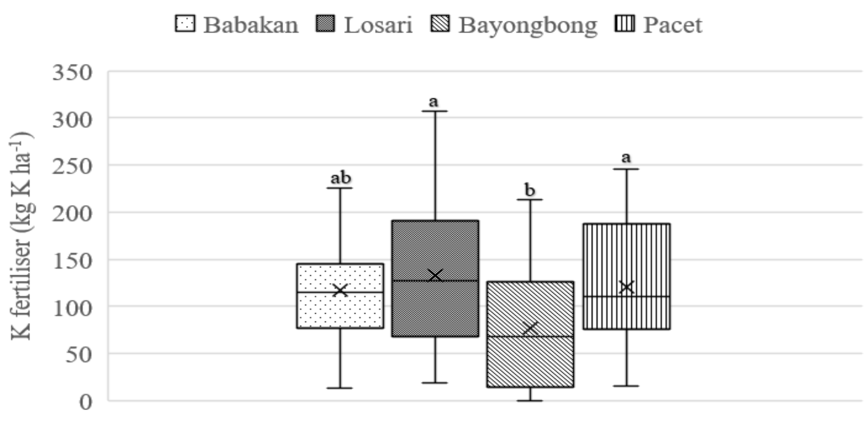

Figure 3.34. Potassium fertiliser use (kg K ha^{1}) for surveyed farmers in each district. Tukey's method for means comparison; means presenting the same letters in the same column are not significantly different at α=5%. Therefore, two values more than 527 kg K ha^{-1} were excluded from the Pacet data set because the values were extremely outlier, more than Q3+3IQR.

Most of the Losari and Pacet farmers applied potassium three times at the first, second and third supplementary fertiliser application. In comparison, Babakan and Bayongbong farmers used K fertiliser two times at the first and second supplemental fertiliser applications (Figure 3.35). Split application of K fertiliser had a positive effect on onion bulb yield (G. E Boyhan et al., 2007).

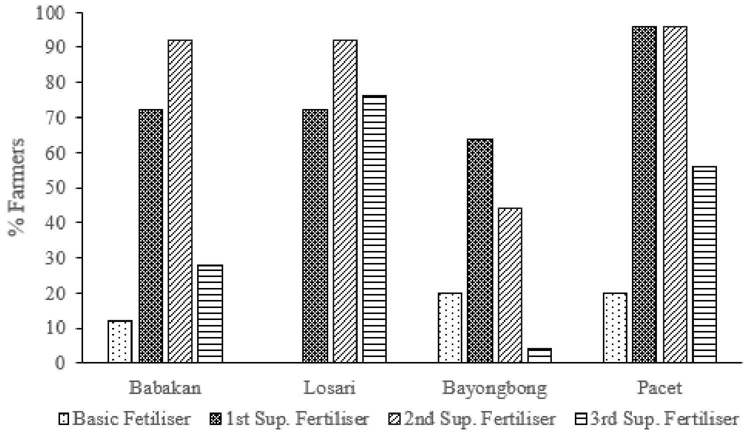

Figure 3.35. Percentage of surveyed farmers who applied K fertiliser in each district.

The highest K fertiliser rate was applied in the second supplementary fertiliser application in the Babakan and Pacet districts. In contrast, farmers in the Losari District applied in the third supplemental fertiliser application (Figure 3.36). Therefore, the general recommendation is that K fertiliser should be applied together with N at the first and second supplementary fertiliser application split in two equal rates (Sumarni & Hidayat, 2005).

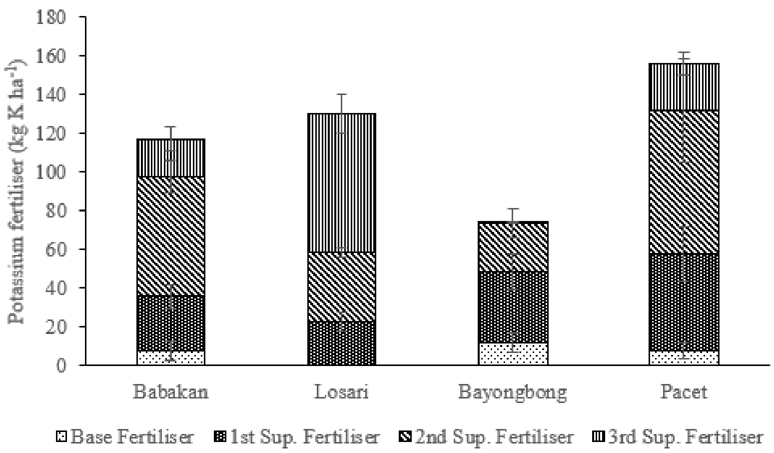

Figure 3.36. Potassium fertiliser rate (kg K ha^{-1}) per application of surveyed farmers in each district.

The correlation between K fertiliser rate and fresh bulb yield was positive (Figure 3.37). When the farmers applied K fertiliser less than 125 kg ha^{-1}, the lower bulb yield was more likely. However, there was no clear relationship between fertiliser K use and bulb yield. The unclear relationship may have been due to the high concentration of initial exchangeable K^+. In another study, the rate of K fertiliser (0 to 199 kg K ha^{-1}) did not have a significant effect on bulb yield when the initial concentration of exchangeable K^+ was > 0.44 cmol (+) kg^{-1} (Sumarni, Rosliani, et al., 2012b).

On average, Pacet farmers applied the highest rate of K fertiliser in comparison to other districts. However, the exchangeable K^+ in this district was lower compared to the others. Therefore, the possible explanation is that the low CEC and BS in this district are likely due to the high leaching and runoff of K fertiliser into subsoil and water system similar to the P fertiliser application. However, P or K loss resulting from the shallot cropping system was not recorded in this or other areas.

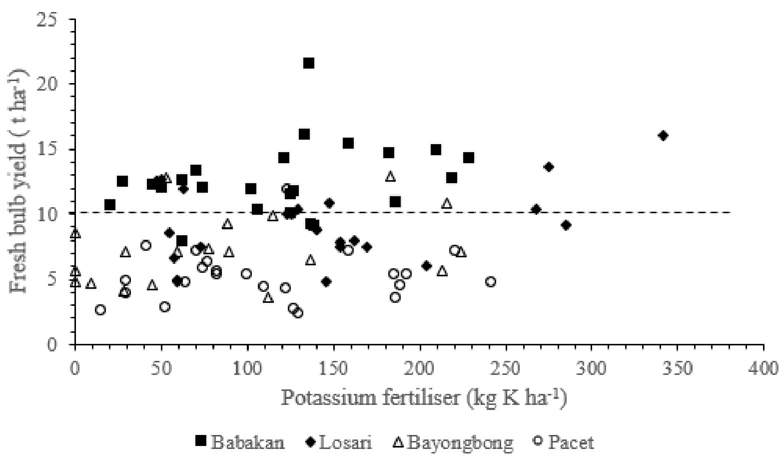

Figure 3.37. Fresh bulb yield (t ha^{-1}) in relation to K fertiliser rates (kg K ha^{-1}) across the districts, n = 98.

Sulphur fertiliser use

Bayongbong farmers applied the highest sulphur (S) fertiliser compared to other districts (Figure 3.38). Sulphur was applied in combination with other elements through ammonium sulphate fertiliser (AS), triple superphosphate (TSP), and compound fertilisers (NPKS) during plant growth. On average, Bayongbong farmers applied 211 kg S ha^{-1}, followed by Pacet farmers 142 kg S ha^{-1}, Losari farmers about 122 kg S ha^{-1} and Babakan farmers about 59 kg S ha^{-1}. There was a high S addition due to the high rate of ammonium sulphate as N fertiliser application in Bayongbong, Pacet and Losari districts (Appendix 3.3). On average Pacet farmers applied 226 kg ha^{-1} urea and 261 kg ha^{-1} AS.

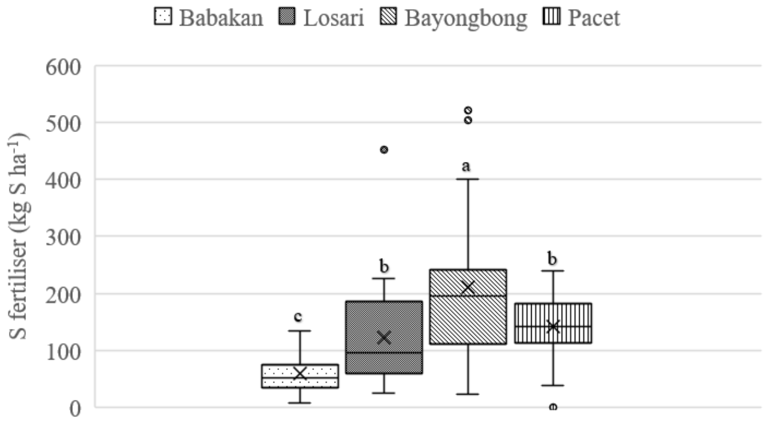

Figure 3.38. Sulphur fertiliser (kg S ha^{-1}) use for surveyed farmers in each district. Tukey's method for means comparison; means presenting the same letters in the same column are not significantly different at α= 5%. Therefore, one value of more than 633 was excluded from the Bayongbong data set because the value was extremely outlier, more than Q3+3IQR.

Most Babakan and Bayongbong farmers applied S fertiliser two times at the first and second supplementary fertiliser applications. On the other hand, Losari farmers applied three times at the first, second, and third supplemental fertiliser applications. Pacet farmers applied most sulphur with the base fertiliser applications and the first and second supplementary fertiliser applications (Figure 3.39).

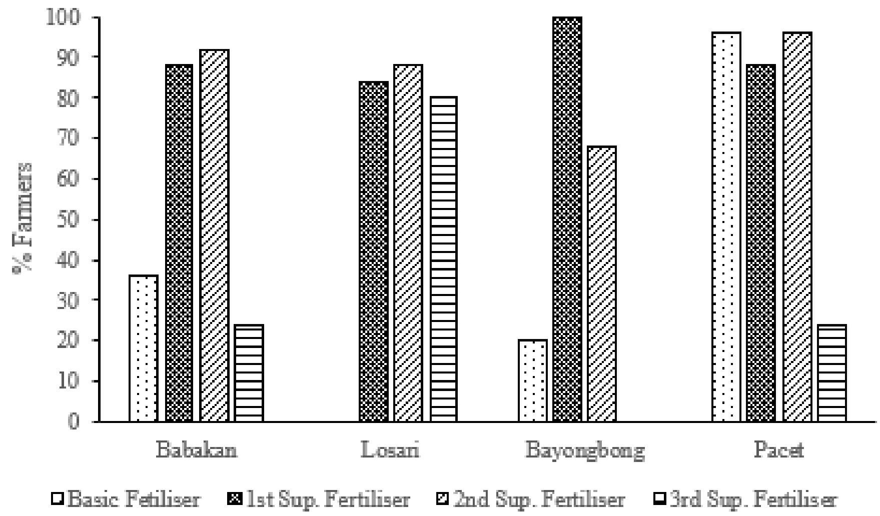

Figure 3.39. Percentage of surveyed farmers who applied S fertiliser in each district.

Bayongbong farmers applied a high S fertiliser rate in the first and second time of supplemental fertiliser application (Figure 3.40). A higher rate of S fertiliser was applied in the Bayongbong District at the first additional fertiliser application. The general recommendation suggested that the S source was applied in the first and second supplemental fertiliser application (Sumarni & Hidayat, 2005). The Pacet farmers applied a high S fertiliser rate at the time of planting. The high rate of ammonium sulphate application during planting time without lime incorporation might reduce the soil pH around the rhizosphere that restricted the root growth. Moreover, most of the surveyed sites had a high initial S-availability (Figure 3.21). Therefore, little or no S fertiliser rate is needed at most farms due to the high initial S concentration in soil solution at all districts.

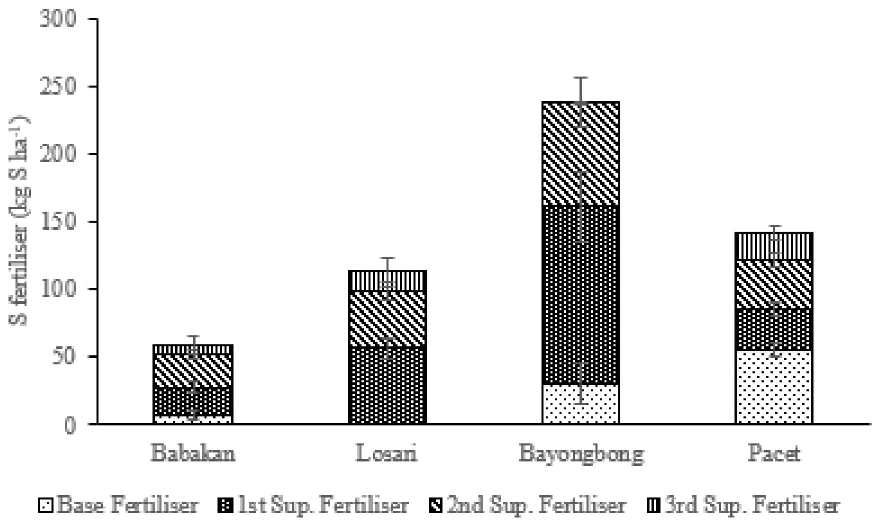

Figure 3.40. Sulphur fertiliser rate (kg S ha^{-1}) per application for surveyed farmers in each district.

There was a negative correlation between S fertiliser rate and fresh bulb yield in all districts ($p < 0.01$ Figure 3.41). As aforementioned, most shallot growers used ammonium sulphate as an S source, and the high rate of ammonium sulphate might decrease shallot bulb yield (Rofiah, 2019). The negative effect of ammonium sulphate on shallot bulb yield might be related to the fertiliser characteristic that is acidic and can reduce soil pH. However, when S was given as an elemental S, the application of 60 kg S ha^{-1} increased shallot bulb yield from 9.4 to 12.1 t ha^{-1} (Muhhamad et al., 2003). Therefore, the ammonium sulphate application needs to be minimised to minimise the negative effect on shallot bulb yield and use other S fertiliser types to meet the shallot S requirement.

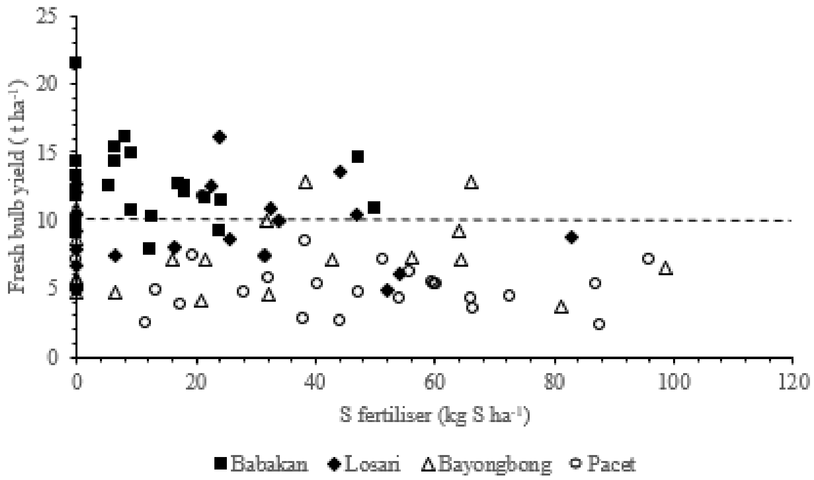

Figure 3.41. Fresh bulb yield (t ha^{-1}) in relation to S fertiliser rates (kg S ha^{-1}) across the districts, n = 99.

Fertiliser uses for surveyed farmers

Overall, shallot farmers split the fertiliser into several applications, often in more applications than is generally recommended. The time of fertiliser application also affects the efficiency of fertiliser. For example, the late application of P fertiliser did not have a positive impact on shallot biomass. Application 59 kg P ha^{-1} at four weeks after planting gave lower shallot biomass than P fertiliser application at planting time with the same rate (shallot biomass was 29 g/plant and 59 g/plant, respectively) (Gunadi & Suwandi, 1989). Split N fertilisers is the best practice to reduce N loss and generally increase crop yield and quality (Havlin et al., 2014). Split N application (pre-plant application and one side dressed application at 6 stage leaves) increased N uptake and nitrogen use efficiency (NUE) in comparison to a single base N application before the planting time (Ma & Herath, 2016). Moreover, the sloped areas have a higher risk than flat land areas of losing N via surface runoff.

Furthermore, the N fertiliser rate might affect NUE due to different abilities on fertiliser recovery efficiency (Baligar et al., 2001). For example, the Pacet District used the highest N fertiliser application on average (271 kg N ha^{-1}) but had the lowest bulb yield (5.4 t ha^{-1}). On the other hand, Babakan District used the lowest N fertiliser (120 kg N ha^{-1}) and gained the highest bulb yield (12.4 t ha^{-1}). Since there was no NUE measurement from each district in this study, Pacet District will likely have a lower NUE than Babakan District. Pacet District is located on a hill with a high slope contour and has high annual rainfall (on average 2000 mm/year). The NUE in this area could be improved by improving plant, soil, fertiliser factors and better management practices, which can better handle abiotic and biotic stresses (Baligar et al., 2001).

Most P fertilisers provide P in soluble forms. However, P is firmly held in soils. Therefore, the P is not very mobile and can only travel a small distance to plant roots by diffusion. Therefore, broadcasting P for vegetable crops is not very efficient. Consequently, it is best to incorporate P into the soil at planting or sowing time rather than broadcast during later applications. Banding P close to the plant below the soil surface also give a higher PUE than P broadcasting. Base P application gave a higher bulb yield than splitting the P (Gunadi & Suwandi, 1989). Pacet farmers applied the highest P fertiliser rate as a consequence of applying P beside shallot bulb as the base fertiliser during planting time and broadcasting P during the growing period. Moreover, the placement might not close enough to the roots. Therefore, it is very likely that the phosphorus use efficiency (PUE) in this district also lower than in other districts.

Fertiliser recommendations rely on target yield and soil fertility status, and history. However, Indonesian farmers, especially shallot growers, rarely soil test due to their limited resources.

The optimal fresh bulb yield of ‘Bima” 14.6 t ha^{-1} in Cirebon-alluvial soil (pH 7.2 and Olsen-P 54.3 mg P kg^{-1}), required about 150 kg N ha^{-1} + 42 kg P ha^{-1} + 105 kg K ha^{-1} (Sopha et al., 2015). In this survey, Babakan and Losari farmers located in Cirebon Regency growing variety Bima on Alluvial soils applied on average 120-222 kg N ha^{-1} + 71-87 kg P ha^{-1} + 74-130 kg K ha^{-1}. These farmers applied NK fertiliser in the recommendation range, while they applied P fertiliser at 82% to 123% above the recommended rate. This practice might explain the high soil available-P concentration in those areas (average Bray1-P= 224 and 161 mg P kg^{-1}). However, most Babakan and Losari farmers had a bulb yield of less than 14.6 t ha^{-1}. The crop growing system is a complex system that is affected by many factors. Fertiliser is only one factor that involves the yield. Other factors are contributing to bulb production, like the climate interaction (rainfall and temperature), crop farming and management (variety and genotype tillage, weeding, irrigation, plant and diseases control, fertiliser application), soil characteristics (chemical, biological and physical properties), pest and disease incidence and management and human factor itself playing significant roles in defining the yield.

Fertiliser effects might differ due to different methods of application (broadcast, side dress, top dress, banding), fertiliser type (urea, ammonium sulphate, ammonium nitrate, compound fertiliser), fertiliser rate and time of application (one base application and supplementary split applications). All those factors would contribute to the efficiency of applied fertiliser. However, since there was no further observation except for some previously discussed factors in other sections above, the reason why the shallot bulb yield of some Babakan and Losari farmers was ≤ 14.6 t ha^{-1} could be not explained further.

The recommended rate of NPK fertiliser in Andisol (pH 5.6, Bray-P > 100 mg P kg^{-1}) was 158 kg N ha^{-1} + 69 kg P ha^{-1} + 131 kg K ha^{-1} (Sopha & Suwandi, 2016). On average, Bayongbong farmers (most of the soil type is Andisol) applied 255 kg N ha^{-1} + 90 kg P ha^{-1} + 74 kg K ha^{-1} which was about 61% above the recommended rate. Farmers applied fertiliser based on their knowledge and experiences. Moreover, about 76% and 60% of Bayongbong surveyed farmers applied ammonium sulphate as an N source in the first and second supplementary fertiliser application Ammonium sulphate (AS) has acidifying effects that reduce soil pH greater than urea and increase exchangeable Al^{3+}. When N was given as ammonium (NH_4^+-N), the soil pH was lower (soil pH 4.52 vs 4.86), and the exchangeable Al^{3+} was higher (Al^{3+} 0.37 vs 0.22 cmol (+) kg^{-1}) than when N was given as nitrate (NO_3^-N) (Wang et al., 2018). Most of the Bayongbong soil was acidic with soil pH less than 5.5 and applying a high rate of AS fertiliser might increase soil acidity, leading to severe shallot root growth and low bulb yields.

Despite a high fertiliser use rate, Pacet farmers produced the lowest bulb yields compared to other districts. The Pacet farmers applied a high rate of NPK fertiliser, about 271 kg N ha^{-1} + 135 kg P ha^{-1+} + 155 kg K ha^{-1} + 142 kg S ha^{-1} that much higher than the general NPK recommendation (150-200 kg N ha^{-1} + 30-40 kg P ha^{-1} + 40-125 kg K ha^{-1} + 60 kg S ha^{-1} (Muhhamad et al., 2003; Sumarni & Hidayat, 2005). The Pacet farmer's practice was inefficient and wasting resources that could be improved. The minimal effect of fertiliser application on shallot bulb yield in Pacet District might be due to the low pH in Pacet District. It seems that this low soil pH condition restricted the shallot growth resulting in reduced shallot bulb yield.

Moreover, to my best knowledge, no proper studies have been conducted on NPK fertiliser applications in very acidic soils (pH <5.0). It is known that liming has a considerable positive impact on acidic soils. High rates of NPK fertiliser without lime applications did not increase the shallot bulb yield in very acidic soils and should be re-considered (Sumarni, Rosliani, et al., 2012a; Sumarni, Rosliani, et al., 2012b). Pacet farmers did not apply lime to increase soil pH. Therefore, the incorporation of lime and fertiliser was worth investigating to obtain a high yield. Despite the lack of lime application, the timing of fertiliser application may also affect the effectiveness of fertilisers that affected the bulb yield. The application of each fertiliser can be seen in Appendix 3.4.

Pest and disease incidence

The primary shallot pest is *Spodoptera exigua*, and the main disease is purple blotch infected by *Alternaria porri*. Upland regions had higher pest and diseases incidences of affected plants compared to lowland regions (Figure 3.42). Therefore, it contributes to the lower bulb yield in the upland (average fresh bulb yield 6.53 t ha^{-1}) than lowland regions (average fresh bulb yield 10.66 t ha^{-1}) because of the differences in the environment and pest and diseases control.

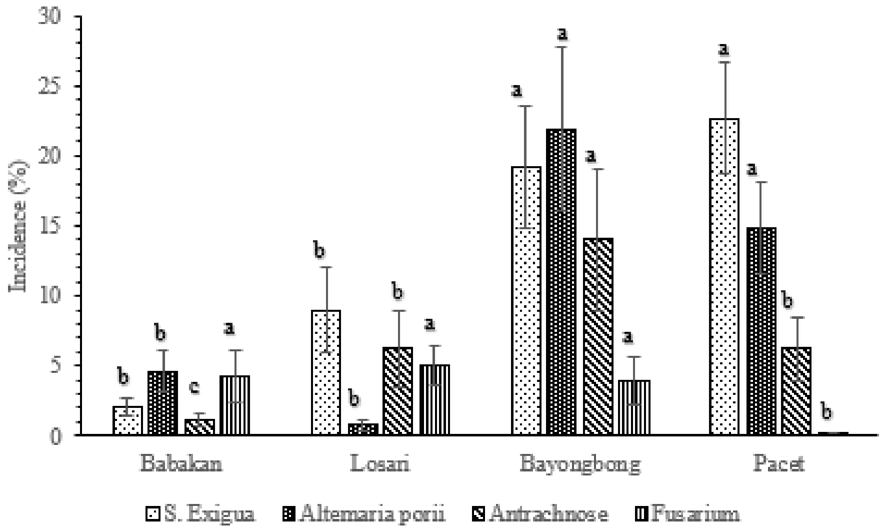

Figure 3.42. The comparison of four main species of pest and disease incidence (% of plants affected) in each location. Error bars are standard errors.

The highest *Spodoptera exigua* incidence (23%) occurred in the Pacet District. Meanwhile, the highest *Alternaria porri* diseases incidence (22%) occurred in the Bayongbong District. The range of pest and disease incidence in the farmer's level of each area is provided in Appendix 3.5. It shows that even with an improved strategy for managing soil fertility, pest and diseases may limit upland shallot yields. Therefore, shallot upland growers might increase their bulb yield through improved soil fertility. Still, the growers should increase their pest and disease control expenditure to get benefits hoped for.

Pest and disease control

The difference between pest and disease incidence was influenced by pest and disease control, which principally involves the types, doses and intervals of insecticides and fungicides the farmers applied. Basuki (2009) reported that Cirebon farmers lacked knowledge and source of information in selecting effective pesticides that resulted in a high dose and short interval of spraying. The origins of information that the farmers used were very limited, fellow farmers and retail pesticide owners. Most farmers usually mix and spray insecticides and fungicides together. The number of insecticides and fungicides that they mixed varies from one spray to another spray, and there is a range of different products used. The number of pesticides, name and doses per application is shown in Appendix 3.6.

On average, Babakan and Losari farmers used pesticides and fungicides more frequently. On average, in these two districts, pesticides and fungicides were applied about 15 times for one growing season, with intervals between sprays being about three days. Meanwhile, in upland areas, sprays were applied on average about 8.5 times for one growing season, with the interval between sprays being about five days for Bayongbong and about seven days for the Pacet (Figure 3.43). Darwis (2017) reported that Cirebon farmers spend about 2% of the total production cost for pesticides and fungicides for one growing season.

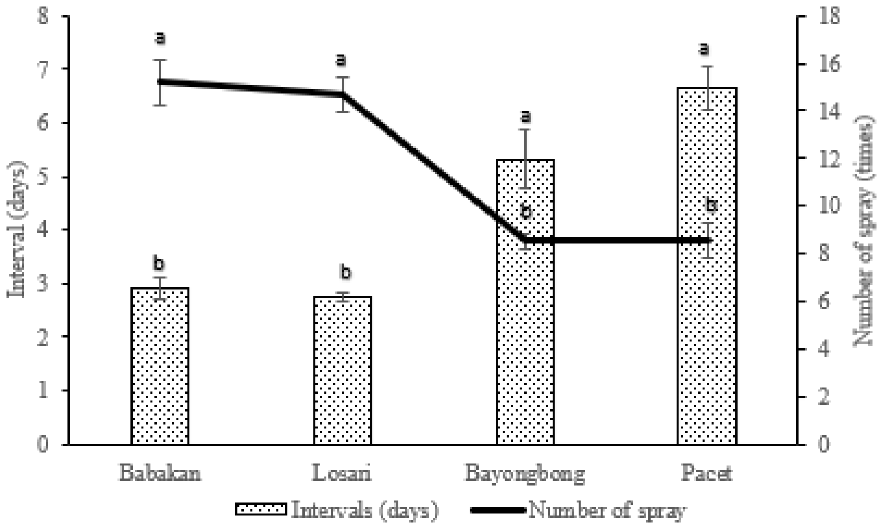

Figure 3.43. The comparison of pesticide spraying in each district. Error bars are standard errors.

The start of pesticide spraying was about 12, 9 and 15 days after planting. The last spray was up to about 51, 49 and 56 days after planting or about 8, 9 and 14 days before harvest time for Babakan, Losari, and Bayongbong growers. The start of pesticide spraying in Pacet District was about 22 days after planting, and the final spray was up to about 72 days after planting or about 18 days before harvest time. The shallot variety harvest age influences the duration of the spray period. The holding period for pesticides and fungicides for shallot crops in Australia was about 1 to 14 days depending on the active ingredients (Davis, 2014). However, there was no detailed information about the holding period of fungicides and pesticides for shallot in Indonesia.

Shallot variety

The other variables that could influence shallot productivity are the varieties used (shown in Appendix 3.7). Pacet farmers plant the 'Sumenep' variety, Babakan farmers planted the 'Bima' variety, and the Bayongbong farmers planted the 'Tuk-Tuk' variety due to specific consumer demand and variety adaptivity.

Shallot cultivar 'Bima' originally came from selecting local shallot 'Brebes' with a potential bulb yield of about 9.9 t ha^{-1} and an early harvest age of about 60 days after planting. Shallot cultivar 'Sumenep' came from local shallot 'Sumenep' in Madura with a potential bulb yield of 12.3 t ha^{-1} and harvest age of about 90 days after planting (Putrasamedja & Suwandi, 1996). The potential bulb yield of 'Tuk-Tuk' is about 11 t ha^{-1} (Nurosid et al., 2018).

Shallots are grown from mother bulbs and produce lateral bulbs that determine bulb yield. The size of the mother bulbs and plant spacing affect the number and size of lateral bulbs created. Plant density increases bulb yield to specific numbers (Sopha, 2020), while bulb size affects the number of lateral bulbs produced. The number of lateral bulbs is also significantly affected by the variety's genotype (Azmi et al., 2016). Shallot 'Sumenep' has a higher ability to multiply from mother bulbs to lateral bulbs (weight to weight) compared to other varieties. The average lateral bulbs and mother bulbs ratio of 'Sumenep' was nine, followed by 'Bima' 5.7-6.7, and the lowest is 5.1 for 'Tuk-tuk'.

Although different areas used different cultivars and plant spacing, the same cultivar was commonly used in the same area. There was a significant difference in lateral bulbs: mother bulbs ratio in each area, especially in Pacet. The ratio of lateral bulbs: mother bulbs is the number of multiplications from mother bulbs (weight) to lateral bulbs (weight). The lowest number of lateral bulbs: mother bulbs ratio in Pacet was 'Sumenep' variety by 3.8; meanwhile, the highest was 17.6 (Table 3.2). This wide rate in values could be influenced by other constraints, such as soil fertility or pest and disease incidence.

Table 3.2. An average of seed bulb, bulb yield, and bulb yield: seed bulb ratio in each district.

	Babakan	Losari	Bayongbong	Pacet
Variety	Bima	Bima	Tuk-tuk	Sumenep
Plant density (plants/m^2)	55 ± 1.7 31 - 83	52 ± 0.8 31 - 100	30 ± 1.5 20 - 50	21 ± 1.1 11 - 33
Bulb weight (g/bulb)	3.5 ± 0.1 2.1 - 5.9	3.5 ± 0.1 2.2 - 5.6	5.5 ± 0.3 2.8 - 10.0	3.1 ± 0.2 1.4 - 4.8
Seed bulb (t ha^{-1})	1.46 ± 0.03 1.12 – 2.00	1.40 ± 0.02 0.80 - 2.40	1.09 ± 0.05 0.57 ± 1.75	0.43 ± 0.02 0.25 -0.60
Bulb yield (t ha^{-1})	12.5 ± 0.6 7.9 - 21.4	9.1 ± 0.6 4.8 – 16.0	7.6 ± 0.5 3.6 – 12.9	5.3 ± 0.4 2.3 – 11.8
Bulb yield: Seed bulb	6.7 ± 0.3 3.0 - 14.0	5.7 ± 0.1 2.7 - 8.0	5.1 ± 0.3 2.0 - 11.8	9.1 ± 0.8 3.8 - 17.6
Harvested age (days after planting)	54 ± 0.4 50 - 60	53 ± 0.9 50 - 70	66 ± 0.9 60 - 80	90 ± 0.4 90 - 100

3.3.4. Pacet District as the selected area for improving shallot production

Of the four districts surveyed, Pacet had the lowest average bulb yield of 5.4 t ha^{-1}, and there was a wide range in bulb yields from 2.3 to 11.8 t ha^{-1}. Therefore, this district was selected for further investigation because it represented an area where farm productivity was particularly low. To further investigate the potential constraints that were impeding shallot production in the Pacet district, soil analysis and questionnaire data were grouped into two groups; those that were low yielding (< 7 t ha^{-1}), and medium to high yielding (> 10 t ha^{-1}). Of the farmers surveyed in this district, 72% of farmers had yields classified as low yielding.

There was a tendency for the low yielding farms surveyed in the Pacet District to have lower average soil pH and soil available-P than the high-yielding farms (Figure 3.44). Average soil pH 4.8 for low yielding farms and 5.3 for high yielding farms. There was also a difference in soil P status between the low and high yielding farms. The average soil Bray1-P1was 11 mg P kg^{-1} for low yielding farms and 30 mg P kg^{-1} for high yielding farms (Figure 3.45).

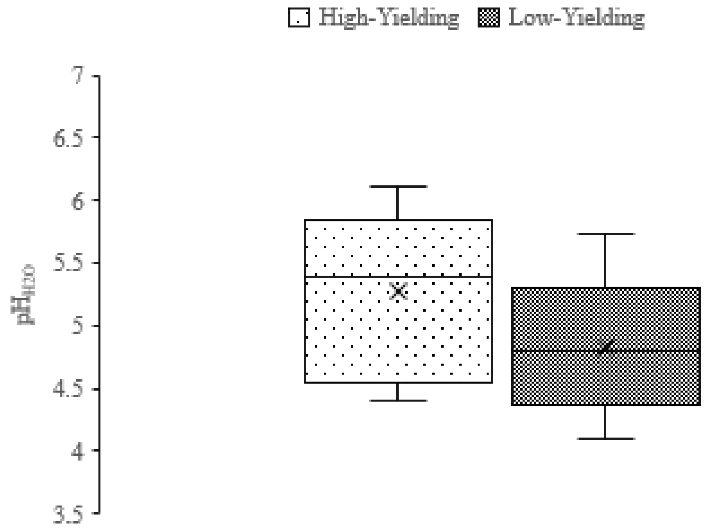

Figure 3.44. The comparison of soil pH_{H2O} in high yielding and low yielding in Pacet District. Error bars are standard errors, n_1 = 6 and n_2 =19.

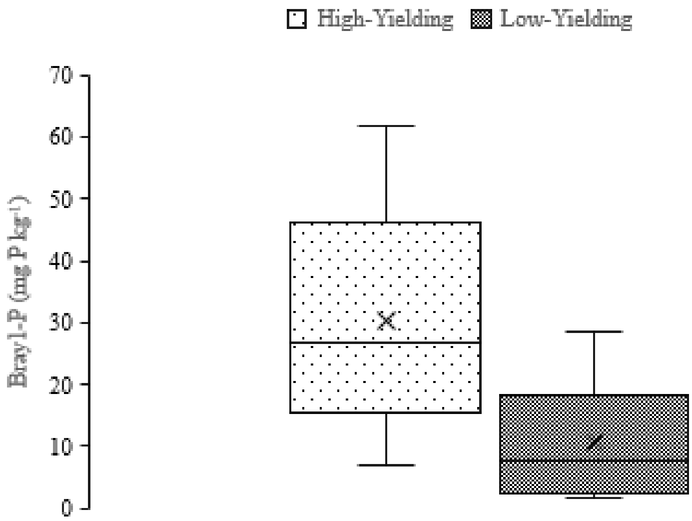

Figure 3.45. The comparison of soil available-P (mg P kg^{-1}) in high yielding and low yielding in Pacet District. Error bars are standard errors, n_1 = 6 and n_2 =19.

Meanwhile, there was no significant difference between low and high yielding farms with base cations, CEC, base saturation (%) or sulphate (ppm) (Table 3.3). On average, the concentration of Ca^{2+} in low and high yielding farms was not significantly different. The concentration of soil Mg^{2+} was lower in the low yielding farms in Pacet. In contrast, the low yielding farms had higher soil K^+ levels. However, there was no published critical range of base cations concentration on growing shallot. When soil contained a high concentration of exchangeable K^+ (> 0.44 cmol (+) kg^{-1}), the application of K fertiliser did not increase shallot bulb yield significantly (Sumarni, Rosliani, et al., 2012b), and when the K^+ concentration is very high, above the optimal value, then the addition of K fertiliser might affect the availability of other nutrient cations due to competition between cations. The exchangeable Ca^{2+} was reduced when KCl was applied because K^+ replaces some of the Ca^{2+} on soil cation exchange sites (Havlin et al., 2014). Further in-depth analysis is needed to understand to identify and to understand the soil fertility constraints on producing shallot in this area.

Table 3.3. An average of base cations, cation exchange capacity (CEC), base saturation (%) and S (ppm) on high yielding and low yielding farms in the Pacet District.

	Ca^{2+}	Mg^{2+}	K^+	Na^+	CEC	BS	SO_4^{2-}
	(cmol (+) kg^{-1})					(%CEC)	(ppm)
High yielding	5.31	2.34	0.46	0.14	13.3	61	26
Low yielding	5.44	1.93	0.98	0.17	14.4	57	41
Std Dev	1.17	0.54	0.27	0.08	1.26	9.0	29
p-value	0.82	0.11	0.10	0.37	0.07	0.34	0.30

Interestingly, in contrast to soil properties, there was no significant difference between the high yielding and low yielding group on the N, P and K fertiliser application rate (Table 3.4). Both groups gave a similarly high rate of N, P and K fertiliser for growing shallot. It was assumed that the relationship between soil chemical properties and fertiliser application rate in this region was unclear due to different soil properties and other agronomy factors (for example, type of fertiliser, fertiliser placement, timing, tillage, soil contour, etc.).

Table 3.4. An average of N, P and K fertiliser rate (kg ha^{-1}) on high yielding and low yielding farms in the Pacet District.

	N	P	K	S
	(kg ha^{-1})			
High yielding	256	130	140	124
Low yielding	260	140	100	160
p-value	0.97	0.40	0.43	0.21

Note: The K fertiliser data set excluded 773 kg K ha^{-1} because the value was very outside the range of other farmers (i.e., extremely outlier).

Spodoptera exigua (armyworm) incidence in low yielding farms was significantly higher than for high yielding farms (Figure 3.46, *p*-value < 0.05). On average, when the armyworm incidence reached about 28% of the plant population, the bulb yield was likely less than 7 t ha^{-1}. In the rainy season, 12% of plant damage by *Spodoptera exigua* decreased the bulb yield up to 23% from 8.0 to 6.2 t ha^{-1} (Setiawati et al., 2014). Farmers use different types of insecticides, and the type and rates of insecticides had a different effect on reducing plant damage by the armyworm (Kolodny-Hirsch et al., 1997).

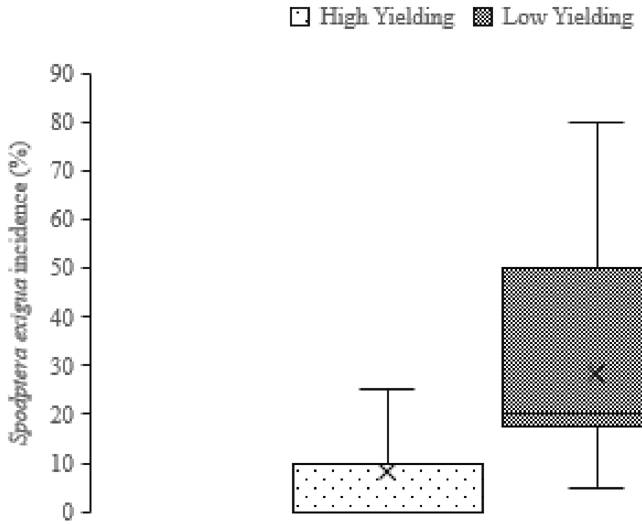

Figure 3.46. The comparison of *Spodoptera exigua* incidence (%) in high yielding and low yielding in Pacet District. Error bars are standard errors, n_1 = 6 and n_2 =19.

The plant damage caused by purple blotch (*Alternaria porii*) and *Anthracnose* were not significantly different between farms (Table 3.5). However, low yielding farms had slightly higher plant damage by diseases compared to high yielding farms. Therefore, high plant damage due to pest and disease incidence rate in Pacet District is likely to have contributed to the lower bulb yields in this district.

Table 3.5. An average of *Alternaria porii* and *Anthracnose* incidence on high yielding and low yielding farmlands in the Pacet District.

	Alternaria porii incidence (%)	*Anthracnose* incidence (%)
High yielding	10.71	3.57
Low yielding	16.50	7.22
StDev	16.55	11.12
p-value	0.441	0.469

Of the four districts surveyed, Pacet was the district with the lowest average shallot yields. This survey highlighted several possible causes of these lower yields: lower soil fertility and higher incidence of pests and diseases than the other districts. An improved pest and disease control, including the frequency and quantity of applied spray, might be helpful to reduce pest and disease crop damage. However, this issue would not be part of this thesis. Instead, to minimise the negative effect of pest and diseases incidence, integrated pest and diseases management practices would be applied in the field trials across the treatments, replications, sites, and seasons.

Of the soil fertility constraints identified, the two that were common among farmers in Pacet were low soil pH and low plant availability P. Low soil pH reduces the availability of key plant growth-limiting nutrients and increases Al and Mn toxicity, which can restrict root development and plant growth. Liming is not a common practice used by farmers in Pacet due to a lack of understanding by farmers of its benefits and because the large quantities of lime and associated transport are required to correct very low pH levels. The large quantities of lime required are a constraint to lime use because many farms are in remote areas with no vehicle access. Therefore, further research is needed to identify the minimum amount of lime required to improve shallot yields in the soil and climate environment of the Pacet District.

Although many of the surveyed farmers used high P fertiliser rates, they did not receive a high yield in return. Also, it is not clear why this has not translated in higher soil available P levels. But it was highlighted the P fertiliser application practices are not ideal yet for optimising the availability of fertiliser P for establishing shallot plants. Therefore, P fertiliser practices for shallots also need further research to provide a recommendation to growers in Pacet.

3.4. Conclusions

- The grower survey identified that average shallot bulb yields in Babakan, Losari, Bayongbong and Pacet Districts were 12.5, 9.2, 7.7 and 5.3 t ha^{-1}. Shallot bulb yields were especially low in the upland districts of Pacet.
- Lowland and upland districts had different soil conditions. On average, the lowland districts of Babakan and Losari had higher soil pH levels than the upland districts of Bayongbong and Pacet (soil pH 6.3, 6.8, 5.1 and 4.9, respectively). As a result, the Babakan, Losari and Bayongbong Districts had a high soil available-P (Bray1-P 96, 70 and 75 mg P kg^{-1}, respectively). Meanwhile, the Pacet District had low soil available-P (Bray1- P=15 mg P kg^{-1}).
- The Pacet District had the lowest lime use, compared to the other districts, with only one farmer surveyed in this district using lime.
- On average, most farmers in all districts applied high rates of NPKS fertiliser. However, even though Pacet farmers applied a high rate of NPKS fertiliser, this did not result in a high yield for many farmers in this district.

- Low yielding farmers in Pacet District might be due to soil acidity and low soil available-P that reduced the shallot bulb yield. Therefore, lime and an optimal P fertiliser addition might improve the soil fertility and enhance the bulb yield in this district.
- Further research is required to understand better how soil fertility can be managed to improve shallot crop yield. In particular, the benefits of lime and P fertiliser and how this can be implemented on farms with limited vehicle access.

Chapter 4

Field Trial 1: Lime and Phosphorus Fertiliser Strategies for Improving Shallot Bulb Yield in Strongly Acid Soils in West Java, Indonesia

4.1. Introduction

4.1.1. Background

Smallholder farmers are those who have limited resources and small areas of land to cultivate. These farmers commonly achieve low yields because of limited access to agronomic advice and crop inputs, such as fertiliser, irrigation, and pesticides. In Indonesia, smallholder farmers or "*Petani Gurem*" are growers who have land areas of less than 0.5 hectares and make up about 56% of total farmers in the country (Susilowati & Maulana, 2016). The survey conducted in this study (Chapter 3) was of shallot farmers in the West Java province of Indonesia. Most shallot growers in West Java are smallholder farmers who do not use machinery in their cropping systems. In addition, the remote locations of many of these farms are another obstacle to farmers gaining access to the resources they need to help them improve crop productivity. Of the four districts surveyed in West Java, the Pacet District had especially low yields (survey average of 5.4 t ha^{-1}). A range of factors identified from the survey could be contributing to these low yields in the Pacet District, such as the choice of shallot variety, pest and disease management practices, and soil fertility. Two soil fertility factors observed as typical constraints in Pacet District were low soil pH and low soil available P.

Acidic soils are common in tropical regions where precipitation is often substantially higher than evapotranspiration, resulting in high drainage and soil weathering rates. High rainfall contributes to the leaching of basic cations, raises the exchangeable H^+ ions in soil solution and decreases soil pH (Von Uexküll & Mutert, 1995). The majority of Indonesia's upland soils are considered to be either strongly acidic (soil pH_{H2O} 5.1-5.5) or very strongly acidic (soil pH_{H2O} 4.5-5.0), with lesser areas of moderately acidic (soil pH_{H2O} 5.6-6.0) or extremely acidic (soil pH_{H2O} 3.5-4.4) (Mulyani et al., 2010; Soil-Survey-Division-Staff, 1993). Soil acidity is a significant cause of reduced crop yield and quality, due to the lower availability of essential plant nutrients. Under acidic soil conditions, plant growth can be constrained by specific factors and their interactions. Acidic soils often increase the levels of Al and Mn, resulting in toxicity, and decrease the availability of P and base cations (Ca^{2+}, Mg^{2+} and K^{+}), causing plant deficiency (Haynes & Mokolobate, 2001; Marschner, 1991).

Gazey (2018), in a study of Australian soils, reported that many crops suffer from Al toxicity when the pH_{Ca} < 4.5, but most crops were not affected by Al toxicity when the pH_{Ca} > 4.8. In a New Zealand soil reported by Moir and Moot (2010), a high concentration of Al^{3+} (> 1.00 cmol (+) kg^{-1}) was recorded when the soil pH_{H2O} < 5.5, which decreased to below 0.50 cmol (+) kg ha^{-1} when the pH_{H2O} > 5.8. Another way of expressing exchangeable Al^{3+}, and the risk of Al toxicity, is using the using Al:Ca ratio. Vanguelova et al. (2007) explained that the soil acidity process increases exchangeable Al^{3+} in the soil solution, leaches divalent cations Ca^{2+} and Mg^{2+}, and replaces these basic cations on root binding sites with exchangeable Al^{3+}.

As *Allium* species, shallot and onion have shallow and hairless roots susceptible to acidic soil conditions. Clarkson (1965) reported that Al concentration in the solution reduced the onion root length linearly. Another symptom is the chlorosis of the upper part of leaves with dieback in some tips. The diminished root growth decreased the nutrient uptake (g/kg dry matter), which reduces the crop biomass (Wheeler & Follett, 1991) and leads to a low bulb yield. In very strongly acidic soil (soil pH_{H2O} 4.5), for example, the bulb yield of onion was 4 t ha^{-1}, which was only 13% of the bulb yield (30 t ha^{-1}) in strongly acidic soil (soil pH_{H2O} 5.2) (Hemphill & McReynolds, 1987).

Research on reducing soil acidity through liming has a long history. The application of lime is a standard method to increase soil pH levels and mitigate the adverse effects of acidic soils on plant growth (Kamprath & Foy, 1985; Kunhikrishnan et al., 2016). However, the effectiveness of liming varies and depends on many factors, including; the initial soil pH, soil type, climate, liming material type, the lime application rate and crop species (Li et al., 2019). For example, an onion pot study found that a very high application of agriculture limestone (equivalent to 30 t ha^{-1}) improved the soil pH from ultra-acidic to moderately acidic (soil pH_{H2O} from 3.0 to 5.8) and increased onion bulb yield by 137% (Mathur & Levesque, 1983). Meanwhile, in a field trial in less acidic soil conditions in Oregon, the United States, Hemphill (1987) reported that an application of 14.8 t ha^{-1} agricultural limestone (95% $CaCO_3$ equivalent) increased soil pH from very strongly acidic to near neutral (soil pH_{H2O} from 5.0 to 6.6) and increased onion bulb yield by about 348%, from 18.8 to 65.5 t ha^{-1}.

Phosphorus fertiliser application is a common technique use for increasing soil-available P and mitigating P deficiency in crops. The P fertiliser rate required for optimum yield varies depending on the difference between the initial and optimum soil available-P levels and P retention. For example, Chagas et al. (2016) reported that for moderately acid soil (soil pH_{H2O} 5.5) and very deficient available-P (Olsen-P 3.2 mg P kg^{-1}), the optimum P rate was as high at 149 kg P ha^{-1}. However, the rate was reduced to 77 kg P ha^{-1} when the initial available -P was higher (Olsen-P 12 mg P kg^{-1}). In another study, when a soil pH was slightly acid soil (soil pH_{H2O} 6.5), and the soil available P was low (Olsen-P 16 mg P kg^{-1}), the P fertiliser recommendation was lower by 59 kg P ha^{-1}. However, the benefit of improving soil fertility will be limited by the most limiting factor. If soil acidity is more limiting than soil available-P, then there may minimally yield response to P fertiliser addition. Therefore, it is important to address the most limiting factor first.

Low shallot yields in West Java are affected by many unique environmental and economic constraints experienced by smallholder farmers. There are also increasing concerns that increased climate variability, as a result of Global Climate Change, is predicted to increase the challenges faced by smallholder farmers. Climate variability can increase the risk of crop failures from droughts or floods and increase the incidence of pests and diseases. In addition, increases in temperatures and rainfall can also contribute to higher leaching losses of essential plant nutrients and weathering of soils, increasing the rate of soil acidification. Therefore, smallholder farmers require improved soil fertility practices that will help them be resilient. In particular, it is important that soil fertility recommendations are suitable for farmers to implement, and they also need to improve the economic returns from growing shallots. Therefore, further specific quantitative information is required to identify the economic optimum soil fertility parameters, especially soil pH, exchangeable Al^{3+} and soil available-P, for farms in low yielding districts of West Java, like Pacet.

4.1.2. Pacet farmers: a portrait of upland smallholder farmers in West Java, Indonesia

Location, climate, and natural vegetation

The Pacet district is located in the Bandung Regency of West Java (*Provinsi Jawa Barat*), between 5°50' – 7°5' South Latitude and 104°48'-108°48; East Longitude (Figure 4.1.). The main feature of West Java is that it is part of the volcanic archipelago (active and inactive). West Java can be categorised into steep mountainous regions in the south (altitudes of more than 1,500 m above sea level), sloping hillsides in the middle (100-1,500 m above sea level), broad plain areas in the north (altitude of 0 to 10 m above sea level) and river basin areas.

Figure.4.1. The administrative divisions in (a) West Java and (b) Bandung Regency. (Source: http://www.bandungkab.go.id/arsip/peta-dan-topografi).

Average annual rainfall exceeds 2000 mm with its seasonal variation (Figure 4.2). However, the rainy season usually starts from October to March, followed by a dry season from April to September. There is also a year-to-year variation, with 2015 being an example of a particularly dry year, which was likely due to the El-Nino weather pattern at that time (Athoillah et al., 2017; G. E Boyhan et al., 2007; Nabilah et al., 2017). El Nino is a symptom of sea irregularities characterised by differences in the ocean's temperature in the Pacific Ocean around the equator, specifically in the central and eastern parts (around the Peruvian Coast). In Indonesia, El Nino can cause prolonged droughts, dry and hot weather that can cause various disasters, such as forest and land fires, also crop failure.

The West Java climate is defined as tropical, with maximum temperatures ranging from about 28.9 to 32.4°C, and the minimum monthly temperature ranging from about was 17.8 to 20.6°C. This region’s natural vegetation is rainforest and evergreen woodland, including trees of different species, sizes, and densities, with a ground cover of perennial and annual grasses incorporating herbs and bushes.

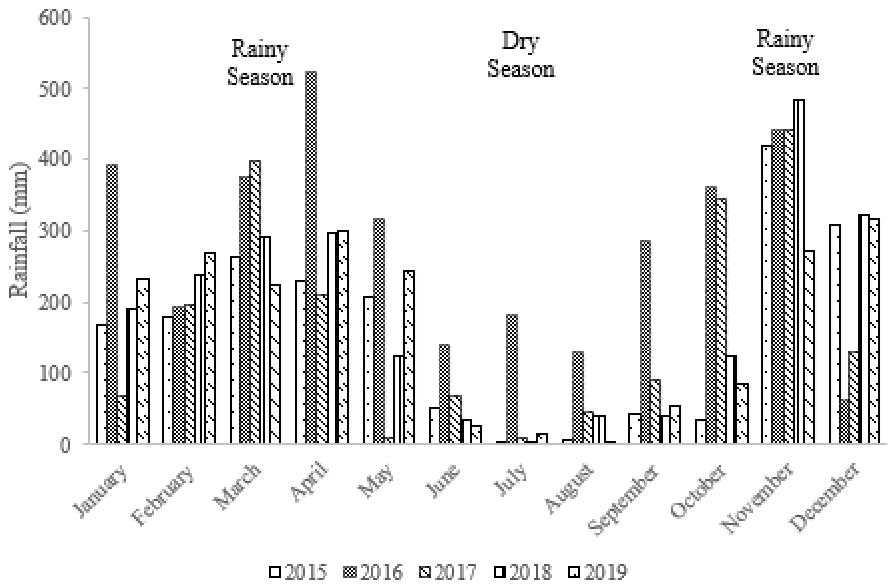

Figure 4.2. The monthly rainfall in 2013-2017 in West Java, Indonesia (data from the climate station located in Bandung, regions capital city).

Land cultivation and soil resources

The Bandung Regency is representative of the landforms and population pressure in West Java. In 2019, the population of Bandung Regency was 3.78 million people living in 1,762.4 km^2 (2,142 people/km^2), and most of the cities of Bandung Regency are within mountainous regions.

In Pacet, based on land used, the dryland can be typically classified into three categories (Figure 4.3). All land categories have sloping topography from 45 to 60^o. The first category is near the village, commonly used to grow crops for more than 80 years. The second category is further away from the village, cultivated around 20 to 80 years ago. The third category was initially cultivated from growing crops less than 20 years. The third category is part of a government-owned enterprise managing the state forests in Java and Madura on a commercial basis. The crop yields have previously been better in these areas, possibly due to high natural soil fertility, particularly higher soil pH than the other categories on average (Table 4.1). However, in 2020, the local government restricted the farmers from growing vegetable crops in Category 3 due to conservation and environmental issues. Therefore, Category 3 is now removed from vegetable production by the Local Government and turn into annual crop productions like coffee and trees due to soil erosion mitigation and reforestation programme. This situation stressed Category 1 and 2 areas to produce more bulb yield to supply consumer demand.

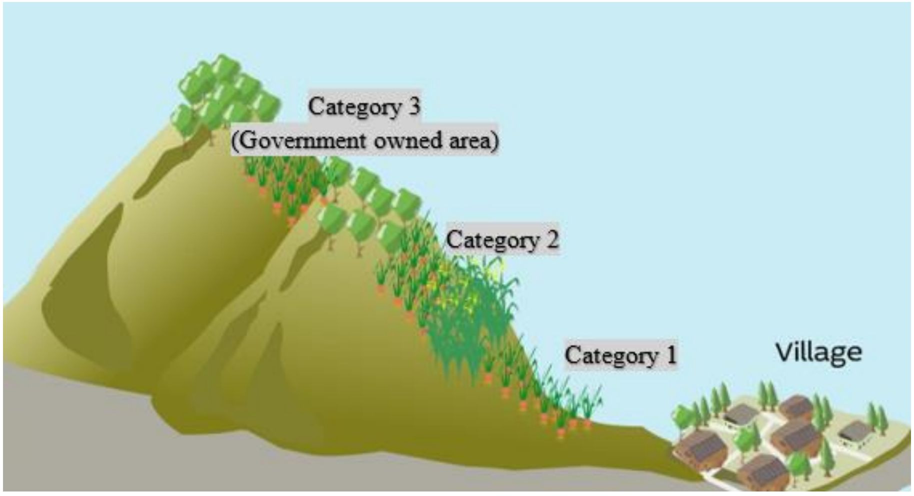

Figure 4.3. A schematic generalised representation of the three distinct areas farmers use to grow crops in the Pacet District.

Table 4.1. The average soil characteristics of farms are located in three categories (soil sample depth 20 cm).

Parameter	Category 1 (> 80 years) *	Category 2 (20 - 80 years)	Category 3 (< 20 years)
pH_{H2O}	4.34	4.58	5.10
Bray1-P (mg P kg^{-1})	13	26	7
Ca^{2+} (cmol (+) kg^{-1})	4.5	4.8	5.8
Mg^{2+} (cmol (+) kg^{-1})	1.8	1.6	2.1
K^{+} (cmol (+) kg^{-1})	0.6	0.6	0.6
Na^{+}(cmol (+) kg^{-1})	0.05	0.08	0.07
Total Cations	6.51	7.07	8.52
CEC	13.61	13.69	13.88

Note: data were an average of the survey activity (Chapter 3). *Years since the initial cultivation.

Common cropping pattern

In Pacet, there areas two main areas for crop production; paddy fields and dry land. In the paddy fields, farmers grow crops during the dry and rainy seasons. Meanwhile, due to the lack of an irrigation system in the dryland areas, farmers grow crops in the rainy season only. The cropping pattern is presented in Table 4.2.

Table 4.2. Climate data in Bandung Regency (Y. 2017) and typical cropping pattern in the Pacet District.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Rainfall (mm)	91	250	286	229	139	173	47	8	91	229	426	196
T min (°C)	21.0	20.4	20.2	20.7	20.0	19.5	18.8	19.4	20.2	20.4	20.4	20.7
T max (°C)	29.1	28.3	29.2	28.2	29.5	28.6	29.2	29.8	30.5	29.8	28.7	29.3
T average (°C)	24.2	23.0	23.3	23.6	23.9	23.4	23.4	23.3	23.7	23.4	23.1	23.9
Paddy Field	R	R	R	R	V	S	S	S	V	V	R	R
Dry Land	S	C	C	C	F	F	F	F	F	F	S	S

Note: Climate data was collected from climate station in Bandung Regency, cropping pattern data was collected from survey activity (Chapter 3); R= Rice, V = Vegetables, S = Shallot, C = Chilli, F= Fallow

Farmers' agronomic practices

This section describes farmers practice on shallot cultivation during the rainy season in the dry land. It is not usual for Pacet farmers to have soil testing conducted on their farms. Therefore, fertiliser recommendations are not based on knowing actual soil fertility. The Pacet farmers surveyed in this study (Chapter 3) applied an average of 217 kg N ha^{-1}, 135 kg P ha$^{-1,}$ 155 kg K ha^{-1} and 142 kg S ha^{-1} to their shallot crops. The fertiliser rates are higher than a general recommendation of 150-200 kg N ha^{-1}, 31-39 kg P ha^{-1}, 41-124 kg K ha^{-1} and 60 kg S ha^{-1} (Muhhamad et al., 2003; Sumarni & Hidayat, 2005).

Pacet farmers split fertiliser application into four times: planting time and two until three supplementary applications (Table 4.3). While splitting fertiliser application is recommended for mobile nutrients like N and K, it is unnecessary for less mobile nutrients like P. Phosphorus is best applied at planting to be incorporated into the soil to increase its proximity to plant roots (Dougherty et al., 2011; Gunadi & Suwandi, 1989). For the Pacet farms surveyed, about 30% of P fertiliser was applied at planting. However, this is not typically uniformly incorporated in the soil. The standard method used for applying P fertiliser to shallots, used by upland farmers, involves forming a hole in the ground approximately 10 cm deep and about 5 cm from each shallot bulb. The hole is formed by pressing the soil with a post (about 10 cm in diameter) and then adding the fertiliser to the hole and leaving it uncovered. This practice results in a high concentration of soil P in a small area of soil, which would cause high spatial variability in the soil available P. This may affect the utilisation of soil P by the crop and make assessing soil P status more challenging. This practice may also help explain how the high rates of P fertiliser used by Pacet farmers (Table 4.3) have not consistently resulted in bulb yield responses.

Table 4.3. Average fertiliser nutrient use for shallots grown on surveyed farms in the Pacet District.

Fertiliser application	N (kg ha^{-1})	P (kg ha^{-1})	K (kg ha^{-1})	S (kg ha^{-1})
Basic fertiliser (±0 dap)	54.4 ± 4.1	41.9 ± 3.0	7.8 ± 3.9	55.7 ± 4.7
1st Sup. fertiliser (± 22 dap)	112.3 ± 12.3	16.2 ± 3.9	49.9 ± 14.4	29.9 ± 4.8
2nd Sup. fertiliser (± 45 dap)	83.1 ± 13.3	32.8 ± 5.2	73.6 ± 26.5	36.2 ± 4.2
3rd Sup. fertiliser (± 67 dap)	21.2 ± 5.6	43.7 ± 6.2	24.3 ± 5.6	20.0 ± 2.8
Total	271.0 ± 22.8	134.6 ± 10.4	155.5 ± 30.3	141.7 ± 11.4

Note: data was an average of the survey activity (Chapter 3), dap = days after planting

It is not common for farmers in the Pacet District to use liming materials. One of the constraints contributing to the low levels of lime use is the high rates of lime needed to correct soil pH and the challenges with transporting it to remote farms. Those farms situated in the hilly or mountainous areas can often only be accessed on foot, meaning that most crop inputs must be carried to the site (Chapter 3). Moreover, the effect of lime on shallot production in this district is not well known. Because of the transportation limitations constraining the ability of farmers to apply large quantities of lime required to move soil pH into the optimum range, it is important to determine the effect of lower lime rates (≤ 1.0 t ha^{-1}) on shallot production. Therefore, quantifying the benefits of low rates of lime, especially when combined with optimum P fertiliser use, will help identify this practice's benefits.

Objective

This study investigates the effect of low to moderate rates lime and a range of P fertiliser rates on shallot growth and yield in acidic soils with varying soil acidity levels, Al toxicity and P status on three farm field sites in different areas of the Pacet District. Based on the study of literature and survey activity, it is expected that lime and P fertiliser has the potential to affect soil pH, exchangeable Al^{3+}, and other soil chemical properties, affecting shallot growth and bulb yield. However, the effect of these practices will be influenced by each farm's initial soil fertility. Therefore, the aim was to identify the optimum lime and P fertiliser management strategies for three contrasting farm sites.

4.2. Materials and Methods

4.2.1. Experimental sites and shallot variety

The experiment was set up in three farmers' fields in the Pacet District, Bandung Regency, West Java (6°41'-7°19'S, 107°22'-108°50'E, Figure 4.4) rainy season in November 2018. Climatic data were collected from an Ancolmekar climate station, 5 to 6 km from the trial site. All experimental field sites were selected from the survey activity (Chapter 2) and are located in the upland region, slope 30 to 45° (Figure 4.5), with Andosol soils (KEMENTAN-RI, 2016). with clay texture (61% clay, 25% silt and 14% sand). Field 1 is located approximately 20 minutes' walk from the nearby road. Meanwhile, Fields 2 and 3 are located about an hour's walk from the road and only accessible by foot.

Field sites 2 and 3 were assigned two categories (Category 2 and 3, respectively) due to their land-use history, and they are close to each other. Based on the farmer's interview, Field site 2 has been cultivated for at least the last 50 and Field site 3 has been cultivated for about 20 years. In addition, Field site 3 is on government-owned land and was permitted to grow vegetable crops in this area up until 2020.

Figure 4.4. The field trial site's locations (a) Pacet Regency, (b) Field site 1, 2 and 3 and distance and pathway (red line) from the main road to each site. The yellow line is used to determine the plots of the experiment. MASL = m above sea level.

Figure 4.5. The three field sites before planting. (a) Field site 1 before soil bed formation; (b) Field site 2 and (c) Field site 3 after soil bed formation.

Shallots (*Allium cepa* var Aggregatum group, variety Sumenep) were planted at 0.2 m x 0.2 m spacing in beds that were 1.0 m x 3.0 m in size on 15th and 16th November 2018. The seedbeds were approximately 30 cm high; the gap between beds was 0.6 m.

4.2.2. Field trial and management

The two-factor experiment was arranged in a completely randomized block design with four replicates of each treatment. The first factor was three levels of lime, and the second factor was four levels of P fertiliser. The levels of lime were 0 (0L), 0.5 (0.5L) and 1.0 (1.0L) t ha^{-1} and four levels of P fertiliser were 0 (0P), 50 (50P), 100 (100P) and 150 (150P) kg P ha^{-1}. Lime was visually assessed as being a very fine powder. Lime and P fertiliser treatments were broadcast evenly across the soil beds in a single application and incorporated using manual ploughing a day before planting.

In this experiment, agricultural lime ($CaCO_3$ equivalents =106%) and triple superphosphate fertiliser (TSP) (0-20-0-0) were used as the treatment materials. All treatments received the same N, K and S rates, 200 kg N ha^{-1}, 160 kg K ha^{-1} and 76 kg S ha^{-1}. Ammonium sulphate (21-0-0-24) and urea (46-0-0-0) were used as nitrogen (N) sources, potassium chloride (KCl) (0-50-0-0) was used as the potassium (K) source. Ammonium sulphate was applied at 317 kg ha^{-1} at 21 days after planting (DAP). Urea was added twice, at 35- and 49-days DAP, at a rate of 145 kg ha^{-1} per application. Potassium chloride was used three times, at 21, 35 and 49 DAP, at a rate of 107 kg ha^{-1} per application.

A combination of insecticides and fungicides were applied weekly, starting from 20 DAP (see Appendix 4.1. for details). When there was a noticeable infestation of *Spodoptera exigua* (Armyworm), this was also controlled by removing caterpillars by hand.

The crops were harvested by hand at 86 DAP, and the roots were cuts off from the bulbs. Also, the leaves were cut off about 3 cm above the top of the bulbs. The bulb yield was then weighed.

4.2.3. Measurements and analysis

Plant and soil analysis has been described in Chapter 2. For dry matter analysis, shallot plants were divided into three sections: root, bulb, and leaf. A whole plant was defined as total biomass.

4.2.4. Statistical analysis

Repeated measures analyse of variance (ANOVA) were used using SAS (9.4 version) to assess the effect of treatments on measured parameters. An ANOVA was applied separately to each site (three lime levels x four P fertiliser levels), with the lime and P fertiliser treatments as the fixed effects. The interaction (lime X P) and the means effect of factors (lime and P) were evaluated for all field sites. Means were grouped by Tukey's test. In figures and tables, separate letters indicate a significant difference at $\alpha \leq 5\%$ and $^{*}\alpha \leq 10\%$. Location was excluded due to the high variation in soil chemical characteristics. Data normality and variance consistency were tested by graphical analysis residual. Some data were transformed through a square root transformation to reach a normal distribution. Data averages were used and combined across the three field sites to measure the relationship (R^2) between measured parameters. Although the data were analysed separately, the data was presented in the same table to determine the differences between field sites.

4.3. Results and Discussion

4.3.1. Weather conditions during the shallot growth

The field trials were conducted from 15 November 2018 to 10 February 2019 (0-86 DAP), and the climate data were collected from an Ancolmekar climate station (6-10 km from the field sites). The total precipitation for the trial period was 840 mm, or about 280 mm per month on average (Figure 4.5). The highest daily rainfall was 83 mm, which occurred at 61 DAP. The relative humidity ranged from 66 to 94% (Figure 4.6). Relative humidity remained high between 7 and 34 DAP due to regular rainfall during that period. During the shallot growth, the minimum temperature ranged from 19-22 ºC, and the maximum temperature ranged from 25-33ºC.

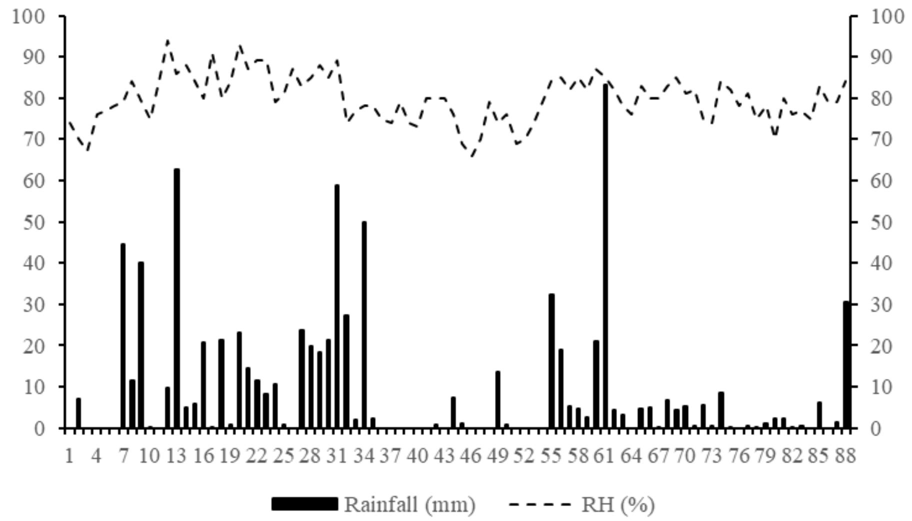

Figure 4.6. The rainfall (mm) and relative humidity (%) during the experimental period.

4.3.2. Effect of lime and P fertiliser application on soil chemical properties

Soil analysis results before experiment

At all three sites, soil samples were collected before soil beds were formed for the shallots. For further details and soil chemical properties, see Table 4.4. All sites are acidic soils with soil pH less than 5.5. Field site 1 had the lowest initial soil pH (pH = 4.23), and Field site 3 had the highest initial soil pH (pH = 5.15). Moreover, Field sites 1 and 3 had a low initial soil available-P (Bray1-P < 20 mg P kg^{-1}), while Field site 2 had a moderate initial soil available-P (Bray1-P > 20 mg P kg^{-1}).

Table 4.4. The field trial sites' characteristics and soil chemical properties approximately one month prior to the shallots were planted.

	Field site 1	Field site 2	Field site 3
Position	7°12'54" S, 107°06'87" E	7°12'73" S, 107°71'88" E	7°12'75" S, 107°71'94" E
Elevation (m asl)	1060	1140	1170
pH_{H2O}	4.23	4.98	5.15
pH_{KCl}	3.30	3.90	4.20
Ca^{2+} (cmol (+) kg^{-1})	4.60	6.79	8.03
Mg^{2+} (cmol (+) kg^{-1})	2.19	3.07	3.88
K^{+} (cmol (+) kg^{-1})	0.70	0.67	0.70
Na^{+} (cmol (+) kg^{-1})	0.07	0.08	0.14
Total Base Cations	7.56	10.61	12.75
Bray1-P (mg P kg^{-1})	14.2 (low)	26.9 (medium)	7.7 (very low)
Retention-P (%)	61	52	48

Soil pH and exchangeable acidity

At the initial soil sampling, about one month before planting, the soil pH_{H2O} values for Field sites 1, 2 and 3 were 4.23, 4.98 and 5.15, respectively (Table 4.4). These values were higher than the average soil pH_{H2O} values for the no lime and no P treatments obtained from the soil sampling conducted 56 DAP. At this time, the soil pH_{H2O} values for Field sites 1, 2 and 3 were 3.90, 4.00 and 4.46, respectively, representing reductions ranging from 0.33 – 0.98 pH units. A possible cause of the differences observed between sampling times could be the initial soil sampling before the soil beds were formed. It appears that bed formation may have resulted in more soil with lower soil pH being redistributed to the soil sampling depth of soil beds. Given these changes to the soil profiles at the field sites between the two soil sampling times, the initial soil test results were primarily used to help identify suitable areas for the study. Therefore, the main comparisons for soil test results should be made between soil samples collected on the same day at 56 DAP.

Across P treatments, lime levels significantly increased soil pH_{H2O} and pH_{KCl} in the three field sites ($p \leq 0.01$, Table 4.5). The highest lime rate of 1.0 t ha^{-1} gave the highest soil pH_{H2O} in all sites. On average, 1 t ha^{-1} lime increased the soil pH_{H2O} by a value of 0.30. However, after liming, the soil pH_{H2O} values were still well below the optimal soil pH_{H2O} for allium crops; for example, onions have an optimum soil pH of 6.1 (Reid & Morton, 2019). Application of a high rate of TSP also increased soil pH_{H2O} significantly in Field sites 1 and 2 ($p \leq 0.10$) and pH_{KCl} in Field site 2 ($p \leq 0.05$) due to the lime effect of TSP. A similar result was reported by Utomo (1995), where the application of 200 mg TSP per kg soil increased soil pH_{H2O} from 4.6 to 4.9. There was no interaction between lime and P fertiliser levels on soil pH_{H2O}, pH_{KCl}, exchangeable Al^{+3} and KCl titratable acidity at all sites ($p > 0.10$, see Appendix 4.2, Table 1 for details).

Table 4.5. Lime and P fertiliser effects on soil pH in each site at 56 DAP.

Treatments	Field site 1		Field site 2		Field site 3	
	pH_{H2O}	pH_{KCl}	pH_{H2O}	pH_{KCl}	pH_{H2O}	pH_{KCl}
0L	3.68^{b}	3.28^{b}	4.10^{b}	3.29^{b}	4.66^{b}	3.76^{c}
0.5L	3.89^{a}	3.31^{b}	4.25^{ab}	3.38^{b}	4.64^{b}	3.91^{b}
1.0L	4.03^{a}	3.40^{a}	4.39^{a}	3.53^{a}	5.14^{a}	4.26^{a}
p-value	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
0P	3.78^{b*}	3.32^{ns}	4.16^{b}	3.29^{b}	4.78^{ns}	3.97^{ns}
50P	3.78^{b}	3.30	4.20^{ab}	3.40^{ab}	4.75	3.94
100P	3.99^{a}	3.35	4.26^{ab}	3.44^{a}	4.86	3.99
150P	3.93^{ab}	3.34	4.36^{a}	3.46^{a}	4.87	4.00
p-value	0.08	0.37	0.05	0.02	0.55	0.82
CV (%)	6.0	2.2	4.0	3.8	5.0	4.4

Tukey's method is used for mean comparison. Means presenting the same letters in the same column are not significantly different at $\alpha = 5\%$, $*\alpha = 10\%$, ns=not significant. Thus, lime values are average across P levels, P values are average across the lime levels.

Every 1 t ha^{-1} lime increased the soil pH_{H2O} by 0.35, 0.29 and 0.48 in Field sites 1, 2 and 3, respectively. The initial pH of a soil can has a bearing on the influence lime has pH change because the pH scale is a log scale. For 1 unit change at lower soil pH represents a more significant change in acidity than a 1-unit change for closer to neutral pH. Therefore, the higher initial pH of Field site 3 may have influenced it showing the most significant pH changes.

The lime application significantly reduced the concentration of exchangeable Al^{3+} and KCl-titratable acidity (the sum of Al^{3+} and H^{+}) at all sites ($p \leq 0.01$, Table 4.6). On average, the lime application of 1.0 t ha^{-1} decreased exchangeable Al^{3+} by 0.40 cmol (+) kg^{-1} and KCl-titratable acidity by 0.51 cmol (+) kg^{-1} across three sites. This highest lime rate decreased exchangeable Al^{3+} from 1.60 to 1.16 cmol (+) kg^{-1} at Field site 1, from 1.13 to 0.65 cmol (+) kg^{-1} at Field site 2, and from 0.27 to 0.04 at Field site 3.

Table 4.6. Lime and P fertiliser effects on exchangeable acidity (cmol (+) kg^{-1}) in each site at 48 DAP.

Treatments	Field site 1		Field site 2		Field site 3	
	Al^{3+}	KCl-titr. acidity	Al^{3+}	KCl-titr. acidity	Al^{3+}	KCl-titr. acidity
	cmol (+) kg^{-1}					
0L	1.60^{a}	1.93^{a}	1.13^{b}	1.43^{a}	0.27^{b}	0.46^{a}
0.5L	1.59^{a}	1.84^{a}	1.00^{b}	1.22^{a}	0.21^{b}	0.40^{a}
1.0L	1.16^{b}	1.39^{b}	0.65^{a}	0.83^{b}	0.04^{a}	0.16^{b}
p-value	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
0P	1.43^{ns}	1.66^{ns}	1.10^{ns}	1.34^{ns}	0.23^{ns}	0.34^{ns}
50P	1.46	1.78	0.98	1.24	0.16	0.39
100P	1.56	1.84	0.81	1.06	0.16	0.34
150P	1.36	1.61	0.83	1.00	0.16	0.29
p-value	0.64	0.53	0.28	0.24	0.77	0.85
CV (%)	9.6	9.5	14.7	13.4	13.7	14.3

Tukey's method is used for mean comparison. Means presenting the same letters in the same column are not significantly different at $\alpha = 5\%$, ns=not significant, KCl-titratable acidity = Al^{3+}+H^{+}. Lime values are average across P levels, P values are average across the lime levels.

When the soil pH_{H2O} results for all research plots at the three sites were compared with exchangeable Al^{3+}, the relationship was moderate quadratic relationship ($R^2 = 0.60$; Figure 4.7). The relationship was particularly weak at Field site 3. At this site, there was a high proportion of soil pH values below 4.60 that also had low exchangeable Al^{3+} of less than 0.5 cmol (+) kg^{-1}. At the other two field sites, most soil pH values below 4.60 had higher exchangeable Al^{3+} of greater than 0.5 cmol (+) kg^{-1}. These results highlight site differences in the relationship between soil pH_{H2O} and exchangeable Al^{3+}.

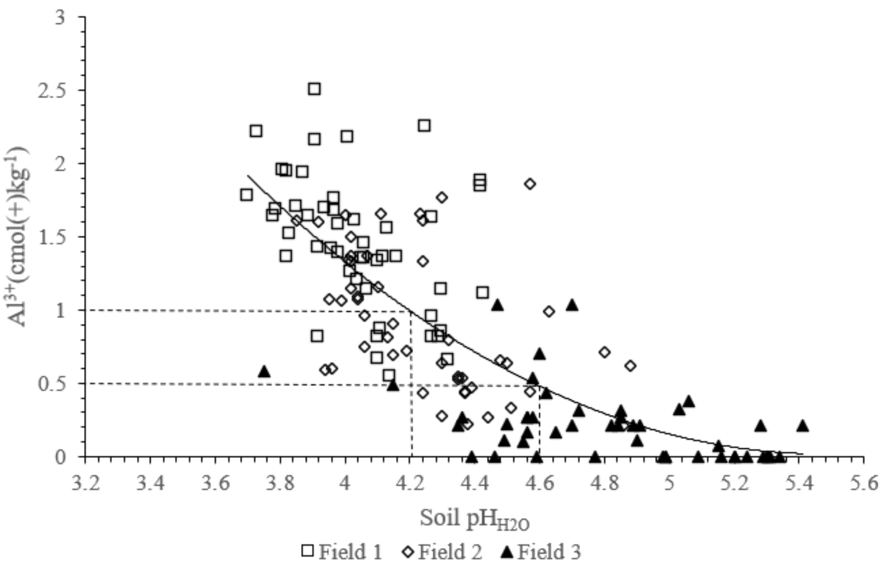

Figure 4.7. The concentration of exchangeable Al^{3+} in relation to soil pH_{H2O} across the sites, $R^2 = 0.60$, n= 168.

When soil pH_{KCl} was compared with exchangeable Al^{3+} at all three sites, the quadratic relationship was stronger (R^2 = 0.79, Figure 4.8). When pH_{KCl} is less than 3.65, most exchangeable Al^{3+} values were higher than 0.5 cmol (+) kg^{-1}. This relationship was more consistent across the three sites than the use of pH measured in water. However, of the three sites, Field site 1 showed the strongest relationship (R^2 = 0.63) between pH_{H2O} and exchangeable Al^{3+}, so the use of pH_{H2O} this Field site 1 to predict the influence of soil acidity on aluminium toxicity may still be a helpful method at some sites.

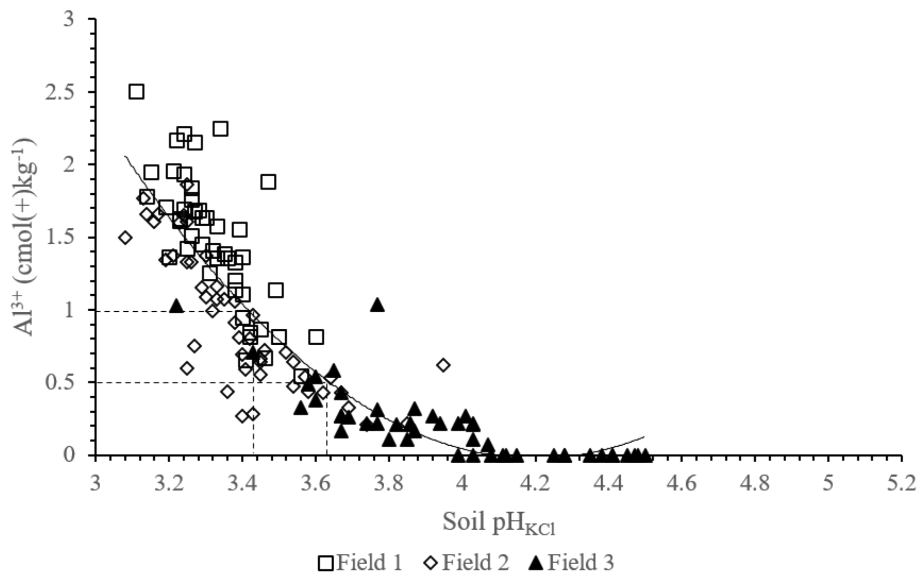

Figure. 4.8. The concentration of exchangeable Al^{3+} in relation to soil pH_{KCl} across the sites, R^2= 0.79, n= 168.

The pH_{KCl} refers to soil acidity in soil solution plus the reserve acidity on the colloids, making it a more suitable method to measure exchangeable acidity than pH_{H2O} in strongly acidic soils. Furthermore, the fixed value of 1 M pH_{KCl} bears a strong correlation with exchangeable Al^{3+} (Wang et al., 2019), in which the salts displaces H^+ and Al^{3+} ions from the exchange complex (Kome et al., 2018).

Exchangeable base cations, cation exchange capacity (CEC) and base saturation (BS)

Alone, the lime and P fertiliser treatments significantly increased ($p \leq 0.05$) the concentration of exchangeable Ca^{2+} in the soil compared to the no-lime and no-P treatment, which increased the sum of the total base cations (TBC) at all sites, primarily due to increases in exchangeable Ca^{2+} (Table 4.7). These increases in exchangeable Ca^{2+} were influenced by the Ca applied in both the lime material and P fertiliser (TSP is typically about 16% Ca) (Utomo, 1995).

Table 4.7. Lime and P fertiliser effects on Ca^{2+} concentration (cmol (+) kg^{-1}) and total base cations (TBC) (cmol (+) kg^{-1}) in each site at 56 DAP.

Treatments	Field site 1		Field site 2		Field site 3	
	Ca^{2+}	TBC	Ca^{2+}	TBC	Ca^{2+}	TBC
	cmol (+) kg^{-1}					
0L	3.33^{b}	5.40^{ns}	4.26^{b}	6.34^{b}	5.52^{b}	8.29^{b}
0.5L	3.80^{ab}	5.76	4.57^{b}	6.61^{b}	6.28^{b}	9.23^{b}
1.0L	4.27^{a}	6.28	5.57^{a}	7.63^{a}	8.51^{a}	11.37^{a}
p-value	<0.01	0.02	<0.01	<0.01	<0.01	<0.01
0P	3.41^{ns}	5.42^{ns}	4.46^{b}	6.55^{b*}	6.58^{ab}	9.53^{ab}
50P	3.77	5.73	4.70^{ab}	6.75^{ab}	6.34^{ab}	9.14^{b}
100P	3.94	6.03	4.73^{ab}	6.77^{ab}	6.45^{ab}	9.22^{b}
150P	4.09	6.08	5.31^{a}	7.38^{a}	7.71^{a}	10.63^{a}
p-value	0.13	0.22	0.05	0.07	0.02	0.02
CV (%)	18.7	14.4	15.2	11.2	17.1	12.9

Tukey's method is used for means comparison. Means presenting the same letters in the same column are not significantly different at $\alpha = 5\%$, $*\alpha = 10\%$. ns = not significant. TBC = $\sum(Ca^{2+}+Mg^{2+}+K^{+}+Na^{+})$. Lime values are average across P levels, P values are average across the lime levels.

There was no interaction between lime and P fertiliser on the concentration of exchangeable Ca^{2+} or total base cations (TBC) (see Appendix 4.2, Table 3 for details). There was also no interaction and no effect of lime and P fertiliser on other base cations at 56 DAP in all sites, except for the concentrations of Mg^{2+} and K^{+} in Field site 3; however, the results were not consistent (see Appendix 4.2, Table 4 for details). Overall, the Mg^{+} and K^{+} concentrations at 56 DAP were in the high range. The concentrations of Mg^{2+} in control treatments were 0.94 to 1.65 cmol (+) kg^{-1} and the concentrations of K^{+} were 0.94 to 1.17 cmol (+) kg^{-1}. The medium range of exchangeable Mg^{2+} for onion is about 0.35-0.59 cmol (+) kg^{-1} and the medium-range of K^{+} is about 0.70-0.80 cmol (+) kg^{-1} (Khokhar, 2019). Moreover, there were no visual symptoms of Mg and K deficiency in all sites. Therefore, soil available Mg and K levels are unlikely to be plant growth-limiting factors in this study.

The CEC levels of the control treatment at Field sites 1, 2 and 3 were 13.70, 12.78 and 14.83 cmol (+) kg^{-1} with base saturation (BS) about 38, 47 and 56%, respectively (Appendix 4.2, Table 5). On the other hand, the 1 t ha^{-1} lime significantly increased BS at Field sites 2 and 3 to 60 and 74%, respectively. At the same time, the highest P fertiliser rate increased CEC in Field site 1, 2 and 3 to 14.45, 13.32 and 14.97 and improved BS in Field site 2 and 3 to 55 and 70%.

Al:Ca ratio

Determining Al phytotoxicity in acidic soils is complex. Soil pH alone does not consistently predict Al toxicity on plant growth (Adams, 1981). Meanwhile, the exchangeable Al^{3+} is dominant in acidic soils (pH < 5.0) and is assumed to be the significant phytotoxic species of Al (Delhaize & Ryan, 1995). The ratio of Al^{3+} and Ca^{2+}, which is another way of expressing the Al toxicity level, has been proposed as a better predictor of the effects of Al toxicity on plant growth (Vanguelova et al., 2007). Nevertheless, there is no current guideline for the ideal ratio of Al:Ca range for shallot nor onion. In this experiment, the relationship between exchangeable Al^{3+} and Ca^{2+} was strongly negative (Figure 4.9).

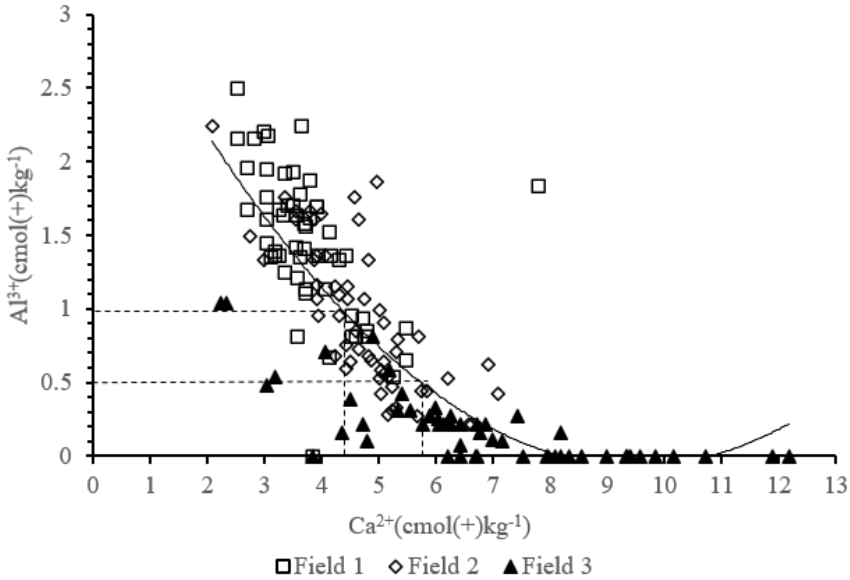

Figure 4.9. The concentration of exchangeable Al^{3+} in relation to exchangeable Ca^{2+} across the sites, R^2= 0.66, n= 168.

There was no interaction between lime and P fertiliser rates on Al:Ca ratio (see Appendix 4.2, Table 3 for details). Al:Ca ratio for 0L across P levels were 0.51, 0.28 and 0.08 for Field sites 1,2 and 3 respectively. The lime reduced the Al:Ca ratio in all sites ($p \leq 0.05$; Table 4.8). The 1 t ha^{-1} lime application gave the lowest Al:Ca ratio in all sites of 0.29, 0.13 and 0.01 at Field sites 1, 2 and 3, respectively. While the application of P fertiliser did not significantly affect the ratio of Al:Ca. Lime reduced Al:Ca ratio by decreasing solubility of exchangeable Al^{3+} via increasing the soil pH and increasing the concentration of exchangeable Ca^{2+} via the direct effect of releasing Ca^{2+} ions from lime materials (Anderson, Hart, Sullivan, Horneck, et al., 2013; Bolan et al., 2003).

Table 4.8. Lime and P fertiliser effects on the ratio of Al:Ca in each site at 56 DAP.

Treatments	Field site 1	Field site 2	Field site 3
0L	0.51[a]	0.28[a]	0.08[a]
0.5L	0.45[a]	0.24[a]	0.07[ab]
1.0L	0.29[b]	0.13[b]	0.01[b]
p-value	<0.01	<0.01	<0.05
0P	0.44[ns]	0.24[ns]	0.05[ns]
50P	0.41	0.27	0.07
100P	0.46	0.18	0.06
150P	0.36	0.17	0.03
p-value	0.43	0.16	0.64
CV (%)	6.8	8.3	6.8

Tukey's method is used for means comparison. Means presenting the same letters in the same column are not significantly different at $\alpha = 5\%$ ns=not significant. Al:Ca = Al^{3+}(cmol (+) kg^{-1}) /Ca^{2+} (cmol (+) kg^{-1}). Lime values are average across P levels, P values are average across the lime levels.

In overview, Ca^{2+} occupied most cation exchange capacity in all sites, and increased Ca^{2+} saturation (Figure 4.10). Moreover, Field site 3 had a higher Ca saturation and the lowest Al saturation of the three field sites. Meanwhile, the saturation of other cations, Mg^{2+}, K^{+}, and Na^{+}, were not significantly different among the sites. Moreover, Na^{+} saturation was the lowest compared to other base cation saturations.

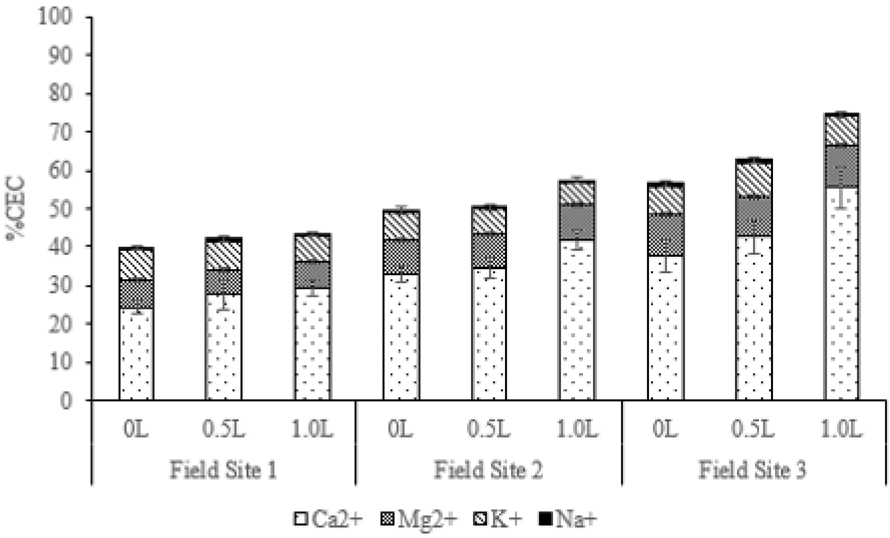

Figure 4.10. The comparison of cation saturation at Field sites 1, 2 and 3 at 56 DAP in lime treatments across all P rates. Error bars are standard errors, n = 16.

Soil available P (Bray1-P)

The application of P fertiliser significantly improved soil available-P in all sites ($p \leq 0.01$, Table 4.9). The highest P fertiliser rate, 150 kg P ha^{-1}, improved the soil available-P significantly to 35.0, 39.8 and 41.3 mg P kg^{-1} P in Field sites 1, 2 and 3 than 0P. While the soil available P (Bray1-P) on 0 kg P ha^{-1} treatments (across all lime rates) were 21.6, 27.6 and 11.9 mg P kg^{-1} for Field sites 1, 2 and 3, respectively, and there was no interaction between lime and P fertiliser levels on soil available P (see Appendix 4.2, Table 6).

Table 4.9. Lime and P fertiliser effects on soil available P (Bray1-P, mg P kg^{-1}) for each site at 56 DAP.

Treatments	Field site 1	Field site 2	Field site 3
0L	25.2^{ns}	31.3^{ns}	26.1^{ns}
0.5L	28.4	35.0	24.6
1.0L	27.8	29.7	28.1
p-value	0.60	0.42	0.74
0P	21.6^{b}	27.6^{b}	11.9^{c}
50P	26.6^{ab}	29.6^{b}	24.1^{b}
100P	25.4^{ab}	30.9^{b}	27.7^{ab}
150P	35.0^{a}	39.8^{a}	41.3^{a}
p-value	0.01	<0.01	<0.01
CV (%)	35.0	25.1	48.3

Tukey's method is used for means comparison. Means presenting the same letters in the same column are not significantly different at α = 5%, ns=not significant. Thus, lime values are average across P levels, P values are average across the lime levels.

4.3.3. Effect of lime and P fertiliser application on plant growth and nutrient uptake

Plant growth

At Field site 3, the control treatment (0L+0P) had better plant growth than at the other two field sites, 15 days after planting (Figure 4.11). The control treatment at Field site 3 had the lowest Al:Ca (0.07) and the lowest soil available-P (Bray1-P 11.7 mg P kg^{-1}), compared to other sites (Al:Ca 0.33 and 0.52, Bray1-P 21.2 and 29.2 mg P kg^{-1} for Field sites 1 and 2, respectively) (see Appendix 4.2, Table 3 and 6 for details). At Field sites 1 and 2, it is likely that soil acidity and Al toxicity are more crucial limiting factors than the availability of soil P. Both sites had higher Al:Ca ratios and Bray1-P levels than Field site 3.

Figure 4.11. Shallot growth in the control treatment (0L+0P) at 15 DAP in all sites.

Lime and P-fertiliser did not significantly affect the number of leaves and number of tillers of shallot cv. 'Sumenep' at 21 and 42 DAP (see Appendix 4.3 for details). It was reported that the number of tillers mostly are likely controlled by genetic traits rather than agronomy traits (Abdissa et al., 2011). However, on average, lime across the P treatments increased shallot shoot length at Field sites 1 and 2. Moreover, P increased the shoot length at Field site 3 (see Appendix 4.3 for details).

The biomass in control treatments (0L+0P) at 56 DAP were 3.42, 6.15 and 8.06 g/plant for Field sites 1, 2 and 3, respectively. At this sampling time, the lime and P fertiliser application alone gave varying effects on shallot plant biomass. When the effect of lime treatments was averaged across all P fertiliser rates, application of 1 t lime ha^{-1} significantly increased plant biomass by 20 and 29% in Field sites 1 and 2, respectively, compared to the 0 kg P ha^{-1} treatments on average. A lime response was not seen at Field site 3, but it had the highest soil pH and lowest exchangeable Al level of the three sites. When the effect of P fertiliser treatments was averaged across all lime rates, applications of 100 and 150 kg P ha^{-1} significantly increased plant biomass, shallot biomass increased by 30% and 29% for the 100 and 150 kg P ha^{-1} treatments, respectively, compared to the 0 kg P ha^{-1} treatments for Field site 3. Of the three sites, Field site 3 had the lowest Bray-1 P level, which was well below optimum for vegetable production, which helps explain why a plant growth response to added P at this site. While there was no significant response to P levels at sites 1 and 2. And there was no interaction between lime and P on shallot total biomass at all sites.

Table 4.10. Lime and P fertiliser effects on shallot total biomass (g/plant) at 56 DAP in each site.

Lime (t ha^{-1})	P-Fertiliser (kg ha^{-1})	Field site 1	Field site 2	Field site 3
0	0	3.42^{ns}	6.15^{ns}	8.06^{ns}
0	50	3.69	7.71	9.09
0	100	4.58	7.61	10.42
0	150	4.24	7.81	9.61
0.5	0	4.60	7.48	7.06
0.5	50	5.02	7.08	9.47
0.5	100	4.49	7.30	9.25
0.5	150	4.85	7.95	10.47
1.0	0	4.11	9.26	8.71
1.0	50	4.78	8.67	11.30
1.0	100	5.14	9.87	11.37
1.0	150	4.68	9.88	10.77
	p-value	0.51	0.55	0.78
	CV (%)	16.7	14.4	21.3
	0L**	3.98^{b}	7.32^{b}	9.29^{ns}
	0.5L**	4.74^{a}	7.45^{b}	9.06
	1.0L**	4.67^{a}	9.42^{a}	10.54
	p-value	0.01	<0.01	0.11
	0P***	4.04^{ns}	7.63^{ns}	7.94^{b}
	50P***	4.50	7.82	9.95^{ab}
	100P***	4.73	8.26	10.35^{a}
	150P***	4.59	8.55	10.28^{a}
	p-value	0.14	0.22	0.02

Tukey's method is used for means comparison. Means presenting the same letters in the same column are not significantly different at $\alpha = 5\%$, $*\alpha = 10\%$, ns=not significant. **Averaged across all P levels, ***Averaged across all lime levels.

The plant growth at 56 DAP can be seen in Figure 4.12. During the trial, spraying insecticides and pesticides was conducted weekly from weeks 3 to 11 after planting, not an observable pest, and disease incidences were reported at the trial sites.

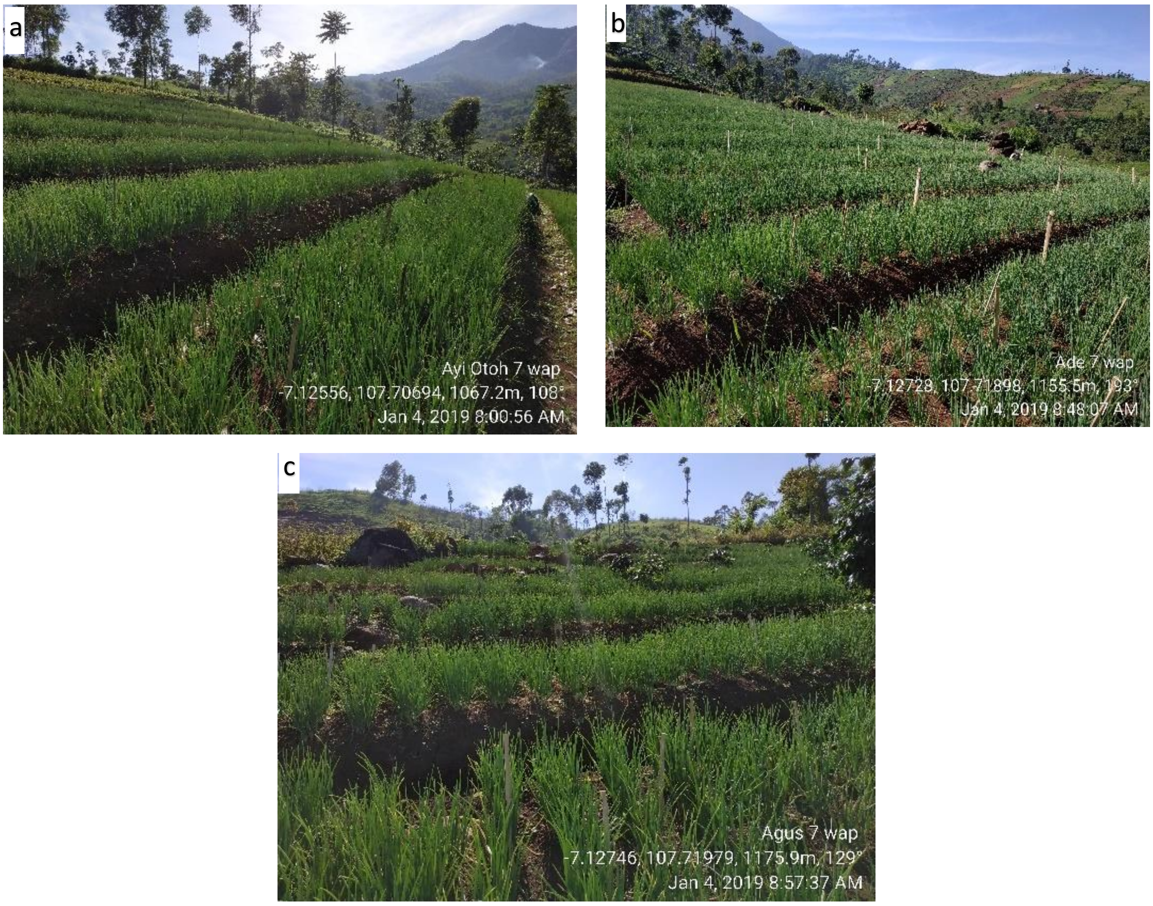

Figure 4.12. Shallot growth at 49 DAP in (a) Field site 1, (b) Field site 2 and (c) Field site 3.

Across all three sites, there was an overall trend of lower root dry weight being associated with higher concentrations of exchangeable Al^{3+} (Figure 4.13). When exchangeable Al^{3+} was lower than 0.5 cmol (+) kg^{-1}, most root dry weight was above 0.25 g/plant. While when the exchangeable Al^{3+} was more than 1.80 cmol (+) kg^{-1}, the majority of the root-dry weight was below 0.25 g/plant. Across the three sites, it seems that 0.5 cmol (+) kg^{-1} was the threshold level of exchangeable Al^{3+} for shallot, below which this is a high likelihood of improved root growth.

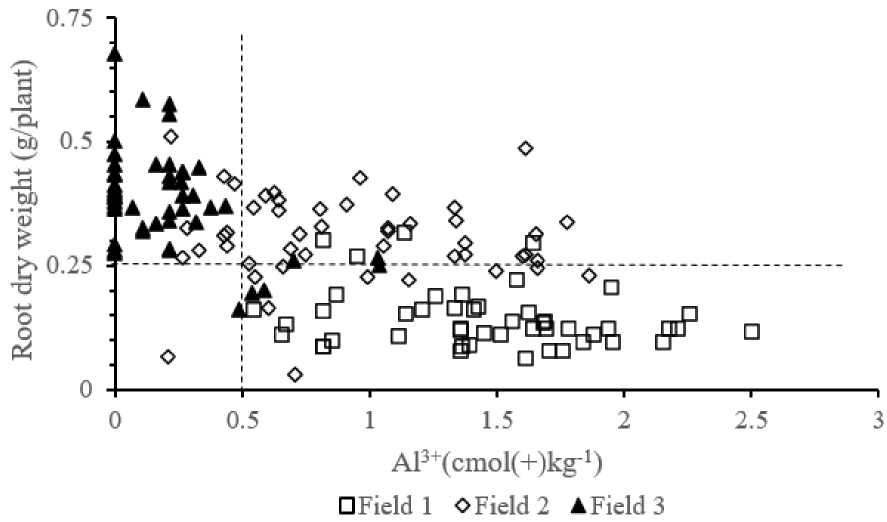

Figure 4.13. Root dry weight, at 56 DAP, in relation to the concentration of exchangeable Al^{3+}. R^2 = 0.43, n=168.

Root dry weight also was negatively correlated with the soil Al:Ca ratio (Figure 4.14). When the Al:Ca ratio less than 0.1, then a root dry weight higher than 0.25 g/plant was more likely. While, when the Al:Ca ratio was more than 0.5, the root dry weight was less than 0.25 g/plant. Therefore, it provides some indication that Al:Ca ratios below 0.1 could indicate low Al toxicity, and Al:Ca ratio more than 0.5 could indicate high Al toxicity. In contrast, between 0.1 and 0.5 show a moderate range of Al toxicity for shallot. While an established Al toxicity range for shallot has not been previously reported, the influence of Al:Ca ratios have been reported for other crops. For example, Fageria et al. (1989) reported the negative relationship between Al:Ca ratio and alfalfa biomass. Compared to control treatment with an Al:Ca ratio of 0, increases in Al:Ca ratio to 0.35 and 0.64 coincided with decreases in alfalfa plant dry weight of 42% and 65%, respectively.

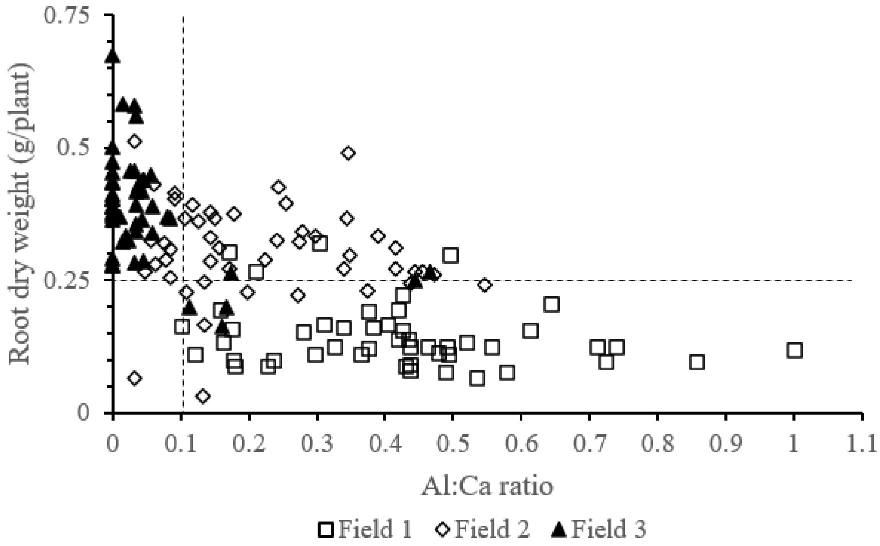

Figure 4.14. Root dry weight, at 56 DAP, in relation to the ratio of Al:Ca across the three field sites. R^2 = 0.44, n=168.

Nutrient uptake

Overall, the uptake of N, P and K were lower for Field site 1 (Table 4.11) than the other two sites, which primarily reflected differences in plant dry matter yield (Table 4.10). The effect of lime treatments averaged across all P fertiliser treatments significantly increased N and P uptake at Field sites 1 and 3 and increased N, P and K uptake at Field site 2. At Field sites 1 and 2, the nutrient increase was primarily due to an increase in plant biomass, whereas, at Field site 3 it was due to a combination of increasing plant biomass and nutrient concentration (see Appendix 4.4 for details). Whereas the effect of P fertiliser levels, averaged across all lime treatments, significantly increased N and P uptake at Field sites 1 and 3. At Field site 3, the increased nutrient uptake was due to increased plant biomass, whereas at Field site 1, it was due to a combined effect of increasing plant biomass and nutrient concentration. However, the total nutrient uptake in Field site 1 was lower compared to other sites, which may have been caused by lower plant dry matter yield.

Table 4.11. Lime and P fertiliser effects on shallot plant total NPK uptake (kg ha^{-1}) at each site at 56 DAP.

	Field site 1			Field site 2			Field site 3		
	N	P	K	N	P	K	N	P	K
0L	27.6^{b}	3.2^{b}	26.9^{ns}	50.7^{b}	5.8^{b}	57.5^{b}	62.3^{b}	6.3^{b}	56.1^{ns}
0.5L	32.8^{a}	3.6^{ab}	30.8	52.2^{b}	6.0^{b}	59.6^{b}	62.2^{b}	6.6^{b}	56.0
1.0L	31.9^{ab}	3.7^{a}	29.6	71.0^{a}	7.9^{a}	79.6^{a}	74.8^{a}	8.0^{a}	66.2
p-value	0.02	0.05	0.18	<0.01	<0.01	<0.01	0.03	0.03	0.22
0P	26.7^{b}	3.0^{b}	25.9^{ns}	56.2^{ns}	6.6^{ns}	63.9^{ns}	55.0^{b}	5.7^{b*}	49.0^{ns}
50P	31.3^{ab}	3.5^{ab}	29.9	55.4	6.0	61.5	69.1^{ab}	7.4^{a}	65.0
100P	31.9^{ab}	3.7^{a}	31.7	61.5	6.9	68.7	70.7^{a}	7.5^{a}	62.6
150P	33.3^{a}	3.7^{a}	29.1	58.6	6.7	68.1	70.9^{a}	7.3^{a}	61.0
p-value	0.03	0.03	0.13	0.39	0.26	0.49	0.03	0.06	0.18
CV (%)	17.7	16.5	20.4	16.2	18.6	20.2	22.1	25.9	31.3

Tukey's method is used for means comparison. Means presenting the same letters are not significantly different at $\alpha \leq 5\%$, * $\alpha \leq 10\%$, ns=not significant. Thus, lime values are average across P levels, P values are average across the lime levels.

4.3.4. Effect of lime and P fertiliser application on shallot bulb yield

There was a general trend of yield increasing with lime levels at Field site 2. At this site, when the effect lime level was average across all P fertiliser rates, there was a statistically ($p \leq 0.01$) significant effect on shallot yield. The use of 1.0 t lime ha-^{1} increased the yield of 10.61 t ha^{-1}, 38% higher than for the no lime treatments on average (Table 4.12).

Table 4.12. Effect of lime and P fertiliser rates on fresh bulb yield (t ha^{-1}) in each site at final harvest (83 DAP).

Lime (t ha^{-1})	P-Fertiliser (kg ha^{-1})	Field site 1	Field site 2	Field site 3
0	0	6.11^{ns}	6.94^{ns}	8.21^{ns}
0	50	5.71	7.77	9.64
0	100	6.19	8.30	10.00
0	150	6.57	7.73	10.04
0.5	0	5.70	9.77	8.94
0.5	50	6.03	7.96	9.49
0.5	100	6.78	8.27	11.35
0.5	150	7.75	9.85	11.40
1.0	0	5.98	10.78	8.93
1.0	50	6.05	8.67	11.08
1.0	100	7.04	11.52	10.26
1.0	150	6.12	11.48	9.95
p-value		0.30	0.66	0.53
CV (%)		14.5	24.6	14.8
0L**		6.15^{ns}	7.67^{b}	9.50^{ns}
0.5L**		6.57	8.96^{ab}	10.30
1.0L**		6.30	10.61^{a}	10.06
p-value		0.43	< 0.01	0.30

	Field site 1	Field site 2	Field site 3
0P***	5.93^{b}	9.16	8.73^{b}
50P***	5.93^{b}	8.13	10.07^{ab}
100P***	6.67^{ab}	9.36	10.47^{a}
150P***	6.81^{a}	9.69	10.54^{a}
p-value	0.04	0.37	0.04

Tukey's method is used for means comparison. Means presenting the same letters are not significantly different at $\alpha = 5\%$, *$\alpha = 10\%$, ns = not significant, harvested area index =70%. **Average across all P rates. ***Averaged across all lime rates.

When the effect of P fertiliser rates was averaged across all lime treatments, evidence of a significant impact at Field sites 1 and 3. At Field site 1, the 150 kg P ha^{-1} treatment achieved a bulb yield of 6.81 t ha^{-1}, which was 15% higher than the 0 kg P ha^{-1} treatments on average. At this site, the average soil test Bray-1 P level for the 0 P ha-1 treatments was 21.6 mg P kg^{-1}. Thus, the increasing yield indicates evidence of a benefit from the P addition at this site. However, this still had low yields on average of < 7 t ha^{-1}, at the higher P rates. Therefore, there are likely to be other factors also liming crop yield response at this site.

Field site 3, the 100 and 150 kg P ha^{-1} treatments achieved bulb yields of 10.47 and 10.54, respectively, 20 and 21% higher than the 0 kg P ha^{-1} treatments on average. At this site, there was little benefit above the 100 kg P ha^{-1}. While the effect of the 50 kg P ha^{-1} rate was not significantly different from the 0 kg P ha^{-1} rate, the average yield was 15% higher for this P treatment. The results support that the majority of the yield increase seen for the 100 kg P ha^{-1} rate was likely achieved with the first 50 kg P ha^{-1} applied. Therefore, the optimum P rate at this site is likely to be between 50 and 100 kg P ha^{-1}.

Root dry weight (56 DAP) positively correlated with fresh bulb yield at harvest (83 DAP, Figure 4.15). When the root weight was less than 0.22 g/plant, most bulb yields were less than 10 t ha^{-1} (i.e., high bulb yield), and when the root was more than 0.46 g/plant, the majority of bulb yield was more than 10 t ha^{-1}. Therefore, this observation supports that when the root dry weight was less than 0.22 g/plant, there is a very low likelihood of a high bulb yield. In contrast, when the root dry weight was above 0.46 g/plant, there was a high possibility of a high bulb yield. Thus, for root dry weight in the range of 0.22 to 0.46 g/plant, there was a wide variation in fresh bulb yields. This relationship provides an early indicator of yield potential. However, the ability to make soil fertility improvements at 56 DAP to improve yield may be of limited benefit but will depend on the cause of yield limitation.

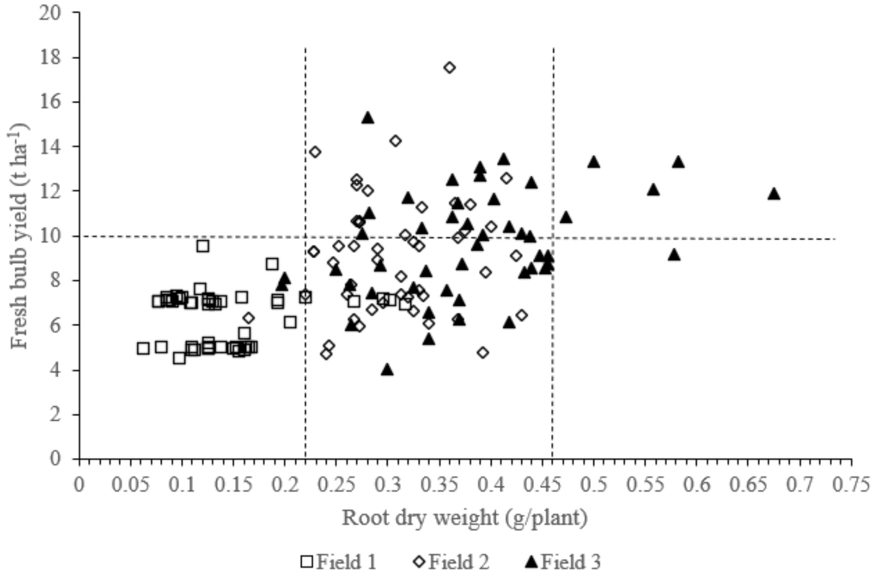

Figure. 4.15. Root dry weight (56 DAP) in relation to fresh bulb yield (t ha^{-1}, 83 DAP) across the sites. R^2 = 0.31, n=168.

Fresh bulb yield has a weak negative relationship with exchangeable Al^{3+} across the treatments and sites (Figure 4.16). When the exchangeable Al^{3+} was above 1.0 cmol (+) kg^{-1}, the majority of fresh bulb yields were less than 10 t ha^{-1}, and when the soil pH was less than 0.5 cmol (+) kg^{-1}, most of the bulb yields were more than 10 t ha^{-1}. However, low yields were also found when the exchangeable Al^{3+} < 0.5 cmol (+) kg^{-1}, which the low bulb yield majority came from Field site 3. This phenomenon might be due to another limitation, low soil available-P in this site resulted in low yields.

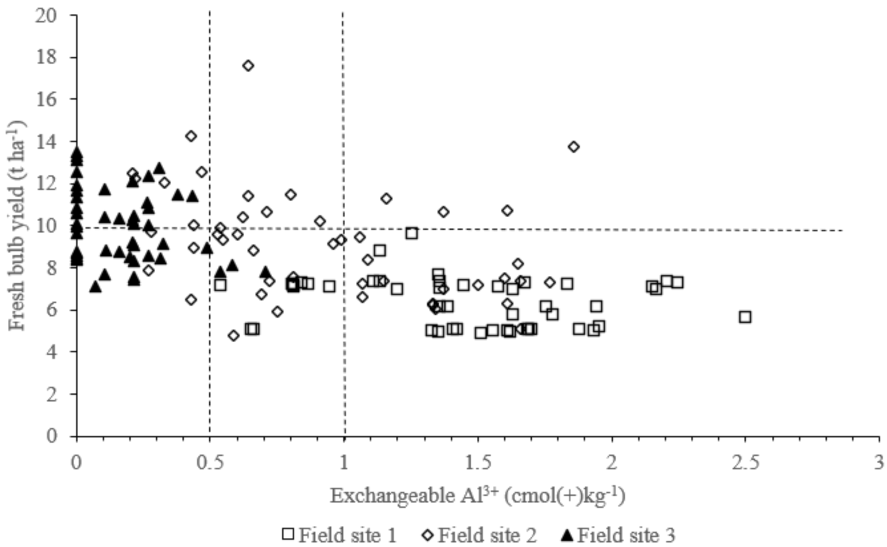

Figure. 4.16. Exchangeable Al^{3+} in relation to fresh bulb yield (t ha^{-1}, 83 DAP) across the three sites. R^2 = 0.37, n =168.

As mentioned above, the Al:Ca ratio has a negative relationship with root dry weight (56 DAP). On the other hand, root dry weight has a positive relationship with fresh bulb yield at harvest time (83 DAP). Thus, fresh bulb yield has a negative relationship with Al:Ca ratio (Figure 4.17). The weak correlation was shown in Figure 4.16 that when the Al:Ca ratio less than 0.1, the majority of high yield (> 10 t ha^{-1}) was more likely. On the contrary, when the Al:Ca ratio was above 0.5, most bulb yields were low (< 10 t ha^{-1}). However, a wide variation occurred between 0.1 and 0.5, which other limiting factors might cause. Moreover, at Field site 3, when the Al:Ca ratio was low (< 0.1), the low bulb yields (< 10 t ha^{-1}) were also found. This finding also identifies another limitation, other than Al:Ca ratio, in Field site 3 that needs to be addressed to improve the shallot bulb yield in this site, which was available soil P (Table 4.12).

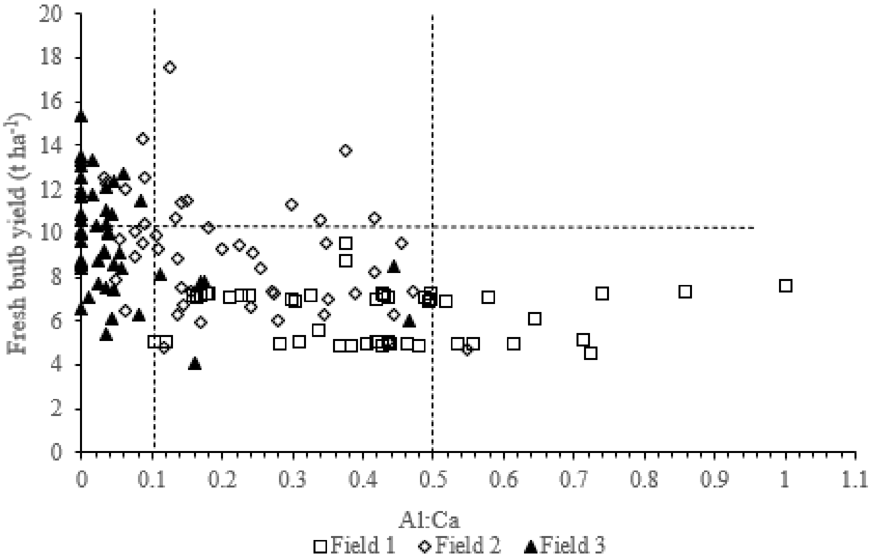

Figure. 4.17. Al:Ca ratio in relation to fresh bulb yield (t ha^{-1}, 83 DAP) across the sites. R^2 = 0.29, n=168.

4.4. The Summary of Shallot Bulb Yield Response to Lime and P Fertiliser at Each Field Site

4.4.1. Field site 1

At Field site 1, there was some evidence of an improvement in bulb yield from P fertiliser addition. However, even with high P fertiliser rates, bulb yields at this site remained low. This indicates that factors other than P availability were containing further improvements in bulb yield. In addition, this site has a moderate level of soil available P, as measured with the Bray1 P soil test, so the benefits of further increasing soil available P would be expected to be limited. The use of low to moderate rates of lime at this site reduced exchangeable Al^{3+}, but levels remained high (> 1 cmol (+) kg $^{-1}$) with the use of 1 t lime ha^{-1}. High exchangeable Al^{3+} has the potential to be causing aluminium toxicity, which could be contributing to the low yields at this site. Field site 1 is located closer to village than the other field sites in this study. Therefore, it has better access for allowing the use of heavy inputs like lime and creates an opportunity to use higher rates of lime (i.e., capital rates) to enable soil pH to be increased to a level that would achieve a low exchangeable Al^{3+}. The farms closer to villages typically have been cropped the longest and may also have the greater need for lime inputs if there has been limited use of lime historically. In addition, recent changes were made by the government to remove Category 3 land from vegetable production (Figure 4.4). This condition puts more pressure on other are of farmland to be more productive. Therefore, further research is required to identify the optimum lime inputs for farms with high exchangeable Al^{3+} and evaluate the benefits for shallot production.

4.4.2. Field site 2

As discussed earlier, the poor accessibly of Field site 2 (Figure 4.4) means that crop inputs need to be carried in by foot. Therefore, this is a critical constraint for farmers using heavy inputs and became a major reason why many farmers in the Pacet District do not use lime regularly despite low soil pH levels. In Field site 2, a moderate rate of lime increased bulb yields significantly. At this site, 1 t lime ha^{-1} was sufficient to reduce exchangeable Al^{3+} from a high level down to a more moderate level (0.65 cmol (+) kg^{-1}) (Table 4.6). At both Field sites 1 and 2, the addition of 1 t lime ha^{-1} decreased exchangeable Al^{3+} by about 0.5 cmol (+) kg^{-1} (Table 4.6). However, Field site 1 had a higher initial exchangeable Al^{3+} than Field site 2, which could explain why this rate of lime was more effective at Field site 2 in terms of improving shallot bulb yield.

Exchangeable Al^{3+} primarily affects buffering capacity in very acidic soils (soil pH < 5.4). It has been identified that determining the lime rate based on exchangeable Al^{3+} could be more efficient than bringing the soil pH to the soil pH target (Kamprath, 1970). For example, the application lime rate was equivalent to the amount of 1.0 x Exch. Al^{3+} reduced the concentration of exchangeable Al^{3+} and increased soybean yield in an Ultisol soil (Wahjudin, 2006) and red chilli yield in acidic Inceptisol soil (Janah, 2020). A similar result was observed in the current study at Field site 2, where the application of 1.0 t ha^{-1}, equivalent to 0.9 x Exch. Al^{3+} increased the shallot bulb yield significantly (Table 4.12). This result is also consistent with another recent study on shallots, where dolomite rate was equivalent to 1.0 x Exch. Al^{3+}

gave a higher bulb yield than 0.5 x Exch. Al^{3+} in acidic Ultisol soil (Nasution et al., 2019). In the current study at Field site 1, the 1 t lime ha^{-1} rate was only equivalent to 0.6 x Exch. Al^{3+}, which could explain why a yield response to lime was not observed at this site.

This study supports that the exchangeable Al^{3+} level could indicate which farms would benefit from low to moderate lime rates to improve shallot yields. Using exchangeable Al^{3+} as the lime rate would be particularly useful for the more remote farms, like Field sites 2 and 3. For example, at Field site 2, when the exchangeable Al^{3+} < 0.82, then high shallot yields (>10 t ha^{-1}) are achievable (Figure 4.18). However, by aiming to maintain exchangeable Al^{3+} < 0.5 cmol (+) kg^{-1}, will help to minimise the risk that aluminium toxicity will limit yield potential.

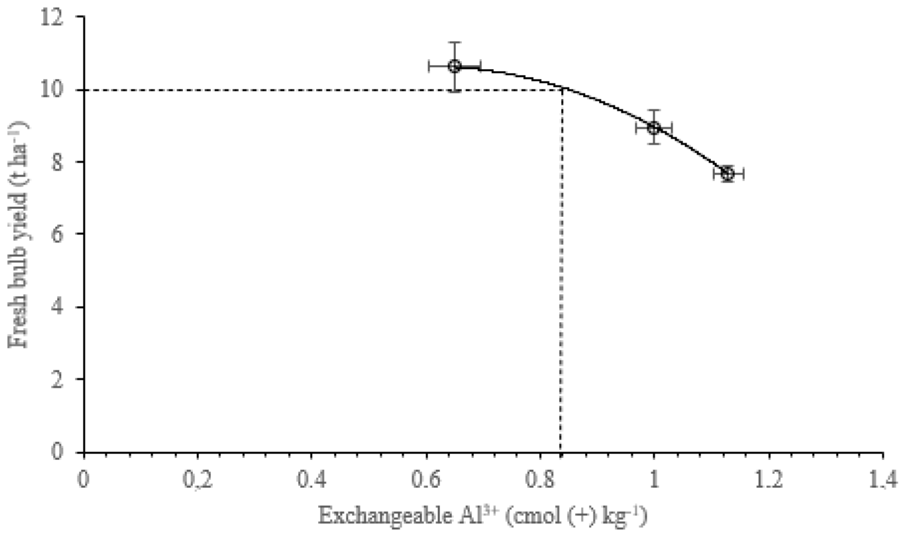

Figure 4.18. The relationship between exchangeable Al^{3+} (cmol (+) kg^{-1}) and fresh bulb yield (t ha^{-1}) on lime treatments across all P levels in Field site 2, error bars are standard error, n=16.

Response to P fertiliser use was not observed at this site, which had a control treatment Bray1-P of 28 mg P kg^{-1}. The no response to P fertiliser rate would indicate that this level of soil available P is adequate to achieve high shallot yields. Therefore, once soil P status is at this level, farmers can reduce P fertiliser inputs to maintenance levels.

4.4.3. Field site 3

At Field site 3, which had low exchangeable Al^{3+} (0.27 cmol (+) kg^{-1}) and low soil available-P (Bray1 P of 12 mg P kg^{-1}), the P fertiliser application significantly improved the shallot bulb yield but not the lime application. At this site, bulb yield increased up to about 10 t ha^{-1}, increasing soil P status up to a soil Bray1 P of 28 mg P kg^{-1} (Figure 4.19). Therefore, this supports that high shallot yields can be achieved with soil Bray1 P levels at this level or higher. At this site, which had a P-retention of 48%, the 100 kg P ha^{-1} P fertiliser rate, when broadcast and mixed into the soil bed just before planting, was sufficient to increase Bray1 P from 12 to 28 mg P kg^{-1}. Therefore, with soils with low initial Bray1 P levels, high yields shallot can be achieved with moderate P fertiliser rates. The lack of a lime response at this site is likely to reflect the low exchangeable Al^{+3} of 0.27 cmol (+) kg^{-1}. Suppose the lime rate was based on applying 1.0 x Exch. Al^{3+}, then only a low rate of 0.27 t lime ha^{-1} would be required.

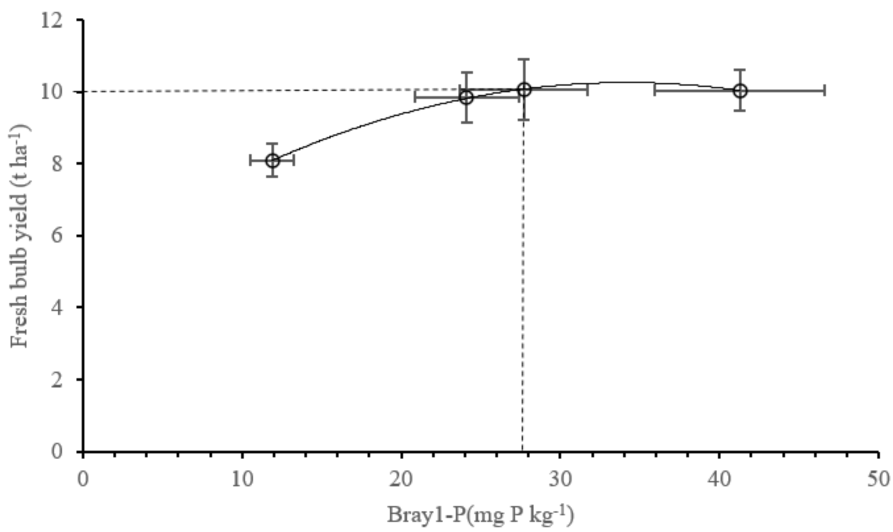

Figure 4.19. The relationship between soil available-P (Bray1-P, mg P kg^{-1}) and fresh bulb yield (t ha^{-1}) on P treatments across all lime levels in Field site 3, error bars are standard error, n=16.

4.5. Conclusions

This field experiment aimed to identify the optimum lime and P fertiliser management strategies for three contrasting farm sites with highly acidic soils in the Pacet District, West Java. This experiment confirmed that exchangeable Al^{3+} and Al:Ca ratio could be an effective approach for determining lime requirements for growing high yielding shallots. A greater likelihood of high yields was observed when exchangeable Al^{3+} is < 0.82 cmol (+) kg^{-1}. Thus, the general approach of determining lime rates from exchangeable Al^{3+} showed promise for use when growing shallots on highly acidic soils, helping to achieve high yields while minimising the use of lime. This is particularly important for those more remote sites, such as Field sites 2 and 3, where site access limits the use of large quantities of lime. Low to moderate rates of lime (≤ 1 t lime ha^{-1} or equivalent to 0.9 - 1.0 x Exc. Al^{3+}) were sufficient for high shallot yields when exchangeable Al^{3+} < 1.2 cmol (+) kg^{-1}. For farms with high exchangeable

> 1.2 cmol (+) kg^{-1}, then higher rates of lime are likely required to achieve high shallot yields. For those farms located closer to villages with better site access, such as Field site 1, there may be the potential to use higher rates of lime but having information on the optimum lime rate is still needed to ensure efficient use of inputs.

In this experiment, high shallot yields were attainable when Bray1-P was ≥ 28 mg P kg^{-1}. Therefore, only maintenance P rates are required once this level of soil P status is achieved. Although the three farm sites all had medium P-retention values (48-61%), the P amount required to increase soil test levels varied widely across sites, from 5 to 23 kg P ha^{-1} for each 1 mg P kg^{-1} increase in soil test value. This variation in the Bray1-P soil test to P fertiliser addition could be due to high spatial variability in soil P status caused by historic P placement methods.

Chapter 5

Incubation Experiment: Effect of Liming Materials and Selected Soil Amendments on Chemical Properties of An Extremely Acidic Soil from West Java, Indonesia

5.1. Introduction

The previous chapter concluded that a moderate rate of lime (1 t ha^{-1}) or about 1.0 x Exch. Al^{3+} had a beneficial effect at Field site 2, a remote site from the village and had moderate exchangeable Al^{3+}. This rate of lime increased the shallot bulb yield significantly at this site. However, at Field site 1, which has a high soil exchangeable Al^{3+}, the 1 t ha^{-1} was insufficient to improve shallot bulb yield. In addition, Field site 1 is located near the village and has better access. Therefore, it is more feasible to higher rates of lime (> 1.0 x Exch. Al) to alleviate Al toxicity. Although liming is a common practice to alleviate Al toxicity in acidic soils, its effectiveness can vary depending on the liming material, soil properties and the crop species (Li et al., 2019).

The proximity of Field site 1 to the village also creates the opportunity to use other soil amendments for maintaining or improving soil fertility. Field site 1 has a low soil cation exchange capacity (CEC; 13.70 cmol (+) kg^{-1}). For long-term cropping systems, the loss of soil organic matter results in a decline in the soil CEC and, therefore, the ability of the soil to store cation nutrients in an exchangeable form is diminished. Some soil amendments, such as biochar and zeolite, have shown an ability to improve a soil CEC. Moreover, some biochar have a liming effect, which enhances soil pH. However, different types of biochar feedstock have different capabilities at increasing CEC and pH. For example, the application of corn biochar increased CEC and soil pH and reduced exchangeable KCl-titration acidity (Al^{3+}+H^{+}) higher than switchgrass biochar in an acidic Entisol soil (Chintala et al., 2014). The different biochar capacity for increasing pH was related to the feedstock of biochar that would determine the composition of ash that held the basic cations (Ca^{2+}, Mg^{2+}, K^{+} and Na^{+}) and the alkalinity of the biochar (Yuan et al., 2011).

Determining an organic material as a biochar feedstock needs to consider various factors, such as accessibility, abundance, and price. Rice husk biochar is commonly used as a nursery medium in Indonesia. The plenty of feedstock and ease of making this biochar suggests it may be an option for farmers. Moreover, the extremely acidic soils have low CEC, low base saturation, and a high concentration of exchangeable Al^{3+}. Some biochar have been shown to have a liming effect that reduces exchangeable acidity and has a porous structure that can increase soil cation exchange capacity (CEC) (Biederman & Harpole, 2013). An application of 10 t ha^{-1} of rice husk biochar increased the soil pH from 3.36 to 4.40, increased CEC from 6.8 to 8.0 cmol (+) kg^{-1} and reduced exchangeable Al^{3+} slightly, from 3.42 to 2.96 cmol (+) kg^{-1} (Masulili et al., 2010). A lower response was reported by Zhang et al. (2017) that 10 t ha^{-1} rice husk biochar increased soil pH from 4.63 to 4.91, increased CEC from 11.8 to 12.3 cmol $(+)^{-1}$ and reduced exchangeable Al^{3+} from 2.77 to 2.40 cmol (+) kg^{-1}. The temperature of pyrolysis and particle's size affects the biochar quality. Masulili et al. (2010) heated the rice husk to a temperature of 600^{o}C and ground the biochar to pass through 0.50 mm. In comparison, Zhang et al. (2017) used coarse rice husk biochar and be heated it to 450^{o}C.

Another soil amendment that has shown an ability to increase the CEC of soil is zeolite. Indonesia has natural reserves of zeolite due to volcanic mountainous in Sumatera, Java, Nusa Tenggara and Sulawesi Islands (Kusdarto, 2008). Therefore, it may be an option for some farmers with degraded soils. The application of 5 t ha^{-1} natural zeolite + 98 kg P ha^{-1} increased soil pH from 4.60 to 5.46 and reduced exchangeable Al^{3+}, from 0.58 to 0.00 (Aainaa et al., 2018).

This incubation experiment aims to quantify the effect of high lime rates and other soil amendments on soil pH, exchangeable Al^{3+} and CEC of an extremely acidic soil from West Java, Indonesia.

5.2. Materials and Methods

5.2.1. Soil and soil amendments

The soil (0-20 cm) was collected from Field site 1 used in Field Trial 1 (Chapter 4; located at Kecamatan Pacet Kabupaten Bandung Barat, West Java, Indonesia 7^{o}12'54" S, 107^{o}06'87" E). The soil was air-dried, crushed, and passed through a 2 mm sieve before chemical characteristics (soil analysis was described in Chapter 2).

5.2.2. Incubation experiment

The research was conducted from June to August 2019 in the Soil Laboratory of the Indonesian Vegetable Research Institute, West Java, Indonesia. Air-dried soil samples of 100 g were placed in plastic cups, and all soil amendments were added. The soil samples were collected from the land and transported by foot while the soil amendments were bought from the nearest agriculture store. The soil amendments rates per ha were calculated using a tillage depth of 20 cm and bulk density of 1020 kg m^{-3}. The soil amendment treatments are shown in Table 5.1.

The soil and soil amendments were mixed and wetted with deionised water to 70% of the field water holding capacity of the soil, and the soils were watered to that extent throughout the experiment. All cups were covered with aluminium foil. A small hole was made to allow gaseous exchange but to minimise moisture loss (Figure 5.1) and then incubated at ambient temperature (average daily temperature ranged from 19 to 23^{o}C). The soils were sampled at 0, 3, 30 and 60 days from incubation initiation and replicated three times for each treatment and incubation time. There were 17 treatments x 3 replications x 3 incubation times = 153 cups plus 1 control (0 day). At each sampling time, three replicate soil incubation cups were used for all treatments, which involved using removing all the soil in each cup (approximately 100 g soils). Selected chemical properties of soil amendments were determined and presented in Table 5.2.

Table 5.1. The treatments of soil amendments.

No	Soil amendments	Rate (t ha^{-1})	Rate (g /100 g soil)
1	Control	0	0
2	Local lime (10LL)	10	0.5
3	Local lime (20LL)	20	1.0
4	Local lime (30LL)	30	1.5
5	Agricultural lime (20AL)	20	1.0
6	Hydrated lime (20HL)	20	1.0
7	Calcium Super (5CaSup)	5	0.25
8	Calcium Super (10CaSup)	10	0.5
9	Rice husk biochar (5B)	5	0.25
10	Rice husk biochar (10B)	10	0.5
11	Rice husk biochar (20B)	20	1.0
12	Zeolite (5Z)	5	0.25
13	Zeolite (10Z)	10	0.5
14	Zeolite (20Z)	20	1.0
15	Local lime + biochar (10LL+10B)	10 + 10	0.5 + 0.5
16		10 + 10	0.5 + 0.5

	Local lime + zeolite (10LL+10Z)		
17	Local lime + biochar + zeolite (10LL+5B+5Z)	10 + 5 + 5	0.5 + 0.25 + 0.25

Table 5.2. Chemical properties of soil amendment materials.

Materials	pH_{H2O}	Water content (%)	CaO (%)	MgO (%)	CCE (%)
Local lime	-	0.47	27.06	0.41	71
Agricultural lime	-	0.60	47.79	0.23	90
Hydrated lime	-	0.08	29.95	0.38	109
Calcium Super	-	3.94	37.2	8.13	108
Biochar rice husk	7.07	3.02	0.33	0.10	n.d
Zeolite	8.57	0.22	2.18	0.42	n.d

Local lime, agricultural limes, hydrated lime and Calcium Super, are fine lime (passing 100 mesh screen), CCE=Calcium Carbonate Equivalent, n. d=not determined

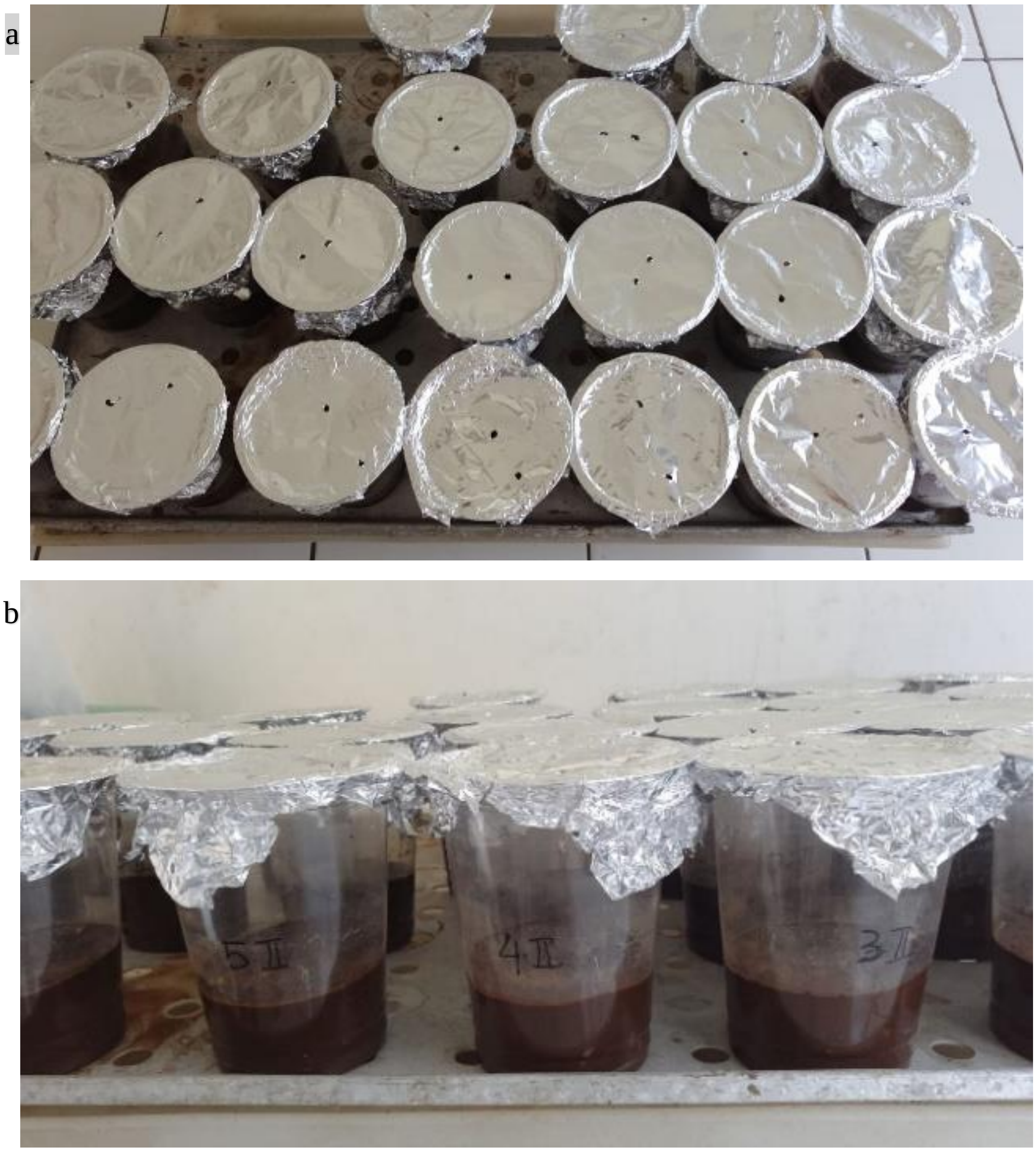

Figure. 5.1. The incubation experiment from (a) the top and (b) the side.

5.2.3 Statistical analysis

A two-way analysis of variance was performed to determine significant differences among treatments and incubation times. The statistical significance of the differences was determined by Tukey's test.

5.3. Results and Discussion

5.3.1. Characterisation of soil and soil amendment materials

The texture of the soil was 60% clay: 24.5% silt and 15.5% sand. The initial pH_{H20} was 4.20 and exchangeable Al^{3+} was 1.68 cmol (+) kg^{-1}. The basic cation concentrations were low, being 2.60 cmol (+) kg^{-1} of Ca^{2+}, 0.59 cmol (+) kg^{-1} of Mg^{2+}, 0.60 cmol (+) kg^{-1} $K^{+}$and 0.04 cmol (+) kg^{-1} Na^{+}, which provided a 32% Base Saturation of the soil's CEC of 12 cmol (+) kg^{-1}.

Overall, all materials had high pH values (range 7.07 – 9.60) and variable contents of CaO (range 0.3 – 47.8%) and MgO (range 0.1 - 8.0%). Lime materials, including local lime, agricultural lime, hydrated lime, and a liming product called Calcium Super, have significantly higher Ca concentration than rice husk biochar or zeolite. The concentration of Mg was higher in Calcium Super than other materials. Local lime has a lower price and quality (lower CCE%) compared to agricultural lime.

5.3.2. Effect of treatments on soil acidity

All liming materials (lime, agricultural limestone, hydrated lime, and calcium super) and the combination of lime and biochar or zeolite significantly increased soil pH in all incubation times compared to control treatment (Table 5.3). The control treatment soil, which received no lime or other soil amendments, had an average soil pH between 4.12-4.33 over the 60-day duration of the incubation experiment. Three days after the incubation period, all treatments containing liming materials showed significant increases in soil pH. For the local lime (LL) treatment, the 10, 20 and 30 t ha^{-1} rates achieved soil pH values of 5.64, 6.66 and 6.96. Soil pH continued to increase over time, being 6.33, 7.20 and 7.73, respectively, at 60 days after the start of the incubation. However, either all or most soil pH changes occurred within the first 30 days, with little or no change occurring between 30 and 60 days after the incubation period. The considered optimum pH of vegetable crops is 6-6.5. Therefore, the 10t ha^{-1} rate of local lime is able to achieve this within 30 days of application.

Table 5.3. The effect of soil amendments and incubation time on soil pH_{H20}.

Treatments	Incubation time (days)			*p*-value
	3	30	60	
Control	4.16 d	4.33 g	4.12 e	0.10
10 t ha^{-1} Local lime (10LL)	5.64 c	6.24 e	6.33 c	<0.01
	B	A	A	
20 t ha^{-1} Local lime (20LL)	6.66 ab	7.27 c	7.20 b	>0.10
30 t ha^{-1} Local lime (30LL)	6.96 a	7.73 a	7.73 a	<0.01
	B	A	A	
20 t ha^{-1} Agricultural limestone	6.82 a	7.39 bc	7.41 ab	<0.01
(20AL)	B	A	A	
20 t ha^{-1} Hydrated lime (20HL)	6.80 a	7.55 ab	7.62 a	<0.01
	B	A	A	
5 t ha^{-1} Calcium Super (5CaSup)	5.64 c	5.64 f	5.49 d	0.02
	A	A	B	<0.01
10 t ha^{-1} Calcium Super (10CaSup)	6.32 ab	6.66 d	6.58 c	
	B	A	A	
5 t ha^{-1} Rice husk biochar (5B)	4.12 d	4.35 g	4.09 e	<0.01
	B	A	B	
10 t ha^{-1} Rice husk biochar (10B)	4.04 d	4.35 g	4.08 e	<0.01
	B	A	A	
20 t ha^{-1} Rice husk biochar (20B)	4.13 d	4.35 g	4.13 e	0.02
	B	A	B	
5 t ha^{-1} Zeolite (5Z)	4.13 d	4.35 g	4.08 e	0.01
	B	A	B	
10 t ha^{-1} Zeolite (10Z)	4.10 d	4.38 g	4.11 e	<0.01
	B	A	B	
20 t ha^{-1} Zeolite (20Z)	4.10 d	4.35 g	4.19 e	<0.01
	C	A	B	
10 t ha^{-1} Local lime + 10 t ha^{-1}	5.73 c	6.38 e	6.26 c	<0.01
Biochar (10LL+10B)	B	A	A	
10 t ha^{-1} Local lime + 10 t ha^{-1}	5.74 c	6.38 e	6.32 c	<0.01
Zeolite (10LL+10Z)	B	A	A	
10 t ha^{-1} Local lime + 5 t ha^{-1}	5.75 c	6.40 e	6.37 c	<0.01
Biochar + 5 t ha^{-1} Zeolite	B	A	A	
(10LL+5B+5Z)				
p-value	<0.01	<0.01	<0.01	
CV (%)	8.6	1.1	2.0	

Tukey's method for means comparison; means presenting the same small letters in the same column and same capital letters in the same row are not significantly different at $p \leq 0.05$.

The agricultural lime and hydrated lime treatments, applied at a rate of 20 t ha^{-1}, showed a similar pattern of pH change over time to that of the local lime. By day 60, the agricultural lime and hydrated lime achieved soil pH levels of 7.41 and 7.62, respectively. Only the hydrated lime treatment soil pH was significantly higher than the value for the local lime at the same rate. This difference reflects the difference in CCE between the liming materials, with the local lime having a value of 71% compared to 109% for the hydrated lime.

The Calcium Super treatments applied at rates of 5 and 10 t ha^{-1} achieved either the majority of the soil pH change in the first three days of the incubation, achieving soil pH values of 5.64 and 6.32, respectively. However, only the higher of the two rates showed a further increase to a pH value of 6.66 at day 30 of the incubation. This is because liming material reacts more quickly to neutralise soil acidy than the other liming materials in the experiment. Also, the soil pH level achieved at day 30 by the 10-t ha^{-1} rate of Calcium Supper was significantly higher than that achieved with the same rate of local lime, which also reflects the difference in CCE. Therefore, the Calcium Supper has a higher CCE of 108%, similar to the hydrated lime value.

The effect of rice husk biochar and zeolite on soil pH when they were applied alone was minimal. Furthermore, when 10 t ha^{-1} rice husk biochar was incorporated with 10 t ha^{-1} lime, the effect was not significantly different from 10 t ha^{-1} lime application alone (soil pH 6.26 vs 6.33 at 60 days incubation). The same result was observed on zeolite + lime treatments (soil pH 6.32). Therefore, it seems that an increase in soil pH, compared to the control treatment (soil pH 4.12), occurred due to lime addition only and was unaffected by rice husk biochar or zeolite addition. Thus, the effect of rice husk biochar and zeolite on soil pH and soil acidity was negligible. In another recent study, Cornelissen et al. (2018) also reported that coarse rice husk biochar did not significantly affect the soil pH and Al:Ca ratio. At the same time, this may be improved by grinding biochar to smaller particle sizes (Masulili et al., 2010). However, this is an expensive additional processing step. Therefore, the use of ground biochar is likely to be cost-prohibitive for farmers to use.

All treatments containing lime rapidly lowered in KCl titratable acidity (Al^{3+}+H^{+}) to below 0.1 (cmol (+) kg^{-1}) (Appendix 5.1, Table 1). This value increased slightly to 0.11 cmol (+) kg^{-1} by 60 d in every case, perhaps due to nitrification during incubation. In the absence of lime, rice biochar or zeolite did not alter KCl titratable acidity, which remained in the range of 2.04 – 2.7 cmol (+) kg^{-1} in all incubated soil samples each time point.

5.3.3. Effect of treatments on soil exchangeable acidity

The control treatment soil, which received no lime or other soil amendments, had an average exchangeable Al^{3+} between 1.43 to 1.56 cmol (+) kg^{-1} and KCl titratable acidity between 2.34 to 2.23 cmol (+) kg^{-1} over the 60-day duration of the incubation experiment. All the liming treatments successfully raised the pH over 5, and the exchangeable Al^{3+}concentration decreased to undetectable values (Table 5.4) and KCl titratable acidity < 0.20 cmol (+) kg^{-1} (see Appendix 5.1, Table 2 for details). The lowest rate of liming material used was 5 t ha^{-1} Calcium Super, which decreased exchangeable Al^{3+} to 0 cmol (+) kg^{-1} and reduced KCl titratable acidity to 0.11 cmol (+) kg^{-1} (increased soil pH to 5.49). This significant reduction in exchangeable Al^{3+} was achieved with a lower rate of lime than some other studies, possibly reflecting the difference in soil pH buffering capacity and/or lime quality. For example, Andrade et al. (2002) reported that 8.8 t ha^{-1} lime reduced exchangeable Al^{3+} from 1.23 to 0.22 cmol (+) kg^{-1} and Fageria et al. (1995) reported that application 8 t ha^{-1} lime decreased the exchangeable Al^{3+} from 0.8 to 0.1 cmol (+) kg^{-1}.

In the first field experiment of the current study (Chapter 4), it was observed that high bulb yield (< 10 t ha^{-1}) was achievable when exchangeable Al^{3+} was < 0.5 cmol (+) kg^{-1} or Al:Ca was < 0.1. Therefore, using liming materials, with similar neutralising effectiveness Calcium Super, at rates of < 5 t ha^{-1} at this site may be adequate to achieve a high shallot bulb yield.

The application of biochar and zeolite did not significantly affect exchangeable Al^{3+} compared to control. The lack of response to rice husk biochar and zeolite to decrease exchangeable Al^{3+} is possibly due to both materials having low acid neutralising capacity (ANC). Acid neutralizing capacity is defined as the number of strong bases that needed to increase the pH of a system to a reference pH value (Breemen et al., 1983). However, biochar or zeolite use did lead to a slight decrease in exchangeable Al^{3+} over time. This reduction in exchangeable Al^{3+} over time was similar to the small effect on raising soil pH noted above. However, the changes were negligible and not significantly different from the control.

Table 5.4. The effect of soil amendments and incubation times on exchangeable Al^{3+} (cmol (+) kg^{-1}).

Treatments	Incubation time (days)			*p*-value
	3	30	60	
Control	1.43 b	1.56 b	1.51 a	0.86
10 t ha^{-1} Local lime (10LL)	0.00 c	0.00 b	0.00 b	-
20 t ha^{-1} Local lime (20LL)	0.00 c	0.00 b	0.00 b	-
30 t ha^{-1} Local lime (30LL)	0.00 c	0.00 b	0.00 b	-
20 t ha^{-1} Agricultural lime (20AL)	0.00 c	0.00 b	0.00 b	-
20 t ha^{-1} Hydrated lime (20HL)	0.00 c	0.00 b	0.00 b	-
5 t ha^{-1} Calcium Super (5CaSup)	0.00 c	0.00 b	0.00 b	-
10 ha^{-1} Calcium Super (10CaSup)	0.00 c	0.00 b	0.00 b	-
5 t ha^{-1} Rice husk biochar (5B)	1.74 ab	1.56 a	1.34 a	0.02

	A	B	B	
10 t ha^{-1} Rice husk biochar (10B)	1.81 ab	1.62 a	1.53 a	0.08
	A	AB	B	
20 t ha^{-1} Rice husk biochar (20B)	1.69 ab	1.40 a	1.56 a	0.32
5 t ha^{-1} Zeolite (5Z)	1.75 ab	1.51 a	1.46 a	0.29
10 t ha^{-1} Zeolite (10Z)	1.86 a	1.52 a	1.46 a	0.00
	A	B	B	
20 t ha^{-1} Zeolite (20Z)	1.83 ab	1.50 a	1.51 a	0.02
	A	B	B	
10 t ha^{-1} Local lime + 10 t ha^{-1} Biochar (10LL+10B)	0.00 c	0.00 b	0.00 b	-
10 t ha^{-1} Local lime + 10 t ha^{-1} zeolite (10LL+10Z)	0.00 c	0.00 b	0.00 b	-
10 t ha^{-1} Local lime + 5 t ha^{-1} Biochar + 5 t ha^{-1} zeolite (10LL+5B+5Z)	0.00 c	0.00 b	0.00 b	-
p-value	<0.01	<0.01	<0.01	
CV (%)	19.5	16.7	15.8	

Tukey's method for means comparison; means presenting the same small letters in the same column and same capital letters in the same row are not significantly different at $p \leq 0.05$

5.3.4 Effect of treatments on basic cations and CEC

All types and rates of liming materials increased the concentration of Ca^{2+}, but this effect was not seen with rice husk biochar or zeolite (Table 5.5). The control treatment soil, which received no lime or other soil amendments, had an ammonium-acetate-extractable-Ca^{2+} between 2.40-3.62 cmol (+) kg^{-1} over the 60 days duration of the incubation experiment. Three days after the incubation period, all treatments containing liming materials showed significant increases in ammonium-acetate-extractable-Ca^{2+}. For the local lime (LL) treatment, the 10, 20 and 30 t ha^{-1} rates achieved ammonium-acetate-extractable-Ca^{2+} of 14.95, 23.38 and 29.87, respectively. All ammonium-acetate-extractable-Ca^{2+} changes occurred within the first three days, with little or no change occurring between 30 and 60 days after the incubation period.

The agricultural lime and hydrated lime, applied at a rate of 20 t ha^{-1} and the Calcium Super applied at rates of 5 to 10 t ha^{-1}, showed a similar pattern of ammonium-acetate-extractable-Ca^{2+} change over time to that of the local lime. By day 60, the agricultural lime and hydrated lime achieved ammonium-acetate-extractable-Ca^{2+} levels of 24 cmol (+) kg^{-1} and were not significantly different from the local lime value at the same rate, 20 t ha^{-1}. However, 30 days after incubation application 5 t ha^{-1}, Calcium Super significantly increased the concentration of ammonium-acetate-extractable-Ca^{2+} by 4.24 cmol (+) kg^{-1} than control from 3.56 to 7.80 cmol (+) $kg^{-1,}$ significantly lower than other lime treatments. While a higher rate of Calcium

Super, 10 t ha^{-1} achieved ammonium-acetate-extractable-Ca^{2+} of 11.32 cmol (+) kg^{-1}, which was not significantly different from the 10-t ha^{-1} local lime value. Therefore, the changes in Ca^{2+} concentration was seemed more affected by lime rates rather than lime types.

Table 5.5. The effect of soil amendments and incubation time on ammonium-acetate-extractable-Ca^{2+} (cmol (+) kg^{-1}).

Treatments	Incubation time (days)			*p*-value
	3	30	60	
Control	2.40 e B	3.56 f A	3.62 f A	0.02
10 t ha^{-1} Local Lime (10LL)	14.95 c	12.76 d	13.78 c	0.60
20 t ha^{-1} Local Lime (20LL)	23.38 b	17.44 c	21.14 b	0.13
30 t ha^{-1} Local Lime (30LL)	29.87 a	24.85 a	26.12 a	0.15
20 t ha^{-1} Agricultural lime (20AL)	23.56 b	19.55 bc	24.63 ab	0.17
20 t ha^{-1} Hydrated lime (20HL)	23.98 b	21.83 b	24.44 ab	0.40
5 t ha^{-1} Calcium Super (5CaSup)	8.31 de	7.80 e	8.16 de	0.26
10 t ha^{-1} Calcium Super (10CaSup)	12.42 cd	11.32 d	12.08 cd	0.09
5 t ha^{-1} Rice husk biochar (5B)	2.22 e B	3.88 f A	3.69 ef A	<0.01
10 t ha^{-1} Rice husk biochar (10B)	2.09 e B	3.70 f A	3.67 e A	<0.01
20 t ha^{-1} Rice husk biochar (20B)	2.32 e B	3.68 f A	3.50 f A	0.02
5 t ha^{-1} Zeolite (5Z)	2.21 e B	3.76 f A	3.70 ef A	<0.01
10 t ha^{-1} Zeolite (10Z)	2.32 e B	3.66 f A	3.60 f A	<0.01
20 t ha^{-1} Zeolite (20Z)	2.38 e B	3.54 f A	4.02 ef A	<0.01
10 t ha^{-1} Local lime + 10 t ha^{-1} Biochar (10LL+10B)	14.19 cd	12.90 d	13.98 c	0.33
10 t ha^{-1} Local lime + 10 t ha^{-1} Zeolite (10LL+10Z)	14.33 cd	13.34 d	14.18 c	0.47
10 t ha^{-1} Local lime + 5 t ha^{-1} Biochar + 5 t ha^{-1} Zeolite (10LL+5B+5Z)	14.74 c A	12.80 d B	13.80 c AB	0.02
p-value	<0.01	<0.01	<0.01	
CV (%)	13.9	8.8	12.8	

Tukey's method for means comparison; means presenting the same small letters in the same column and same capital letters in the same row are not significantly different at α=5%.

Liming materials increased the soil concentration of Ca^{2+} directly proportional to the added Ca. There was no significant difference between local lime and calcium super on increasing the concentration of Ca^{2+} at the same rate. On average, every 1 t ha^{-1} lime increased the concentration of Ca^{+2} by 1.07 cmol (+) kg^{-1}, while calcium super increased the concentration of Ca^{2+} by 1.09 cmol (+) kg_{-}^{1} after 60 d of incubation. A lower result was reported by

Mosharrof et al. (2021) in sandy clay loam soil using dolomite; every 1 t ha^{-1} dolomite increased the concentration of exchangeable Ca^{2+} by 0.27 cmol (+) kg^{-1} after 60 d of incubation. The lower increase in exchangeable soil Ca^{2+} for dolomite, compared to lime, will be due to the lower Ca content of dolomite.

Calcium super, which was the only soil amendment to contain significant quantities of Mg^{2+}, enhanced the concentration of exchangeable Mg^{2+} in proportion to the amount added (Appendix 5.1, Table 4). No other treatments altered soil exchangeable Mg^{2+}. In addition, exchangeable Mg^{2+} was practically unaffected by incubation times apart from a minor decline when biochar or zeolite was added in the presence of lime.

The incorporation of Calcium Super increased the Mg^{2+} linearly due to the Mg concentration of Calcium Super (Figure 5.6). On average, every 1 t ha^{-1} of Calcium Super increased the concentration of Mg^{2+} by 0.21 cmol (+) kg^{-1}. The result was quite similar to Sienkiewicz et al. (1994), who reported a linear function for dolomite (21.9% MgO) and magnesium sulphate (18% MgO) addition on the concentration of exchangeable Mg^{2+}. Every 1 t ha^{-1} dolomite increased exchangeable Mg^{2+} by 0.52 cmol (+) kg^{-1} and every 1 t ha^{-1} magnesium sulphate raised exchangeable Mg^{2+} by 0.47 cmol (+) kg^{-1}. The lower effect on this study occurred due to the lower concentration of Mg on Calcium Super than dolomite and magnesium sulphate.

Biochar treatments raised the concentration of K^{+} in incubated soils after three days of incubation time (Appendix 5.1, Table 4). The increasing K concentration in the soil solution may come from cation substances from biochar. For example, rice husk biochar may contain about 175 mg kg^{-1} of K (Varela Milla et al., 2013), increasing K^{+} concentration. A significant change was reported by Masulili et al. (2010) that the application of 10 t ha^{-1} rice straw biochar increased K^{+} ions by 0.31 cmol (+) kg^{-1} from 0.20 to 0.51 cmol (+) kg^{-1}. In this experiment, the application of 10 t ha^{-1} rice husk biochar increased the concentration of K^{+} by only about 0.08 cmol (+) kg^{-1} from 0.67 to 0.75 cmol (+) kg^{-1}. The different results of K^{+} changing might be due to the difference in pyrolysis temperature, heating rate, holding time and particle size that may affect the rice husk biochar characteristics (Ji-Lu, 2007). It is important to note that by 60 d of incubation, this small change was no longer present, and all incubated soils showed the same amount of exchangeable K^{+}.

Zeolite significantly increased the exchangeable sodium (Na^{+}) compared to other treatments (Appendix 5.1, Table 6). If the exchangeable Na^{2+} was higher than 15% of CEC, it might lead to serious soil physical problems such as crusting that reduces water infiltration and inhibits plant growth (Laker & Nortjé, 2019). In this experiment, the highest Na^{2+} saturation was 2.12% (Na^{2+}=0.274 cmol (+) kg^{-1}, CEC=12.91 cmol (+) kg^{-1}) which is much lower than the critical value. Therefore, it seems that zeolite application at this rate should not negatively impact plant growth. The increase in Na^{+} due to zeolite content has previously been ascribed to Na_2O in the zeolite, which dissolves when applied to soil (Wang et al., 2012).

All liming materials increased total base cations, and the effect became more significant when the rate of liming materials increased (Table 5.6). Moreover, incubation times did not affect total base cations after any liming treatment (lime, agriculture limestone, hydrated lime, and calcium super). On the other hand, there was a significant increase in total base cation concentration in control, rice husk biochar and zeolite treatments over time, to a maximum of 5 cmol (+) kg^{-1}. Still, these differences were minor compared to the impact of liming, where total base cations achieved 31 cmol (+) kg^{-1} in 30 t ha^{-1} lime treatment. The increase of total base cation was mainly due to the rise in exchangeable Ca^{2+}.

Table 5.6. The effect of soil amendment and incubation time on total base cations (TBC, cmol (+) kg^{-1}).

Treatments	Incubation time (days)			*p*-value
	3	30	60	
Control	3.69 d	4.94 f	4.91 e	0.02
	B	A	A	
10 t ha^{-1} Local lime (10L)	16.23 c	14.08 d	15.00 cd	0.61
20 t ha^{-1} Local lime (20L)	24.67 b	18.76 c	22.48 b	0.14
30 t ha^{-1} Local lime (30L)	31.15 a	26.16 a	27.31 a	0.15
20 t ha^{-1} Agricultural lime (20AL)	24.85 b	20.85 bc	25.76 ab	0.19
20 t ha^{-1} Hydrated lime (20HL)	25.29 ab	23.6 b	25.60 ab	0.42
5 t ha^{-1} Calcium Super (5CaSup)	10.79 c	10.48 e	10.57 d	0.60
10 t ha^{-1} Calcium Super (10CaSup)	15.42 c	14.81 d	15.24	0.52
5 t ha^{-1} Rice husk biochar (5B)	3.58 d	5.29 f	5.04 e	<0.01
	B	A	A	
10 t ha^{-1} Rice husk biochar (10B)	3.50 d	5.15 f	5.03 e	<0.01
	B	A	A	
20 t ha^{-1} Rice husk biochar (20B)	3.76 d	5.18 f	4.89 e	0.02
	B	AB	A	
5 t ha^{-1} Zeolite (5Z)	3.55 d	5.12 f	4.99 e	<0.01
	B	A	A	
10 t ha^{-1} Zeolite (10Z)	3.83 d	5.03 f	4.95 e	<0.01
	B	A	A	

20 t ha^{-1} Zeolite (20Z)	3.93 d B	4.98 f A	5.54 e A	0.04
10 t ha^{-1} Local lime + 10 t ha^{-1} Biochar (10LL+10B)	15.59 c	14.29 d	15.22 c	0.36
10 t ha^{-1} Local lime + 10 t ha^{-1} Zeolite (10LL+10Z)	15.79 c	14.67 d	15.48 c	0.43
10 t ha^{-1} Local lime + 5 t ha^{-1} Biochar + 5 t ha^{-1} Zeolite (10L+5B+5Z)	16.18 c A	14.18 d B	15.06 cd AB	0.01
p-value	<0.01	<0.01	<0.01	
CV (%)	12.4	7.8	11.6	

Tukey's method is used for means comparison. Means presenting the same small letters in the same column and the same capital letters in the same row are not significantly different at α= 5%.

At the end of the incubation time (60 days after incubation), the cation exchange capacity (CEC) was improved significantly by the application of 20 t ha^{-1} local and hydrated lime, 10 t ha^{-1} Calcium Super and zeolite, 10 t ha^{-1} local lime + 10 t ha^{-1} biochar and 10 t ha^{-1} local lime + 5 t ha^{-1} biochar + 5 t ha^{-1} zeolite but not with other treatments (Table 5.7). There was also no significant difference in CEC over time. It seems that in specific values, lime affected the CEC more significantly than biochar and zeolite. Application of lime increased CEC or negative charge commonly because of the detachment of H^+ from organic materials (Bolan et al., 2003) or because the soils contained the high clay minerals with pH-dependent surface charge (Von Uexkull, 1986). A similar result was reported by Sharma et al. (1990) that applying 1 t ha^{-1} lime increased root CEC in clay tropical acidic soil.

The non-significant effect of biochar on this study was contrary to Jien and Wang (2013), who found that the application of wood white biochar significantly improved CEC due to the porous structure of the biochar. Moreover, they explained that slow oxidation of the biochar raised carboxyl group numbers and led to increasing CEC value. In this experiment, the structure and the oxidation rate of rice husk biochar was not measured. However, rice husk biochar has less surface area than wood biochar (2.21 versus 37.95 m^2) that might relate to the biochar's porosity (Varela Milla et al., 2013).

Table 5.7. The effect of soil amendments and incubation time on CEC (cmol (+) kg^{-1}).

Treatments	Incubation time (days)		
	3	30	60
Control	11.9^{ns}	11.4^{d}	11.5^{e}
10 t ha^{-1} Local lime (10L)	11.2	11.8^{cd}	12.4^{a-e}
20 t ha^{-1} Local lime (20L)	13.1	13.2^{ab}	13.2^{a-c}
30 t ha^{-1} Local lime (30L)	12.9	12.8^{a-d}	12.7^{a-e}
20 t ha^{-1} Agricultural lime (20AL)	12.6	12.5^{a-d}	12.4^{a-e}
20 t ha^{-1} Hydrated lime (20HL)	14.1	13.4^{a}	12.7^{a-d}
5 t ha^{-1} Calcium Super (5CaSup)	13.1	12.8^{a-d}	12.2^{a-e}
10 t ha^{-1} Calcium Super (10CaSup)	12.2	12.8^{a-d}	13.5^{ab}
5 t ha^{-1} Rice husk biochar (5B)	11.9	11.7^{cd}	11.5^{de}
10 t ha^{-1} Rice husk biochar (10B)	12.1	11.9^{bcd}	11.6^{cde}
20 t ha^{-1} Rice husk biochar (20B)	12.0	11.8^{bcd}	11.7^{cde}
5 t ha^{-1} Zeolite (5Z)	12.8	12.5^{a-d}	12.2^{a-e}
10 t ha^{-1} Zeolite (10Z)	12.1	12.4^{a-d}	12.7^{a-d}
20 t ha^{-1} Zeolite (20Z)	12.2	11.8^{bcd}	11.5^{de}
10 t ha^{-1} Local lime + 10 t ha^{-1} Biochar (10LL+10B)	12.7	12.9^{abc}	13.1^{a-d}
10 t ha^{-1} Local lime + 10 t ha^{-1} Zeolite (10LL+10Z)	12.6	12.7^{a-d}	12.7^{a-e}
10 t ha^{-1} Local lime + 5 t ha^{-1} Biochar + 5 t ha^{-1} Zeolite (10L+5B+5Z)	12.7	13.3^{a}	13.9^{a}
p-value	0.39	0.04	0.01
CV (%)	8.80	5.84	6.93

Tukey's method is used for means comparison. Means presenting the same letters in the same column are not significantly different at α=5%, ns= not significant.

Overall, the dominant cation was exchangeable Ca^{2+} in all treatments, including the control treatment (Figure 5.10). There was no significant difference between control and biochar or zeolite treatments on cation base saturation. Local lime and Calcium Super application increased Ca^{2+} saturation and increased the base saturation. Calcium Super also improved Mg^{2+} saturation. On average, Ca saturation in no lime treatments (control, 10 t ha^{-1} rice husk biochar and 10 t ha^{-1} zeolite) was 32%, and the total base saturation was 40%. Moreover, the high concentration of Ca in lime treatment exceeds the saturation more than 100% of the CEC.

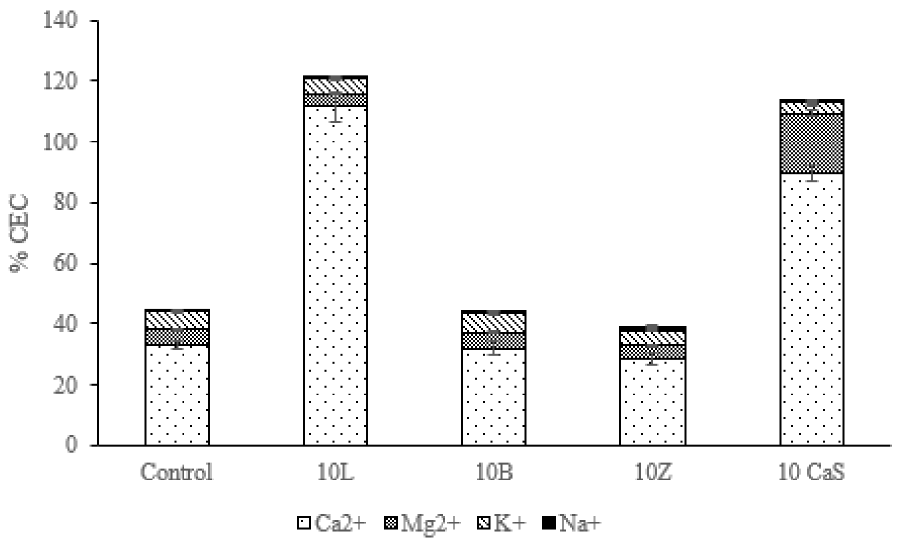

Figure 5.2. The comparison of control, 10 t ha^{-1} local lime (10LL), Calcium Super (10CaSup), rice husk biochar (10B) and zeolite (10Z) on cation saturation at 60-days after incubation. Error bars are standard errors.

5.3.5 The relationship and correlation between soil chemical properties

Liming materials reduced Al:Ca ratio to undetectable levels for all rates at all incubation times (Appendix 5.1, Table 3). By contrast, the Al:Ca ratio in the presence of rice husk biochar or zeolite was not significantly different from those of the control. A similar result was reported by Cornelissen et al. (2018) that applying 5 to 15 t ha^{-1} rice husk biochar rate did not significantly affect Al:Ca ratio in Indonesian Ultisol soil.

Exchangeable Al^{3+} was measurable only in soils below pH 5.42 (Figure 5.3). No data were captured in the soil pH range between pH 4.45 and 5.42. However, from the trendline, it was assumed that for 0.8 cmol (+) kg^{-1} of exchangeable Al^{3+} (the threshold from Chapter 3), the critical pH_{H2O} was 4.6. And when the pH_{H2o} was above 4.8, the concentration of exchangeable Al^{3+} was lower than 0.5 cmol (+) kg^{-1}. However, this finding should be investigated further.

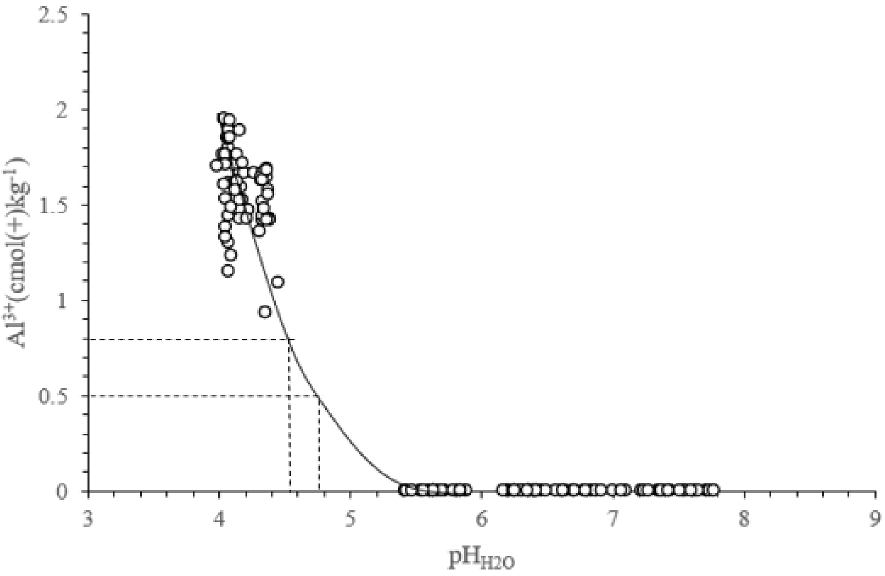

Figure 5.3. The scatter points between pH_{H2O} and Al^{3+} concentration, n=153.

Lime application increased soil pH through hydrolysis of calcium carbonate or calcium oxide in lime materials. Generally, in neutral soils, about 75 x 10^{-3} cmol (+) kg^{-1} of exchangeable Ca^{2+} was adequate for most crops (Havlin et al., 2014). However, in acidic soils, the deficiency of Ca^{2+} and toxic Al^{3+} commonly occur and restrict crop growth. In this experiment, the lowest Ca^{2+} concentration was 1.7 cmol (+) kg^{-1}, which is technically higher than the Ca deficiency threshold (Havlin et al., 2014). However, the low performance of shallots in these soils and the interference from exchangeable Al^{3+} on Ca absorption led to an inference that a higher Ca concentration is required in these acid soil solutions to counteract the negative impact of exchangeable Al^{3+} and to supply the plant requirement. Moreover, Ca^{2+} has an antagonistic effect with other cations, Mg^{2+}, K^+ and Na^+. Thus, the critical level for Ca^{2+} sufficiency would be better counted as a ratio of Ca to other cations (Adams, 1981).

Combining the above data, the Al:Ca ratio was high in acidic soils below pH 5.42 (Figure 5.4). Increasing the soil pH above 5.4 reduced the Al:Ca ratio to the baseline. There was no Al^{3+} data from pH 4.45 to 5.42. However, using the trendline to reach the Al:Ca ratio below 0.1, the soil pH was above 4.8.

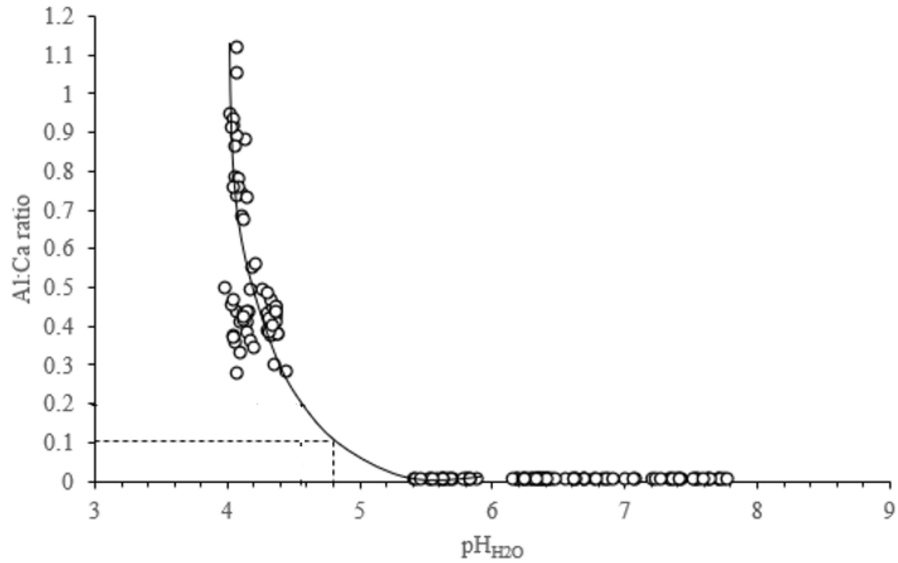

Figure 5.4. The scatter points between pH and Al:Ca ratio across the treatments, replications and incubation time, n=153.

The magnitude of pH change from Calcium Super was higher than Local lime (Figure 5.5). The phenomenon is likely due to Calcium Super having a higher CCE% than the Local lime. When the soil pH is 4.6 and 4.8, the exchangeable Al^{3+} is less than 0.8 and 0.5 and the Al:Ca ratio is less than 0.2 and 0.1, respectively. From the previous chapter, it was reported that the exchangeable Al^{3+} threshold for Field site 2 was 0.8 cmol (+) kg. However, using the combined data from all sites, the high bulb yield (> 10 t ha^{-1}) was more likely found when the exchangeable Al^{3+} less than 0.5 cmol kg^{-1}. Therefore, the soil pH target was pH 4.8. To increase soil pH from 4.2 (initial pH) this would require a pH change of 0.6. Therefore, it is estimated from Figure 5.5, that using a high-quality liming material, like Calcium Super, would require about 2.5 t ha^{-1} and the local lime was required about 3 t ha^{-1}. In comparison to using the general approach of using 1 x Exch. Al (described in Chapter 4), an estimated 1.4 – 1.6 t lime ha^{-1} would be needed. Therefore, it seems that using 1.5 to 2.0 x Exch. Al for this site may be more suitable.

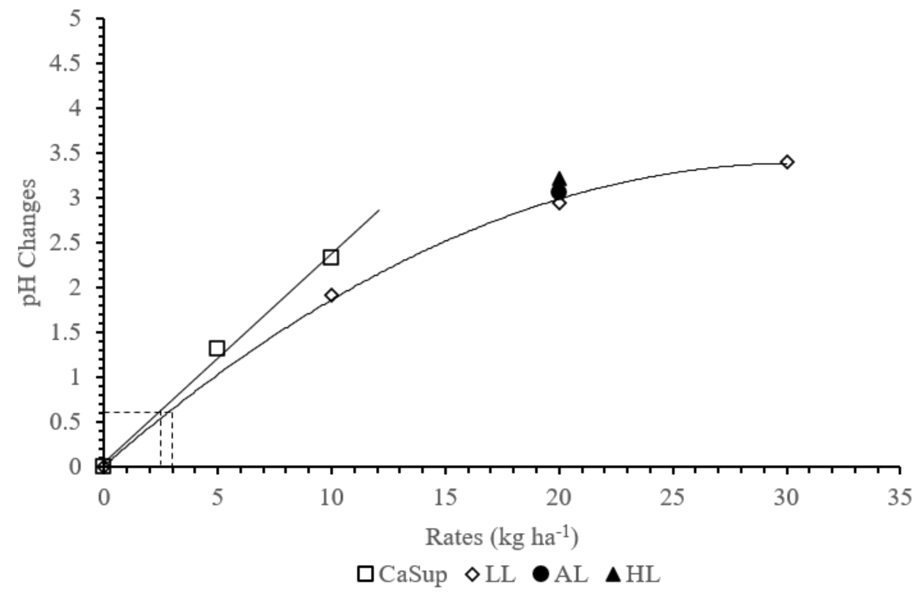

Figure 5.5. Lime rates in correlation to pH changes.

It is estimated that about 2.5 t ha^{-1} Calcium Super is required, or about 3 t ha^{-1} local lime. While about 20% more local lime is required than Calcium Super, Calcium Super is much more expensive, NZ $ 1,670 per ton than lime, only NZ $ 67 per ton. Therefore, the local lime will be the most cost-effective option for liming.

5.4 Conclusion

This incubation experiment aimed to quantify the effect of high lime rates and other soil amendments on soil pH, exchangeable Al^{3+} and CEC of an extremely acidic soil from West Java, Indonesia. Lime materials, i.e., lime, agriculture limestone and hydrated lime, have a similar effect on increasing soil pH and reducing the exchangeable Al^{3+} in weathered acidic soil. In contrast, Calcium Super seems more effective in increasing soil pH and reducing exchangeable Al^{3+} than local lime. To reach the soil pH target, 4.8 (Exch. $Al^{3+} < 0.5$), 3 t ha^{-1} of lime or 2.5 t ha^{-1} of Calcium Super might be required and would help on improving shallot growth and bulb yield. Application lima rates 1.5 to 2.0 times of exchangeable Al^{3+} might reduce the exchangeable Al^{3+} and Al:Ca to the target values.

However, rice husk biochar and zeolite application alone did not significantly affect the soil pH, exchangeable Al^{3+} and CEC. Incorporating 10 t ha^{-1} lime with biochar and zeolite also did not improve the effectiveness of those soil amendments on soil properties.

The following field trial would be conducted to study the effect of higher lime rates (≥ 1.5 to 2.0 x Exch. Al^{3+}) and nitrogen and phosphorus fertiliser on shallot growth in Field site 1 (high exchangeable Al^{3+}, low soil available-P).

Chapter 6

Field Trial 2: The Effect of Liming and Phosphorus Fertiliser Application on Alleviating Acidic Cation Toxicity and Improving the Shallot Bulb Yield on An Extremely Acidic Soil

6.1. Introduction

The first field trial in this study (Chapter 4) demonstrated that the exchangeable Al^{3+} threshold for shallot was 0.82 cmol (+) kg^{-1} where above this point the bulb yield was low (< 10 t ha^{-1}). Moreover, there was a greater likelihood of a high shallot fresh bulb yield (> 10 t ha^{-1}) being achieved when soil exchangeable Al^{3+} was < 0.5 cmol (+) kg^{-1}. The field trial also identified that low to moderate rates of lime (≤ 1 t lime ha^{-1}) were effective for achieving high shallot yields on-farm sites with exchangeable Al^{3+} levels ≤ 1.1 cmol (+) kg^{-1}. This supports the use of exchangeable Al^{3+} for determining lime rates to ensure shallot growers are using enough lime to improve yields without using more lime than required. This is particularly important for remote farms sites, where limited farm access discourages the use of heavy farm inputs like lime. However, the first field trial also showed that for the farm (Field site 1) with high exchangeable Al^{3+} (1.60 cmol (+) kg^{-1}), a lime rate of 1 t lime ha^{-1} was insufficient to reduce exchangeable Al^{3+} to a level where high shallot yields were more likely to be achieved. Based on the incubation study (Chapter 5), it was estimated that 2-3 t lime ha^{-1} (range depending on CCE% of the lime) is likely required to reduce exchangeable Al^{3+} to a low level. Therefore, further research is required to assess, under field conditions, the rates of lime required for soils with high exchangeable Al^{3+} to achieve high shallot yields.

The earlier experiments in this study focused on the effects of soil acidity on aluminium toxicity. In some soils, very acidic conditions can also result in high levels of soil exchangeable manganese (Mn), which can also be detrimental to plant growth. Manganese toxicity can reduce plant growth, photosynthesis activity, chlorophyll content, inhibits enzyme activities and damage the chloroplast (Yuan et al., 2019). Manganese has been shown less toxic than aluminium on onions root growth (Fiskesjö, 1988). However, it is helpful to assess whether manganese toxicity is also occurring to assess the benefits of liming.

Field site 1, being located close to a village, approximately 20 minutes' walk from the nearby road, has a long history of cropping (> 80 years of cropping; Category 1 land; Chapter 4). Therefore, this farm site has better access, compared to farms on Category 2 and 3 lands, which makes the use higher rates of bulky crop inputs like lime more feasible. It is becoming increasingly more important for the productivity of vegetable cropping on Category 1 land to be improved, due to recent changes to prohibit the use of Category 3 for vegetable production. This change, along with increasing population growth and the effects of Climate Change, puts greater pressure on existing farmland to be more productive, much of which is farmed by smallholder farmers. These farmers typically have limited resources limited access to agronomic advice. Therefore, it is important to identifying soil fertility recommendations that a more farm specific and practical for smallholder farmers, to help improve crop productivity and the efficiency of fertiliser and lime inputs, which are costly and limited resources.

At Field site 1 (Chapter 4), there was a small but significant influence of phosphorus (P) fertiliser on yield response, but which may have been limited by the high soil acidity and high exchangeable Al^{3+}. Therefore, further research is required to determine the P fertiliser response when soil acidity is improved to level where exchangeable Al^{3+} is low.

The objectives of this research were to investigate the effects of lime and P fertiliser rates on soil exchangeable acidity, exchangeable Al^{3+}, Al:Ca ratio, exchangeable Mn^{2+} and available P at Field site 1 (site with high exchangeable Al, low Bray1-P), and to determine the effects of lime and P fertiliser rates on shallot growth and bulb yield at this site.

6.2. Materials and Methods

6.2.1. Field site and shallot variety

This field trial was conducted from December 2019 to March 2020 and was located at Field site 1, which was part of the first trial of this study (Chapter 4), Sukarame Pacet, Kabupaten Bandung, West Java Indonesia (Figure 6.1). The GPS reference of this location is at latitude 7°12'54" S and longitude 107°06'87" E, with an elevation of 1060 m above sea level. The planting date was 11 December 2019, and harvest time was performed 80 days later, on 29 February 2020. The shallot cultivar used in this trial was Sumenep, which was also used in the first field trial. The land was planted with a crop of red-hot chilli peppers (*Capsicum annum*) before the shallot crop was sown. The pH of the topsoil (0-20 cm) at the site was 4.25, and the exchangeable aluminium was 1.27 cmol (+) kg^{-1} and other soil chemical properties before planting are presented in Table 6.1. The soil is classified as Andisol (KEMENTAN-RI, 2016).

Figure 6.1. The field site used for the experiment trial, showing shallots (5 weeks after planting) with kidney beans (*Phaseolus vulgaris*) as the border plants in the foreground.

6.2.2. Experimental design and treatments

The experimental design for the field trial involved 17 treatments combinations of different rates of lime and rates of P fertilisers arranged in a completely randomised design. The treatments are presented in Table 6.1. Each treatment was replicated four times. Each replicate plot was 300 cm long and 100 cm wide, the space between plots along the beds about 20 cm, and 30-40 cm between beds.

Table 6.1. Lime and P fertiliser treatments used in this field trial.

Treatments	Liming material rate (t ha^{-1})	Phosphorus fertiliser rate (kg P ha^{-1+})	Nitrogen fertiliser rate (kg N ha^{-1})
T1 (control)	0.0	0	200
T2	0.0	60	200
T3	0.0	120	200
T4	1.0 Local Lime	120	200
T5	2.0 Local Lime	120	200
T6	4.0 Local Lime	120	200

T7	8.0 Local Lime	0	200
T8	8.0 Local Lime	60	200
T9	8.0 Local Lime	120	200
T10	0.25 Calcium Super	120	200
T11	0.5 Calcium Super	120	200
T12	1.0 Calcium Super	0	200
T13	1.0 Calcium Super	60	200
T14	1.0 Calcium Super	120	200
T15 (Nil-N Control)	0.0	0	0
T16	1.0 Calcium Super	120	0
T17	1.0 Calcium Super	120	150
T18	1.0 Calcium Super	120	250

All treatments also received potassium fertiliser at a rate of 125 kg K ha^{-1}.

6.2.3. Field operations (land preparation, fertilisation, planting and harvesting)

The field trial was conducted from 11 December 2019 to 29 February 2020 (0-81 days after planting, DAP), in the rainy season. The climate data was compiled from an Ancolmekar climate station, 5.29 km from the trial site.

Prior to starting the field experiment, the land was cleared from weeds, ploughed to a 20 cm ploughing depth, and then levelled into seedbeds in early December 2019 (Figure 6.2). No herbicide was applied during site preparation. Two days before planting, the lime materials and P fertiliser (TSP 20% P) were applied to plots, and a manual plough was used to incorporate them into the final seedbed up to a soil depth of 15-20 cm (Figure 6.3a and 6.3b). On 11 December 2019, shallot sets were hand-planted with one to two bulbs per position at a depth of 3-5 cm. The shallot bulbs were planted in five rows per seedbed with a spacing of 20 cm between rows and 15 cm between plants. During the sowing time, the insecticide-nematicide carbofuran (3% doses at a rate of 20 kg ha^{-1}) was applied to control *Agrotis ipsilon* (black cutworm) and parasite nematode like Meloidogyne (Juliandri, 2019).

A total of 200 kg N ha^{-1} was applied by hand in three even split applications. First, ammonium sulphate (21% N and 23% S) was applied once 23 days after planting (DAP). Then, urea (46% N) was used as the N fertiliser in the second (46 DAP) and third (60 DAP) dressing of N fertiliser. For the plots that did not receive N fertiliser, no additional S fertiliser was added to achieve the same S rate due to the high initial sulphate soil test level. Potassium chloride (KCl, 60% K_2O) was used as the K fertiliser, which was applied to all treatments at a rate of about 160 kg K ha^{-1}, split over three even applications, by manual side dressing at 23, 46 and 60 DAP. The liming materials included Calcium Super (contains 37.2% calcium oxide and 8.13%

magnesium oxide), with a Calcium Carbonate Equivalence (CCE) of 108%, and a local lime with 71% CCE. Lime materials were applied two days before planting and incorporated into the soil.

Figure 6.2. The plant preparation of the field experiments, clearing from the weeds and first ploughing (a), ploughing deep 20 cm (b), flatten and building beds (c), sowing bulb seeds (d). Photographs were taken from 3 – 11 December 2019.

Manual weeding was conducted to control weeds in the plots (Figure 6.3.c) four times; the first three times were before each of the three split applications of fertiliser (22, 45, and 59 DAP), and the last time was one week before the harvest date (73 DAP). In addition, a combination of insecticides and fungicides were applied weekly, starting from 21 DAP (see Appendix 6.1). The crops were harvested by hand at 81 DAP, and the roots were cuts off from the bulbs. Also, the leaves were cut off about 3 cm above the top of the bulbs. The bulb yield was then weighed.

Figure 6.3. The activity in the field experiment, liming (a), incorporating lime, P fertiliser and soil (b), weeding (c), additional fertiliser application (d). Photos a and b were taken two days before sowing, and photos c and d were taken 21 DAP.

6.2.4. Measurement and analysis

Four soil samples (0-20 cm depth, 16 cores per sample) were collected, one from each of the four treatment replication areas, prior to applying treatments. The soil samples were sent to *Laboratorium Penguji BALITSA* or Analytical Research Laboratory IVEGRI, Lembang, for chemical analysis (results are shown in Table 6.2). At 56 DAP, soil samples were also collected from each treatment plot (6 cores per plot sample) to determine the soil pH, the soil P status (Bray1-P), concentration of KCl-titratable acidity (Al^{3+} and H^{+}) and base cations (Ca^{2+}, Mg^{2+}, K^{+} and Na^{+}). Soil samples were air-dried and sieved to < 2 mm. The methodology for soil analyses is provided in Chapter 2.

Three plant samples were collected from each plot at 56 DAP. Plant samples were oven-dried and ground to less than 0.5 mm. The procedure for herbage N, P, K, Ca, Al, and Mn analyses are described in Chapter 2.

6.2.5. Statistical analysis

Repeated measures analyse of variance (ANOVA) were used using SAS (9.4 version) to assess the effect of treatments on measured parameters. An ANOVA was applied separately to each treatment as the fixed effects. Means were grouped by Tukey's test. In figures and tables, separate letters indicate a significant difference at *p-value* $\leq$ 0.05 and *p-value* $\leq$ 0.10*. Data normality and variance consistency were tested by graphical analysis residual. Some data were transformed through a square root transformation to reach a normal distribution.

6.3. Results and Discussion

6.3.1. Weather conditions during shallot growth

During the period from planting to harvesting (81 days) that total rainfall was 809 mm and relative humidity ranged from 68-93% (Figure 6.4.a). The rainfall was similar to the long-term average rainfall for the same 81-day period of 835 mm. However, rainfall was not evenly distributed during the experimental period, with higher rainfall in the second half of the trial. In addition, there was low level of rainfall (42 mm) between 20 and 42 DAP, which has potential to have resulted water availability becoming limited to shallot growth. During the experiment, the minimum temperature ranged from 19 to 22.6^{o}C, and the maximum ranged from 25 to 32.3^{o}C.

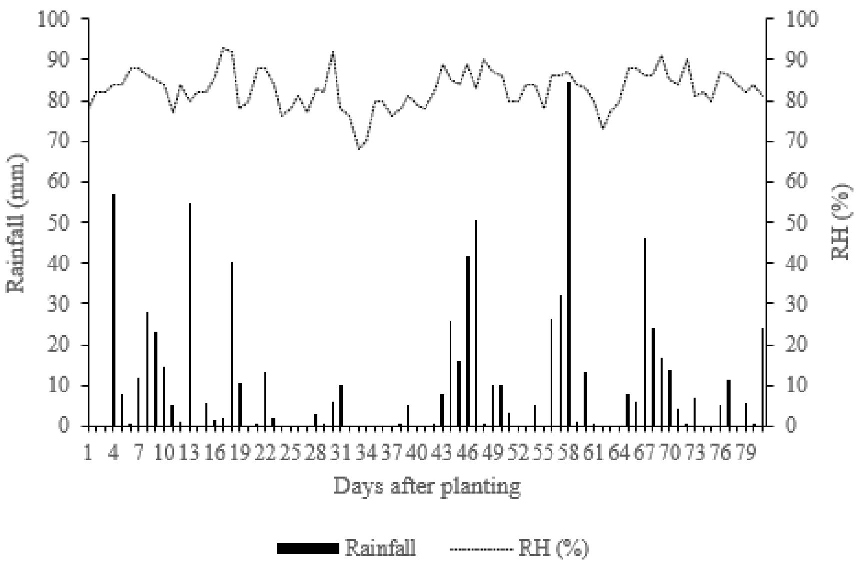

Figure 6.4. The daily rainfall (mm) and relative humidity (%) during the experiment (November 2019 to March 2020).

6.3.2. Effect of treatments on soil chemical properties

Soil analysis results before the experiment

The soil analyses at the trial site, approximately 1 month prior to shallot planting, are shown in Table 6.2. The soil is highly acidic with soil pH below 4.5 and a high exchangeable Al^{3+} of 1.27 cmol (+) kg^{-1}. The soil also has a low cation exchange capacity (CEC) and low base saturation (BS), which is typical of weathered tropical upland soils. The soil available-P at this this area of farm was lower than for the first field trial site, which has initial Bray1-P of 14.2 mg P kg^{-1}. This difference may be due to the different areas of the farm used for the two trial sites.

Table 6.2. Soil chemical properties at the field trial site (approximately 1 month prior to shallot planting).

	Average	Interpretation	Optimum*/Medium range
pH	4.25± 0.05	Highly acidic	5.5-6.5
Al^{3+} (cmol (+) kg^{-1})	1.27 ± 0.17	High (toxic)	<0.82
H^{+} (cmol (+) kg^{-1})	0.35 ± 0.13		
Al + H (cmol (+) kg^{-1})	1.61 ± 0.28		
Al:Ca ratio	0.40 ± 0.07	Very high	<0.20
Base cations:			
Ca^{2+} (cmol (+) kg^{-1})	3.30 ± 0.20	Low	6.0-7.0
Mg^{2+} (cmol (+) kg^{-1})	0.80 ± 0.05	High	0.35-0.59
K^{+} (cmol (+) kg^{-1})	0.64 ± 0.07	Low	0.70-0.80
Na^{+} (cmol (+) kg^{-1})	0.02 ± 0.00		
Total Base Cations	4.79 ± 0.31		
CEC (cmol (+) kg^{-1})	14.5 ± 0.07		
BS (%)	33.3 ± 2.02	Low	>75%
Bray1-P (mg P kg^{-1})	6.50 ± 1.56	Low	24-40
P-retention	61.42±1.38	Low	
SO_4^{2+}-S (ppm)	66 ± 2.59	High	59
Organic C (%)	1.01 ± 0.02	Low	
N-Kjeldhal (%)	0.14 ± 0.00	Low	
C:N ratio	7.25 ± 0.25		
N-NH_4^{+} (ppm)	1.50± 0.13	Medium (0-5)	
N-NO_3^{-} (ppm)	17.69 ± 6.17	Medium (10-50)	
Micronutrients:			
Fe (ppm)	1.95 ± 0.67	Low	2.5-5.0
Mn (ppm)	66 ± 5.77	Very high (toxic)	3-9
Cu (ppm)	0.5 ± 0.00	Medium	0.25-0.5
Zn (ppm	0.85 ± 0.06	High	0.25-0.5
B (ppm)	0.96 ± 0.09	Medium	0.5-1.0

BS=Total base cations/CEC x 100%. Soil analysis was conducted by IVEGRI's Analytical Laboratory in Lembang, West Java, Indonesia. Sources: (APAL, 2020; Dai & Richter, 2000; Khokhar, 2019; Lee et al., 2012; Muhammad et al., 2000) *Optimum values for shallots and other vegetable crops in general. Trace elements were extracted by Morgan Venema pH 4.8 and were measured by AAS.

Soil pH and exchangeable acidity

Treatments with low rates of liming material (Calcium Super) did not adequately increase soil pH and reduce exchangeable Al^{3+}. Therefore, the results for this liming treatment are not discussed in this chapter.

At 56 DAP, the Control treatment with 200 kg N ha^{-1} (T1) had the lowest soil pH of 4.12 and the highest exchangeable Al^{3+} of 1.93 cmol (+) kg^{-1}. In comparison, the Nil-N Control treatment had a pH of 4.33 and exchangeable Al^{3+} of 1.43 cmol (+) kg^{-1}. While the differences were not significant, it is possible that the N fertiliser addition, especially the ammonium fertiliser, could have contributed to further soil acidification.

Liming significantly increased soil pH and reduced exchangeable Al^{3+} and Al:Ca ratio ($p\leq$ 0.01, Table 6.3). Overall, there was a general trend of increasing soil pH with increasing lime rate up to the highest lime rate of 8 t ha^{-1}. The 8-t lime ha^{-1} rate with the highest P rate (120 kg P ha^{-1}; T9) gave the highest soil pH of 5.53 and the lowest exchangeable Al^{3+} of 0. The pH level achieved by the T9 was significantly higher than all other treatments that had liming materials at rates at 2 t ha^{-1} or less. In the first field trial (Chapter 4) it was identified that there was a greater likelihood of a high shallot fresh bulb yield (> 10 t ha^{-1}) being achieved when soil exchangeable Al^{3+} was < 0.5 cmol (+) kg^{-1}. When lime was applied at only 2 t ha^{-1} then exchangeable Al^{3+} was at 0.98 cmol (+) kg^{-1}, which decreased to 0.44 (+) kg^{-1} when the lime rate was doubled to 4 t ha^{-1}. This indicates that a lime rate of approximately 4 t ha^{-1} of local lime (71% CCE) or greater is required to achieve a low level of exchangeable Al^{3+} at this site. The relationship between lime addition and change in soil pH is shown in Figure 6.5. Based on this relationship a total of 6.2 t ha^{-1} of local lime is required to increase pH by a value of 1.

Table 6.3. Comparison of different liming material and fertiliser effects on soil pH and exchangeable acidity (cmol (+) kg^{-1} (0-20 cm soil depth) at 56 DAP.

Treatments	pH_{H2O}	Al^{3+}	KCl titratable acidity
		cmol (+) kg^{-1}	
T1=0L+0P (Control)	4.12^{d}	1.93^{a}	2.90^{a}
T2=0L+60P	4.11^{d}	1.94^{a}	2.83^{a}
T3=0L+120P	4.20^{d}	1.49^{ab}	2.26^{ab}
T4=1L+120P	4.36^{d}	1.16^{a-d}	1.61^{a-e}
T5=2L+120P	4.55^{b-d}	0.98^{bcd}	1.30^{b-e}

T6=4L+120P	4.74^{a-d}	0.44^{cde}	0.87^{b-e}
T7=8L+0P	5.24^{abc}	0.32^{de}	0.45^{de}
T8=8L+60P	5.38^{ab}	0.31^{de}	0.54^{de}
T9=8L+120P	5.53^{a}	0.00^{e}	0.21^{e}
T14=1CaSup+120P	4.50^{d}	1.30^{abc}	1.73^{a-d}
T15=0L+0P+0N (Nil-N Control)	4.33^{d}	1.43^{ab}	1.94^{abc}
p-value	<0.01	<0.01	<0.01
CV (%)	7.4	35.8	36.7

Note: Selected treatments shown in the table and results for all treatments are provided in the Appendix 6.2. CV=Coefficient of Variance; KCL titratable acidity = sum Al^{3+} + $H^{+,}$ ns=not significance; Tukey's method for means comparison; means presenting the same letters in the same column are not significantly different at α=5%. All treatments, except T15, also received 200 kg N ha^{-1}. All treatments received 125 kg K ha^{-1}.

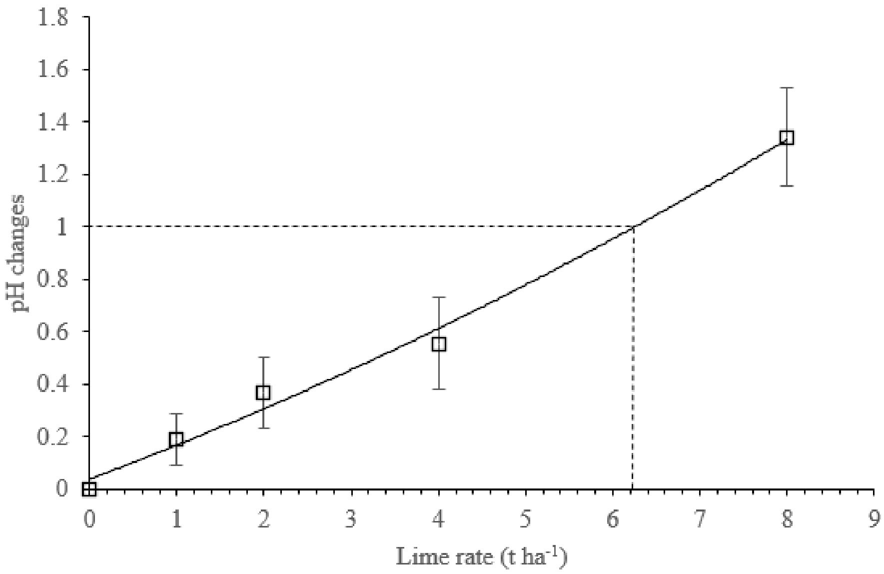

Figure 6.5. Local lime rates (t ha^{-1}) in correlation to pH changes, n = 4. Error bars are standard error.

From the previous chapters (Chapter 4 and 5), it was found that pH_{H2O} had a negative correlation with the concentration of exchangeable Al^{3+} at Field site 1. The similar trend was found in this experiment and the relationship (R^2 = 0.51, Figure 6.6). When pH_{H2O} was less 5.0, most exchangeable Al^{3+} values were higher than 0.5 cmol (+) kg^{-1}. This critical pH_{H2O} was higher than the value at Field Trial 1 (Chapter 4), which was 4.60. Those findings show the complex relationship between soil pH and exchangeable Al^{3+}. Therefore, when assessing the potential effects of soil acidity on plant growth, measuring the pH_{H2O} alone is not sufficient, but should be used in combination with exchangeable Al^{3+}.

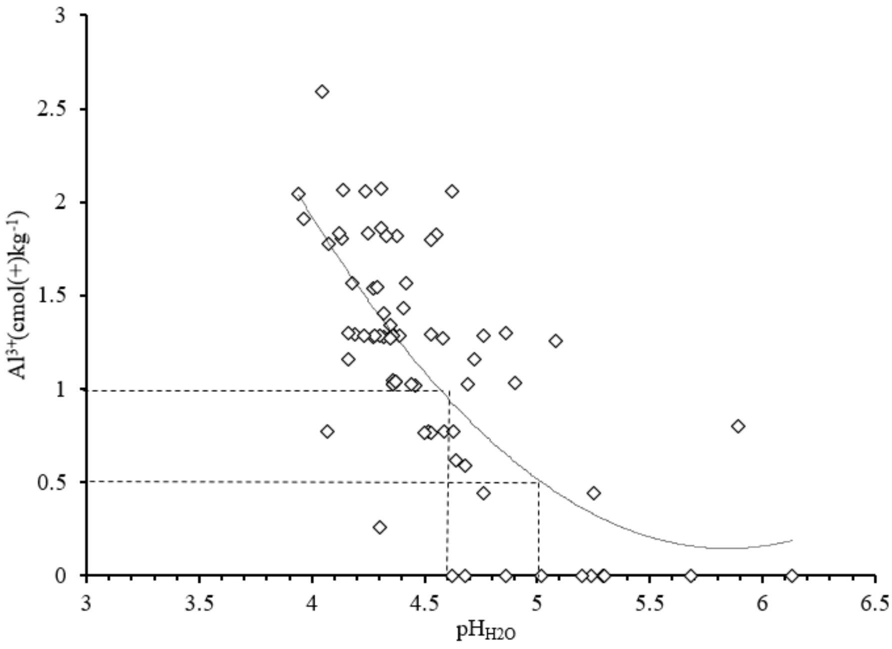

Figure 6.6. The exchangeable Al^{3+} (cmol (+) kg^{-1}) in relation to soil pH in different rates of lime and fertilisers, $R^2 = 0.51$, n=72.

In this experiment, the N fertiliser was provided with ammonium and urea fertilisers, which could have contributed to a reduction in soil pH and an increase exchangeable Al^{3+}. The 200 kg N ha^{-1} (Control treatment) reduced soil pH from 4.25 to 4.12 and increased exchangeable Al^{3+} from 1.27 to 1.93 cmol (+) kg^{-1}. A similar result was reported by (Wang et al., 2018), where the application of ammonium at a rate of 88.9 mg N kg^{-1} soil reduced soil pH from 4.62 to 4.53 and increased exchangeable Al^{3+} from 0.25 to 0.35 cmol (+) kg^{-1}. Reducing soil pH through nitrogen-ammonium base fertiliser increases exchangeable Al^{3+} linearly due to the ability to execute net excess H^+ by the plants and exacerbate the acidification of the rhizosphere. In addition, if a proportion of the nitrified ammonium then leaches as nitrate, this will contribute to further soil acidification (Widowati et al., 2012).

An application of 4 t ha $^{-1}$ lime reduced exchangeable Al^{3+} to the target Al concentration, < 0.5 cmol (+) kg^{-1} (Figure 6.7). This rate was higher than at Field site 2 (Field trial 1, Chapter 4), which had an initial exchangeable Al^{3+} of 1.13 cmol (+) kg^{-1} that was reduced to < 0.5 cmol (+) kg^{-1} with the application of only 1 t lime ha^{-1}. If the exchangeable Al^{3+} is used as a guide to determine liming rate, this would equate to 0.88 t lime per cmol (+) Al^{3+} kg^{-1}. However, when the same calculation is used Field site 1 in the current experiment, this would equate to 2.1 t lime per cmol (+) Al^{3+} kg^{-1} (i.e., 4 t lime/1.93 cmol (+) kg^{-1}). Therefore, this demonstrates that soil differences between sites, may change the amount of lime required to achieve low exchangeable Al levels. Therefore, a simple relationship between lime rate and exchangeable Al may not be adequate to determine the amount of lime needed to achieve low exchangeable Al levels at different sites.

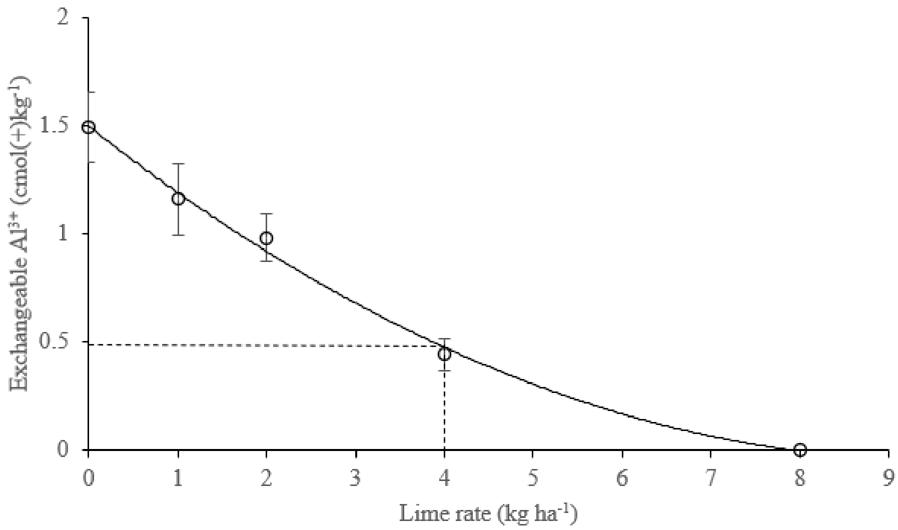

Figure 6.7. The means of exchangeable Al^{+3} (cmol (+) kg^{-1}) in relation to different lime rates + 120 kg P ha^{-1} + 200 kg N ha^{-1}. The error bars are the standard error, n = 4.

Lime applied at the rate of 8 t ha^{-1} (T9) also reduced exchangeable Mn^{2+} significantly (Figure 6.8). Similarly, Yuan et al. (2019) reported that lime increased soil pH and base cations and reduced the exchangeable Mn^{2+}. However, when we compared T1 (0L+0P+200N) and T15 (0L+0P+0N), the concentration of Mn^{2+} at T15 was significantly lower than T1. As previously discussed, the addition N fertiliser may have contributed to further soil acidification and, thereby, increasing exchangeable Mn^{2+} (Hem, 1963). Cheng and Ouellette (1970) also observed the addition of N fertiliser decreased soil pH from 4.00 to 3.89 and increased Mn concentration from 8.9 to 10.3 mg Mn kg^{-1}.

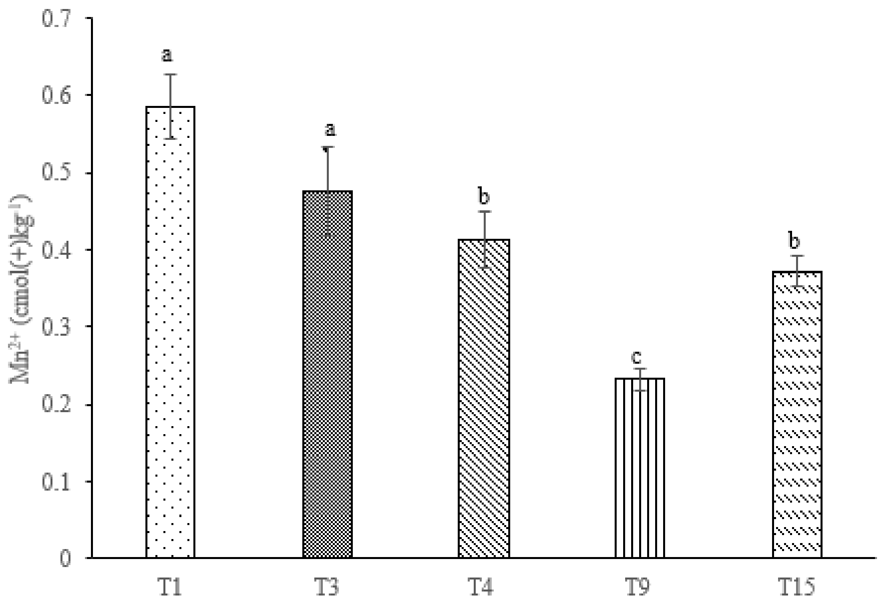

Figure 6.8. Influence of lime, P and N fertiliser rates on exchangeable Mn^{2+} (cmol (+) kg^{-1}). Means with a different letter indicates significant differences using Tukey's test at α =5%. The error bars are the standard error (n=4), T1= 0L+0P+200N (Control), T3=0L+120P+200N, T4=1L+120P+200N, T9=8L+120P+200N, T15=0L+0P+0N (Nil-N Control).

In this experiment, the concentration of exchangeable Mn^{2+} ranged from 0.23 to 0.59 cmol (+) kg^{-1}. Concentrations of soil exchangeable. Mn^{2+} were up to 0.59 cmol (+) kg^{-1} for the no lime treatment, whereas an application of 8 t lime ha^{-1} reduced the exchangeable Mn^{2+} to 0.23 cmol (+) kg^{-1}. There is no published threshold point for manganese toxicity for shallot nor onion, therefore, further investigations are needed to determine the critical point of soil exchangeable Mn^{2+} for these crops. The manganese threshold varies among the plant species and the environment. Kale was affected by manganese toxicity when the exchangeable Mn^{2+} was > 0.58 cmol (+) kg^{-1}, swede at > 0.32 cmol (+) kg^{-1}, lettuce at > 0.44 cmol (+) kg^{-1} and potato > 0.41 cmol (+) kg^{-1} (Hale & Heintze, 1946). Manganese concentration in soil solution was negatively correlated with soil pH (r = -0.76, Figure 6.9). At a soil pH of 5.0, the exchangeable Mn^{2+} is estimated to be approximately 0.25 cmol (+) kg^{-1}.

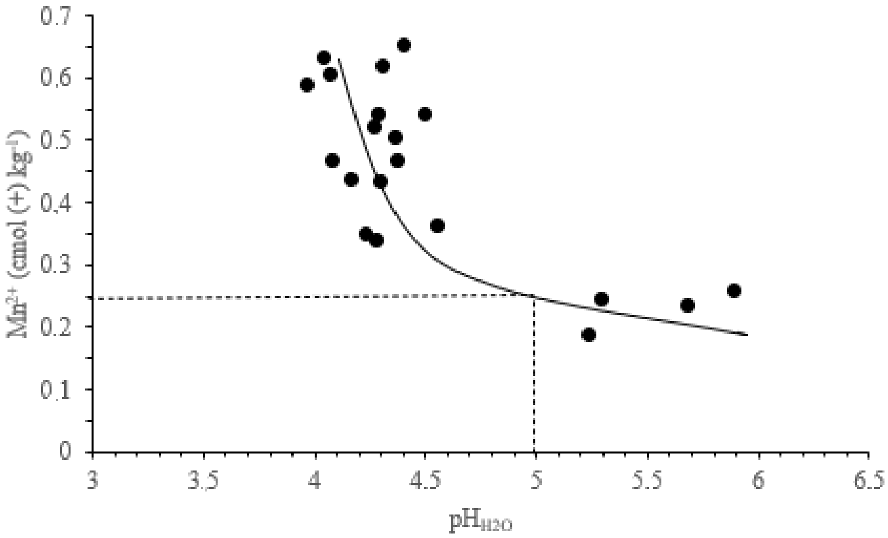

Figure 6.9. The exchangeable Mn^{2+} (cmol (+) kg^{-1}) in relation to soil pH in different rates of lime and fertiliser with a quadratic trendline, n = 20.

Exchangeable base cations, cation exchange capacity (CEC) and base saturation (BS)

Overall, the application of 8 t ha^{-1} lime + 120 kg P ha^{-1} (T9) gave the highest concentration of Ca^{2+}, total base cations (TBC) and base saturation (BS) (Table 6.4). The CEC levels of the Control treatment (0L+0P) was 14.2 cmol (+) kg^{-1} with BS about 28%. The application of 8 t ha^{-1} lime without P fertiliser significantly increased BS to 67%, and the addition of 120 kg P ha^{-1} further increased BS to 80%. Soil exchangeable Ca^{3+} amounts less than 6.0 cmol (+) kg^{-1} are considered to be low and the Control treatment had a value less than half of this value (2.59 cmol (+) kg^{-1}). Only lime rates of 4 t ha^{-1} or higher achieved soil Ca level near or above 6.0 cmol (+) kg^{-1}. On average, across lime and fertiliser treatments, every 1 t ha^{-1} of local lime increased exchangeable Ca^{2+} by 0.85 cmol (+) kg^{-1}. The increase of Ca^{2+}concentration is expected due to the high calcium content of the lime. A similar response was reported by Fernando (2016), who observed that for every 1 t dolomite ha^{-1} increased concentration of Ca^{2+} by 0.60 cmol (+) kg^{-1} in Inceptisol soils, West Sumatra, Indonesia.

Table 6.4. Comparison of different liming materials and fertiliser effects on Ca^{2+}, Mg^{2+}, total base cations (TBC), cation exchange capacity (CEC) and base saturation (BS) at 56 DAP.

Treatments	Ca^{2+}	Mg^{2+}	TBC	CEC	BS
	(cmol (+) kg^{-1})				(%)
T1=0L+0P (Control)	2.59^{c}	0.56^{c}	4.10^{d}	$14.2^{b\text{-}e}$	28^{c}
T2=0L+60P	2.49^{c}	0.64^{bc}	4.05^{d}	15.1^{abc}	28^{c}
T3=0L+120P	3.23^{c}	0.78^{abc}	4.93^{cd}	13.7^{de}	34^{c}
T4=1L+120P	4.25^{bc}	0.78^{abc}	5.91^{bcd}	$14.7^{a\text{-}e}$	41^{bc}
T5=2L+120P	4.47^{bc}	0.68^{abc}	5.93^{bcd}	$14.1^{b\text{-}e}$	41^{bc}
T6=4L+120P	5.97^{abc}	0.72^{abc}	7.88^{abc}	$14.45^{a\text{-}e}$	54^{abc}
T7=8L+0P	8.36^{ab}	0.65^{bc}	9.78^{ab}	$14.4^{a\text{-}e}$	67^{ab}
T8=8L+60P	9.40^{a}	0.68^{bc}	10.92^{a}	$15.0^{a\text{-}d}$	75^{a}
T9=8L+120P	10.12^{a}	0.70^{abc}	11.58^{a}	15.4^{ab}	80^{a}
T14=1CaSup+120P	3.53^{c}	1.01^{abc}	5.43^{bcd}	13.4^{e}	37^{bc}
T15=0L+0P+0N (Nil-N Control)	2.85^{c}	0.78^{abc}	4.71^{cd}	$14.0^{c\text{-}e}$	32^{c}
p-value	<0.01	<0.01	<0.01	<0.01	<0.01
CV (%)	36.7	21.4	26.9	3.6	26.9

Note: Selected treatments shown in the table and results for all treatments are provided in the Appendix 6.2. Total base cations (TBC) = $Ca^{2+}+Mg^{2+}+K^{+}+Na^{+}$, base saturation (BS)=TBC/CEC x 100%, CV=Coefficient of Variance; ns=not significance; Tukey's method for means comparison; means presenting the same letters in the same column are not significantly different at α =5%. All treatments, except T15, also received 200 kg N ha^{-1}.

Control treatment had a soil exchangeable Mg^{2+} value of 0.56 cmol (+) kg^{-1}, which is at the upper end of the considered optimum range. All other treatments had high values of greater than 0.60 cmol (+) kg^{-1}. The 1.0 t ha^{-1} Calcium Super treatment (T14) achieved the highest soil exchangeable Mg^{2+} concentration of 1.01 cmol (+) kg^{-1}. This was due to this liming material containing Mg.

The sum of basic cations as a percentage of CEC (base saturation) are presented for the different lime rates in Figure 6.10. The Control treatment, which received no lime application had the lowest base saturation of 28%. Base saturation increased with increasing lime rate up to a value of 80% for the 8-t lime ha^{-1} treatment. Only the 4 and 8 t lime ha^{-1} treatment achieved base saturation values of greater than 50%. The increase in basic cations, as a proportion of soil CEC that resulted from lime application, was primarily due to increases in Ca, resulting from the Ca content of the local lime. At the highest rate of lime, the K % decreased, which is possibly due to competition for soil exchange sites with Ca.

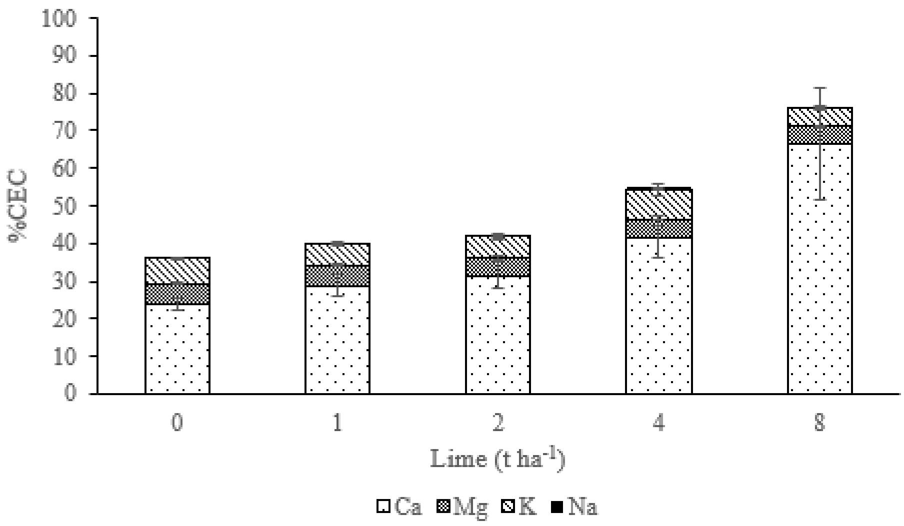

Figure 6.10. The effect of lime rate (t ha^{-1}) on the basic cation saturation of soil CEC at 56 DAP (all treatments received of 120 kg P, 200 kg N and 125 kg K ha^{-1}; error bars are the standard error, n=4).

Al:Ca ratio

The relationship between exchangeable Al^{3+} and Ca^{2+} is negative (R^2 = 0.64, Figure 6.11). When the concentration of exchangeable Ca^{2+} was more than 6.0 cmol (+) kg^{-1}, the majority of exchangeable Al^{3+} was lower than 0.5 cmol (+) kg^{-1}. While, when the concentration of exchangeable Ca^{2+} was lower than 4.5 cmol (+) kg^{-1}, the majority of exchangeable Al^{3+} was more than 1.0 cmol (+) kg^{-1}.

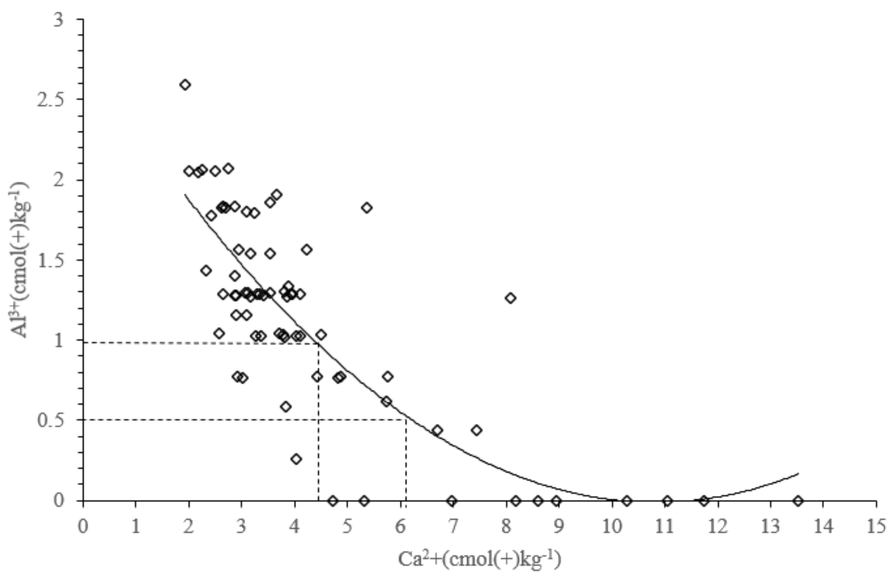

Figure 6.11. The concentration of exchangeable Al^{3+} (cmol (+) kg^{-1}) in relation to exchangeable Ca^{2+} (cmol (+) kg^{-1}) across the treatments, R^2 = 0.68, n = 72.

When the exchangeable Al^{3+} and Ca^{2+} are expressed as a ratio, the Control treatment (T1) had a high Al:Ca ratio of 0.80. Lime application reduced Al:Ca ratio across fertiliser treatments (Table 6.5). Application of 8 t ha^{-1} lime decreases Al:Ca ratio from 0.80 to 0.11, for the treatments without P fertiliser addition, which decreased to zero when 120 kg P ha^{-1} was also applied with this lime rate. The 4-t ha^{-1} lime + 120 kg P ha^{-1} treatment also achieved an Al:Ca ratio of 0.07, which was below the target of 0.10 (Figure 6.12). Moreover, a higher rate of lime decreased the Al:Ca ratio to zero.

Table 6.5. Comparison of different liming material and fertiliser effects on Al:Ca ratio.

Treatments	Al:Ca
T1=0L+0P (Control)	0.80^{a}
T2=0L+60P	0.80^{a}
T3=0L+120P	$0.38^{a\text{-}e}$
T4=1L+120P	$0.32^{c\text{-}f}$
T5=2L+120P	$0.25^{c\text{-}f}$
T6=4L+120P	0.07^{def}
T7=8L+0P	0.11^{ef}
T8=8L+60P	0.04^{ef}
T9=8L+120P	0.00^{f}
T14=1CaSup+120P	$0.39^{a\text{-}d}$
T15=0L+0P+0N (Nil-N Control)	0.50^{ab}
p-value	<0.01
CV (%)	8.6

Note: Selected treatments shown in the table and results for all treatments are provided in the Appendix 6.2. CV=Coefficient of Variance; ns=not significance; Tukey's method for means comparison; means presenting the same letters in the same column are not significantly different at α =5%. All treatments, except T15, also received 200 kg N ha^{-1}.

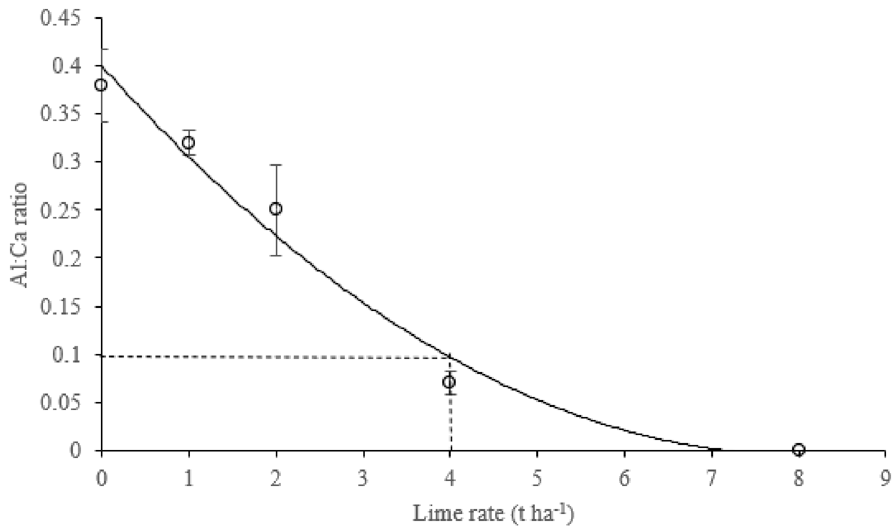

Figure 6.12. The means of Al:Ca ratio in relation to different lime rates (t ha^{-1}) + 120 kg P ha^{-1} + 200 kg N ha^{-1} (error bars are the standard error, n = 4).

Soil available-P (Bray1-P)

The application of P fertiliser significantly increased soil Bray1-P (Table 6.6). The Bray1-P for the Control treatment was low, being 9.8 mg P kg^{-1}. Bray1-P increased with increasing P fertiliser rate up to the highest P fertiliser rate of 120 kg P ha^{-1}, which achieved an average of 22 mg P kg^{-1} when it was applied + 8 t lime ha^{-1}. This level of Bray1-P is just below the range considered optimum for shallot growth (Table 6.2). In Field Trail 1 (Chapter 4) it was observed that there was a higher likelihood of high shallot yields (> 10 t ha^{-1}) when Bray1-P was > 28 mg P kg^{-1}. Therefore, the Bray1-P levels in this experiment, even with the highest P fertiliser used, having potential to limit high shallot yields. A high P fertiliser rate was based on the first trials from the same site, that supported approximately 100 kg P ha^{-1} could achieve the optimal Bray1-P in the site. Therefore, the rate used was reduced from 150 to 120 kg P ha^{-1}. The initial Bray1-P in the site is similar to Site 3 at the First Field Trial, which had an optimal P-fertiliser rate on 100 kg P ha^{-1}. Therefore, similar rate was applied in this site.

There was a linear trend between P fertiliser addition and Bray1-P changes (Figure 6.13). On average, 8.5 kg P ha^{-1} was required for a 1 mg P kg^{-1} change in Bray1-P. There was no significant effect of lime treatments on Bray1-P.

Table 6.6. The effect of liming materials and fertiliser on soil available -P (Bray1-P, mg P kg^{-1}) at 56 DAP.

Treatments	Bray 1-P (mg P kg^{-1})
T1=0L+0P (control)	9.8^{bc}
T2=0L+60P	16.7^{abc}
T3=0L+120P	21.0^{ab}
T4=1L+120P	27.0^{a}
T5=2L+120P	23.7^{a}
T6=4L+120P	24.8^{a}
T7=8L+0P	8.5^{bc}
T8=8L+60P	18.8^{abc}
T9=8L+120P	22.2^{ab}
T14=1.0CaSup+120P	21.2^{abc}
T15=0L+0P+0N (Nil-N Control)	6.68^{c}
p-value	<0.01
CV (%)	26.5

Note: Selected treatments shown in the table and results for all treatments are provided in the Appendix 6.2. CV=Coefficient of Variance; ns=not significance; Tukey's method for means comparison; means presenting the same letters in the same column are not significantly different at α =5%. All treatments, except T15, also received 200 kg N ha^{-1}.

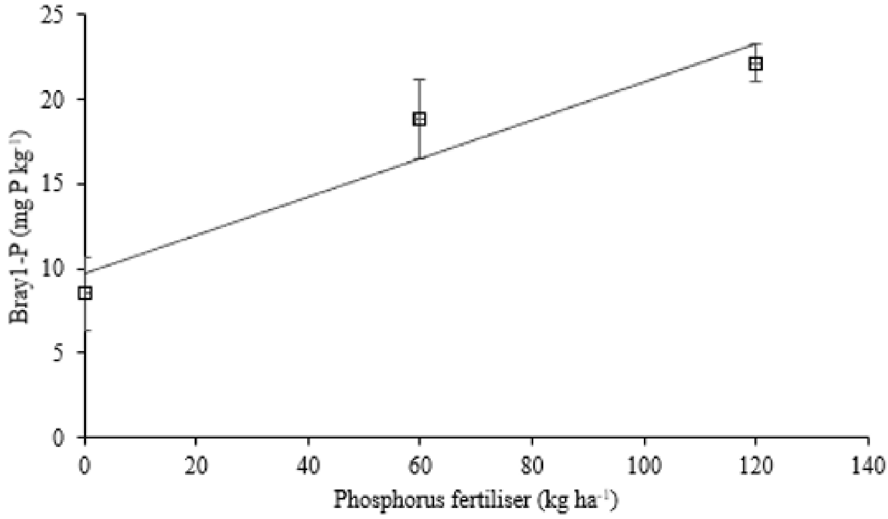

Figure 6.13. The means of soil available-P (Bray1-P) in relation to different P-fertiliser rates + 8 t lime ha^{-1} + 200 kg N ha^{-1} (error bars are the standard error, n = 4).

6.3.3. Effect of treatments on plant growth and nutrient uptake

Low rainfall that occurred of a period about 3 weeks, from 20 to 42 DAP, during the experiment is likely to have contributed to low shallot vegetative growth for all treatments. Subsequently, after 45 DAP, heavy rainfall occurred that led to high disease incidence, would have further influenced plant growth. These constraints are likely to have caused shallot growth and bulb yield to be lower overall in this experiment compared to Field trial 1 at this site.

Shoot length

Lime and P fertiliser gave a significant effect on shoot length at Field trail 1 (Chapter 4). Thus, this parameter was used to predict the effect of treatments on shallot growth in this experiment. Overall, the application of 8 t ha^{-1} + 120 kg P ha^{-1} (T9) had the longest shoot lengths at 21, 42 and 63 DAP, which were significantly longer than for the Control treatment (T1) (Table 6.7). At 42 and 63 DAP, 4 t ha^{-1} + 120 kg P ha^{-1} (T9) also significantly increased shoot length significantly compared to the Control treatment. There was a general trend of shoot length increasing with P fertiliser rate; however, the differences were not statistically significant.

Table 6.7. The effect of liming materials and fertilisers on shoot length (cm).

Treatment	21 DAP	42 DAP	63 DAP
T1=0L+0P (Control)	14.8^{b}	18.4^{d}	16.4^{c}
T2=0L+60P	15.3^{ab}	19.1^{cd}	17.7^{bc}
T3=0L+120P	16.2^{ab}	21.4^{a-d}	21.2^{abc}
T4=1L+120P	17.0^{ab}	22.4^{abc}	22.7^{b}
T5=2L+120P	16.6^{ab}	22.6^{abc}	21.8^{abc}
T6=4L+120P	16.8^{ab}	24.1^{a}	24.0^{a}
T7=8L+0P	17.2^{a}	23.1^{ab}	21.8^{ab}
T8=8L+60P	16.9^{ab}	24.1^{a}	24.8^{a}
T9=8L+120P	17.3^{a}	25.1^{a}	25.9^{a}
T14=1.0CaSup+120P	16.3^{ab}	21.6^{a-d}	21.3^{abc}
T15=0L+0P+0N (Nil-N Control)	16.3^{ab}	19.9^{bcd}	17.4^{bc}
p-value	0.02	<0.01	<0.01
CV (%)	5.8	6.9	10.2

Note: Selected treatments shown in the table and results for all treatments are provided in the Appendix 6.3. DAP=days after planting; CV=Coefficient of Variance; ns=not significance; Tukey's method for means comparison; means presenting the same letters in the same column are not significantly different at α =5%. All treatments, except T15, also received 200 kg N ha^{-1}.

Plant biomass

At 56 DAP (25 days before final harvest), the total plant dry weight for the Control treatment (T1) was 2.63 g DM plant^{-1}, of which 77% was the bulb weight contribution (Table 6.8). Increasing P fertiliser rate without lime increased total plant dry weight, but not sufficiently to be statistically different. However, all lime treatments (with and without P fertiliser) did significantly increase plant dry weight compared to the Control treatment. However, there was no significant differences in plant dry matter yield, with the 1 t local lime + 120 kg P ha-1 treatment achieving a plant dry weight of 5.49 g DM plant^{-1}, which was more than double the Control treatment value but almost the same as the similar to the 8 t local lime + 120 kg P ha^{-1} treatment. A response to increasing lime was expected, given the changes observed to exchangeable Al and Mn with the higher lime rates. However, as mentioned earlier other constraints, such as soil moisture and disease incidence may have limited the plant response.

Table 6.8. The effect of liming materials and fertilisers on shallot dry weight per plant at 56 DAP (g DM $plant^{-1}$).

Treatment	Roots	Bulbs	Above ground (Stems Leaves)	Total
T1=0L+0P (Control)	0.15^{ab}	2.03^{c}	0.45^{e}	2.63^{e}
T2=0L+60P	0.17^{ab}	2.66^{bc}	0.54^{de}	3.37^{cde}
T3=0L+120P	0.18^{ab}	3.07^{abc}	0.87^{b-e}	4.12^{a-e}
T4=1L+120P	0.23^{ab}	3.98^{a}	1.27^{abc}	5.49^{a-d}
T5=2L+120P	0.22^{ab}	3.95^{a}	1.26^{abc}	5.42^{ab}
T6=4L+120P	0.25^{ab}	3.44^{ab}	1.28^{abc}	4.97^{abc}
T7=8L+0P	0.24^{ab}	3.67^{ab}	1.28^{abc}	5.19^{ab}
T8=8L+60P	0.27^{a}	3.98^{a}	1.35^{ab}	5.60^{a}
T9=8L+120P	0.27^{a}	3.77^{ab}	1.46^{a}	5.50^{ab}
T14=1.0CaSup+120P	0.25^{ab}	3.32^{ab}	1.07^{a-d}	4.64^{a-d}
T15=0L+0P+0N (Nil-N Control)	0.12^{b}	2.57^{bc}	0.52^{de}	3.21^{de}
p-value	<0.01	<0.01	<0.01	<0.01
CV (%)	27.6	15.2	21.8	14.7

Note: Selected treatments shown in the table and results for all treatments are provided in the Appendix 6.4. CV=Coefficient of Variance; ns=not significance; Tukey's method for means comparison; means presenting the same letters are not significantly different at α =5%. All treatments, except T15, also received 200 kg N ha^{-1}.

At 56 DAP, there were also visually observable differences between the plant growth of some of the treatments. The application of lime increased the shallot biomass significantly (Figure 6.14). On average, application 1.0 t ha^{-1} lime increased the plant biomass by 15%, compared to the Control treatment when both treatments also received 120 kg P ha^{-1}. Higher rates of lime to not results in singifincalty higher plant dry weights, which is possibly due to other aforemented constraintes to plant growth (i.e. soil moisture limitations and disease incidence).

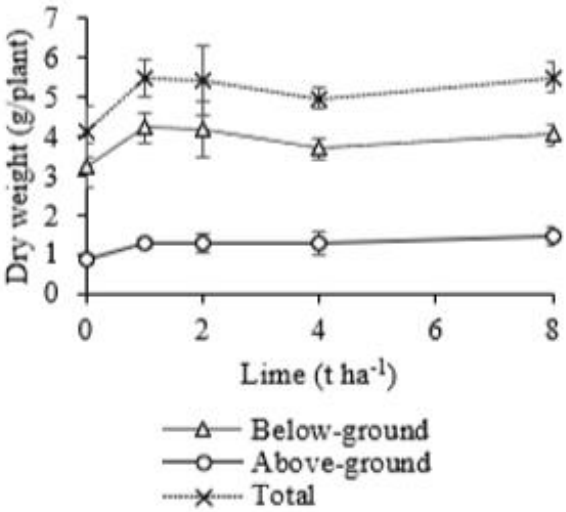

Figure 6.14. Shallot plants mean biomass dry weight response to increasing rates of lime, at 56 DAP (120 kg P, 200 kg N and 125 kg K N ha^{-1} applied to all treatments, error bars are the standard error, n=4).

The application of 120 kg P ha^{-1} increased the total biomass (a whole plant) by 57% when no lime was applied, compared to the Control treatment (Figure 6.15). However, the differences between treatment means were not large enough to be strongly statistically significant. There was no evidence of a P fertiliser response when applied with the highest lime rate (8 t ha^{-1}).

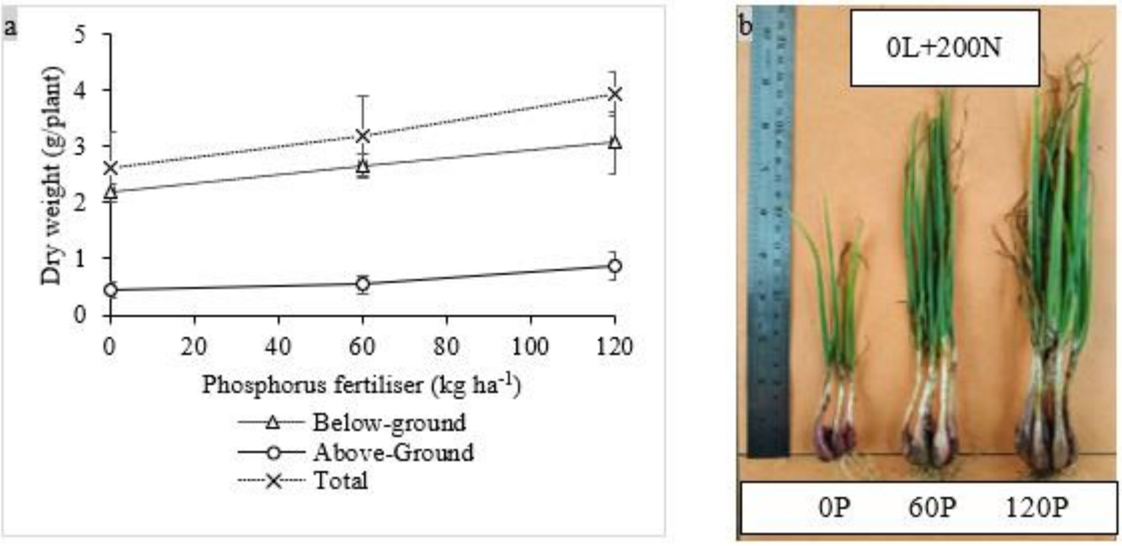

Figure 6.15. (a) Shallot plants mean biomass dry weight response to increasing rates of P fertiliser when no lime, at 56 DAP (200 kg N and 125 kg K N ha^{-1} applied to all treatments, error bars are the standard error, n=4) (a). (b) Visual comparison of shallot growth at the different P fertiliser rates.

The rate of biomass per plant from 21 to 77 DAP has been recorded weekly with destructive measurements in subplots for the following contrast treatments: T9 = 8L + 120P + 200N; T14 = 1CaSup + 120P + 200N; and T15= 0L + 0P + 0N. The plant biomass is the sum of root dry weight + bulb dry weight + shoot dry weight at 56 DAP. The detailed information of root dry weight and bulb dry weight can be seen in Appendix 6.2.

Shallot plant dry weight for three selected treatments up to 77 DAP, which was four days before the final bulb harvest, is shown in Figure 6.16. Treatment 15 shows the effect of no lime or N and P fertiliser applications. With this treatment, plant dry weight increased at a steady rate up to about 40 DAP and then increased a diminishing rate, achieving an average weight of 4.7 g DM plant^{-1} at 77 DAP. Early in the crop's development it is likely that soil fertility status for the treatment became a major limitation to plant development. In contrast, the T9 treatment, which received 8 t lime, 120 kg P and 200 kg N, resulted in a steady increase in shallot plant dry weight throughout the 77-day duration, achieving a plant weight of 9.2 g DM plant^{-1} at the last sampling. This was a 96% increase in plant weight compared to the T15 treatment. When a lower rate of liming material is used (T14; 1 t Calcium Super), then the plant weight achieved was lower, being an average of 7.0 g DM plant $^{-1}$ at 77 DAP. As previously discussed, the use of low rates of lime (~ 1 t lime ha^{-1}) at this site, are likely to be insufficient to mitigate the effect of soil acidity and acidotic cation toxicity on limiting plant growth.

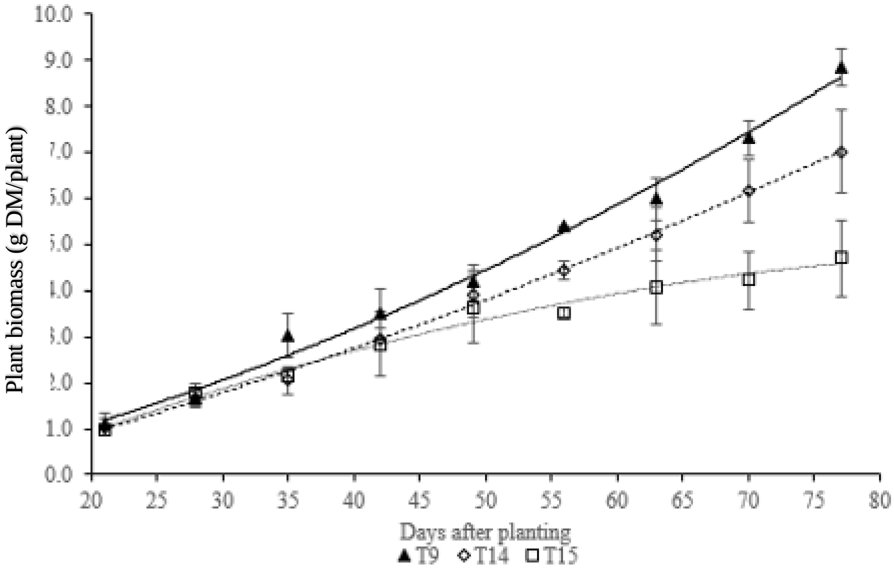

Figure 6.16. Shallot plant (below and above ground) biomass from 21 to 77 DAP in different treatments T9=8L+120P+200N, T14= 1.0 CaSup +120P+200N, T15= 0L+0P+0N; All treatments also received 125 kg K ha^{-1}; error bars are the standard error, n=4.

Nutrient uptake

The Control treatment (T1) achieved the lowest quantities of N, P, K, and Ca uptake by shallots among the treatments, being 9.5, 0.7, 8.5 and 2.5 kg ha^{-1} at 56 DAP (Table 6.9). These levels of nutrient uptake are very low, which reflect in part the low plant growth. All treatments with lime applied had significantly higher uptakes of these nutrients, compared to the Control treatment. The highest uptake of all four nutrients was for the 8-t lime + 120 kg P ha^{-1} (T9) treatment, but the uptake of N and K where not significantly different to that of the other lime treatments.

The T9 treatment significantly increased P uptake compared to all other lime treatments expect the 1 t CaSup + 120 kg P ha^{-1} (T14) treatment. When lime was applied at a rate of 8 t lime ha^{-1}, the P fertiliser application rate of 120 kg P ha^{-1} increased shallot P uptake by 67 and 39% compared to the 0 and 60 kg P ha^{-1} rates, respectively. In addition, increasing the lime rate from 1 t to 8 t ha-1, when 120 kg P ha^{-1} was also applied, increased P uptake by 56%. The T14 treatment was the only lime that resulted in Ca uptake that was significantly lower than the T9 treatment.

Overall, nutrient uptake by the shallot crop was low, even for the treatment that achieved the highest level of uptake. The quantities of N, P and K plant uptake for the T9 treatment only represent 11.6, 2.1 and 19.2% of the amounts applied in fertiliser. The overall low yields in this experiment support that factors other than soil chemical fertility, such as soil moisture and disease incidence, may have become more limiting as phosphorus and lime rates increased, thereby limiting the response to these inputs.

Table 6.9. The effect of liming materials and fertilisers on shallot nutrient uptake (kg ha^{-1}) at 56 DAP.

Treatment	N	P	K	Ca
T1=0L+0P (Control)	9.5^{d}	0.7^{g}	8.5^{e}	2.5^{f}
T2=0L+60P	10.8^{d}	0.9^{fg}	9.6^{de}	3.0^{f}
T3=0L+120P	13.0^{d}	1.1^{efg}	13.3^{cde}	4.6^{ef}
T4=1L+120P	20.0^{abc}	$1.6^{b\text{-}e}$	22.6^{ab}	8.8^{abc}
T5=2L+120P	19.5^{abc}	$1.6^{b\text{-}e}$	21.5^{ab}	9.3^{abc}
T6=4L+120P	19.7^{abc}	$1.7^{b\text{-}e}$	21.7^{ab}	9.1^{abc}
T7=8L+0P	18.9^{abc}	$1.5^{d\text{-}f}$	21.5^{ab}	10.2^{ab}
T8=8L+60P	21.3^{ab}	1.8^{bcd}	22.4^{ab}	11.3^{a}
T9=8L+120P+200N	23.1^{a}	2.5^{a}	24.0^{a}	11.7^{a}
T14=1 CaSup+120P	18.6^{abc}	2.0^{abc}	18.4^{abc}	7.4^{bcd}
T15=0L+0P+0N (Nil-N Control)	11.2^{d}	$1.2^{d\text{-}f}$	9.7^{de}	3.2^{ef}
p-value	<0.01	<0.01	<0.01	<0.01
CV (%)	15.1	15.6	17.0	17.6

Note: Selected treatments shown in the table and results for all treatments are provided in the Appendix 6.5. CV=Coefficient of Variance; ns=not significance; Tukey's method for means comparison; means presenting the same letters are not significantly different at α =5%. All treatments, except T15, also received 200 kg N ha^{-1}.

The concentration of root Al in the Control treatment (T1) is compared to a selection of other treatments is presented in Figure 6.17. The application of 1 t lime plus 120 kg P ha^{-1} (T4) reduced root Al concentration from 4.02% to 2.25% and a higher lime rate 8 t ha^{-1} plus 120 kg P ha^{-1} (T9) reduced the Al concentration further to 1.79%. These results reflect that the application of lime increases exchangeable Ca^{2+} and reduces exchangeable Al^{3+} (Rengel, 1992). Increased Ca^{2+} in soil solution improves Ca uptake and reduces the Al uptake. The Nil-N Control treatment (T15) also had a lower root Al concentration (2.36%) than the Control treatment. This is likely due to the N fertiliser application in Control treatment reducing soil pH and increasing exchangeable Al^{3+}. The application of 120 kg P ha^{-1} without lime (T3) also reduced the root Al concentration compared to the Control treatment. Dissolve phosphates from P fertiliser react with Al and Fe in the soil solution to form Al- and Fe-phosphates (Breeuwsma

& Silva, 1992), which reduces the exchangeable Al^{3+} in the root zone and decreases the Al uptake. In addition, P has a positive interaction with Mg^{2+} and increases the magnesium uptake that reduces the aluminium uptake (Fageria, 2001).

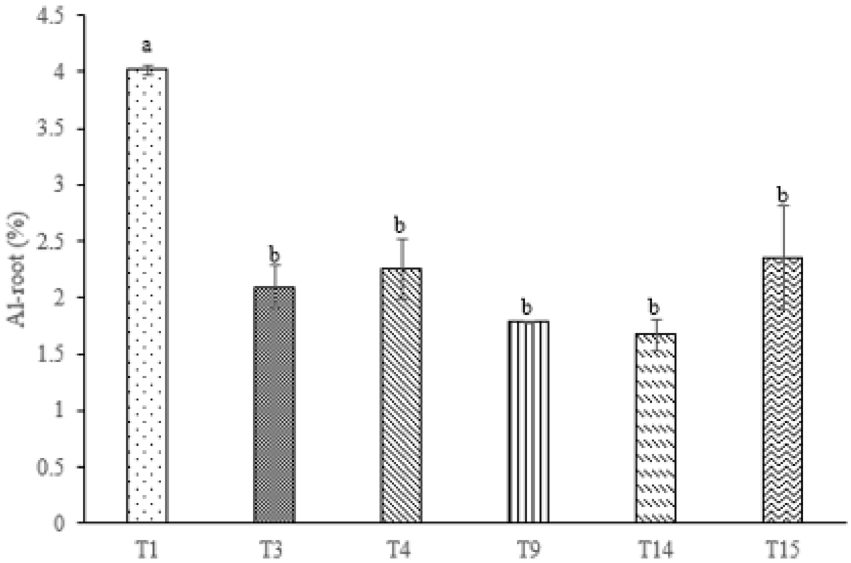

Figure 6.17. Influences of lime, P and N fertilisers on the concentration of Al in the shallot roots at 56 DAP. Means for total Al concentration with different letters indicate significant differences using Tukey's test at $p < 0.05$. The error bars are the standard error, n=4. T1=0L+0P+200N, T3=0L+120P+200N, T4=1L+120P+200N, T9=8L+120P+200N, T14=1CaSup+P+200N, T15=0L+0P+0N.

The concentration of root Ca in the no lime treatments (T1, T3 and T15) were significantly lower than those that received lime (T4, T9, and T14; Figure 6.18). Lime rates of 1 and 8 t ha^{-1} increased root Ca concentrations to 0.73 and 0.82%, respectively, compared to the no lime treatment (T3) value of 0.54%.

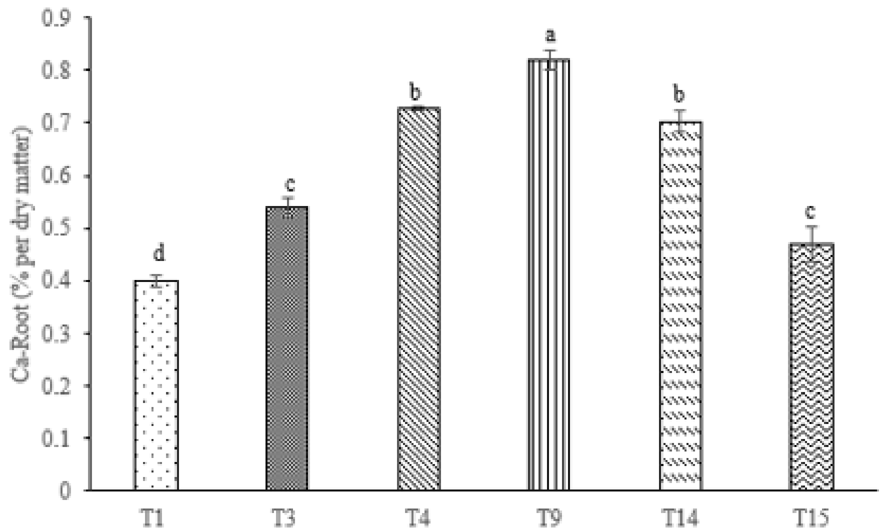

Figure 6.18. Influences of lime, P and N fertilisers on the concentration of Ca in the shallot roots at 56 DAP. Means for the total Ca concentration with different letters indicate significant differences using Tukey's test at $p < 0.05$. The error bars are the standard error, n=4. T1=0L+0P+200N, T3=0L+120P+200N, T4=1L+120P+200N, T9=8L+120P+200N, T14=1CaSup+0P+200N, T15=0L+0P+0N.

The effect of selected treatments on manganese accumulation in the above-ground biomass (shoots) is shown in Figure 6.19. The Control treatment (T1) contained the highest Mn concentration compared to other treatments. Lime rates 1 and 8 t ha^{-1} reduced Mn shoot concentration to 576 and 480 ppm, respectively compared to no lime treatment value 770 ppm that receive the same P and N fertilisers rate. Surprisingly, the concentration of Mn in all treatments was excessive or toxic (300-500 ppm) (Benton Jones Jr., 1991). Manganese concentration in the Control treatment (877 ppm) was 41% higher than the Nil-N Control treatment (621 ppm). This finding was in line with Al-root uptake that N increased the metal uptake, including Al and Mn. Increasing Mn uptake due to N fertiliser application also was reported by (Goldberg et al., 1983) in barley crop that Mn uptake increased linearly with N fertiliser rates.

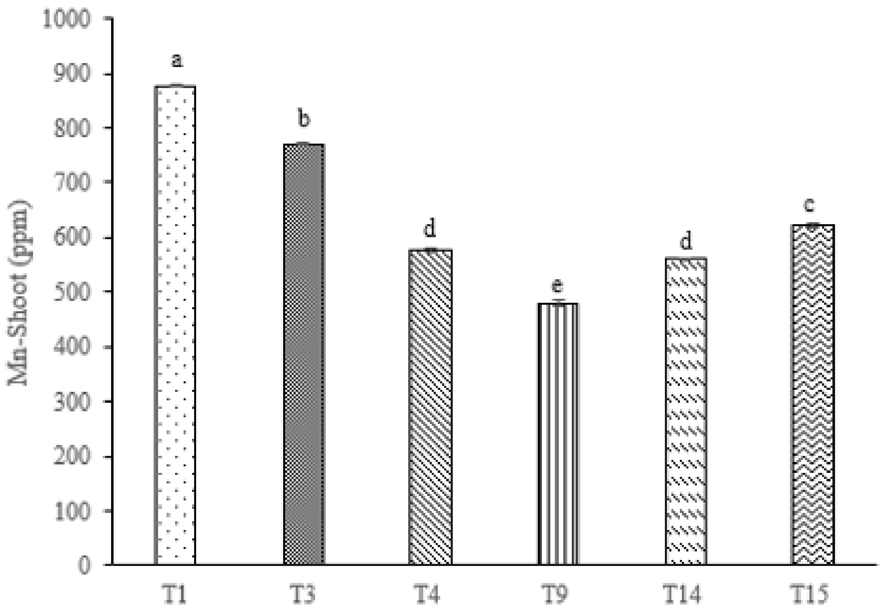

Figure 6.19. Influences of lime, P and N fertilisers on the concentration of Mn in the shallot leaves at 56 DAP. Means with different letters indicate significant differences using Tukey's test at $p \leq 0.05$ (error bars are the standard error, n=4). T1=0L+0P+200N, T3=0L+120P+200N, T4=1L+120P+200N, T9=8L+120P+200N, T14=1CaSup+0P+200N, T15=0L+0P+0N.

6.3.4. Effect of treatments on shallot bulb yield

While the application of liming materials and P fertiliser increased shallot bulb yields, overall yields were low (Table 6.10). The Control treatment and Nil-N Control treatment both had fresh bulb yields of less than 4 t ha^{-1}. All lime treatments achieved bulb yields significantly higher than both of the control treatments. The application of 4 and 8 t lime ha^{-1}, applied with the highest rate of P fertiliser, had the highest bulb yields, of 6.22 and 6.38 t ha^{-1}, respectively, which were about double the very low Control treatment yield of 3.10 t ha^{-1}. While there was a general trend of bulb yield increasing with lime rate, the effect of different lime rates on bulb yield were not significantly different. In addition, the 120 kg P ha^{-1} treatment without lime significantly increased bulb yield by 57.7% compared to the Control treatment. At the highest rate of lime, where was also a general trend of bulb yield increasing with P rate, however, the differences were not statistically significant.

Table 6.10. The effect of liming materials and fertilisers on fresh bulb yield (t ha^{-1}) at final harvest (81 DAP).

Treatments	Fresh bulb yield (t ha^{-1})
T1=0L+0P (Control)	3.10^{g}
T2=0L+60P	4.03^{efg}
T3=0L+120P	4.89^{a-f}
T4=1L+120P	5.51^{a-d}
T5=2L+120P	5.79^{abc}
T6=4L+120P	6.22^{ab}
T7=8L+0P	5.54^{a-d}
T8=8L+60P	5.59^{a-d}
T9=8L+120P	6.38^{a}
T14=1CaSup+120P	5.19^{a-f}
T15=0L+0P+0N (Nil-N Control)	3.78^{fg}
p-value	< 0.01
CV (%)	11.8

Note: Selected treatments shown in the table and results for all treatments are provided in the Appendix 6.6. CV=Coefficient of Variance; ns=not significance; Tukey's method for means comparison; means presenting the same letters are not significantly different at α =5%, harvested area index = 70%. All treatments, except T15, also received 200 kg N ha^{-1}.

The local lime treatment, applied at 1 t ha^{-1} (T4), achieved a bulb yield of 5.51 t ha^{-1}, which was a similar yield to the Calcium super treatment applied at the same rate (T4). Therefore, although the Calcium super has a higher liming value, it did not result in a higher yield. The local lime treatment applied at 2 t ha^{-1} also achieved a bulb yield similar to the 1 t ha^{-1} treatment, therefore, there was no observed yield benefit from the higher lime rate. The lack of a yield difference between these lime rates may help to explain why the Calcium super also did not provide a yield advantage. In addition, although the Calcium super also contains Mg, the initial soil exchangeable Mg^{2+} levels showed that the availability of this nutrient was not likely to be a limiting plant growth.

The 4-t ha^{-1} lime rate achieved a bulb yield of 6.22 t ha^{-1}, which was higher than for the lower lime rates (Figure 6.20), but the yield increase was not large enough to be strongly significantly different. The 4-t ha^{-1} reduced exchangeable Al^{3+} to a level of 0.5 cmol (+) kg^{-1} (Al:Ca ratio of 0.10), which was the level below which high shallot bulb yields (> 10 t ha-1) were more likely in Field trial 1 (Chapter 4). Although the 8-t ha^{-1} lime rate further decreased exchangeable Al^{3+} to a level of 0.0 cmol (+) kg^{-1}, there was no further yield advantage compared to the 4-t ha^{-1} lime rate. The lack of a yield response at the higher rate of lime, and lower levels of soil exchange Al^{3+}, may be due to the soil moisture and disease incidence limitations previously mentioned. This would help to explain why the full benefit of improving soil fertility status was not observed in shallot bulb yields and why overall bulb yields remained low despite the high inputs of nutrients and lime.

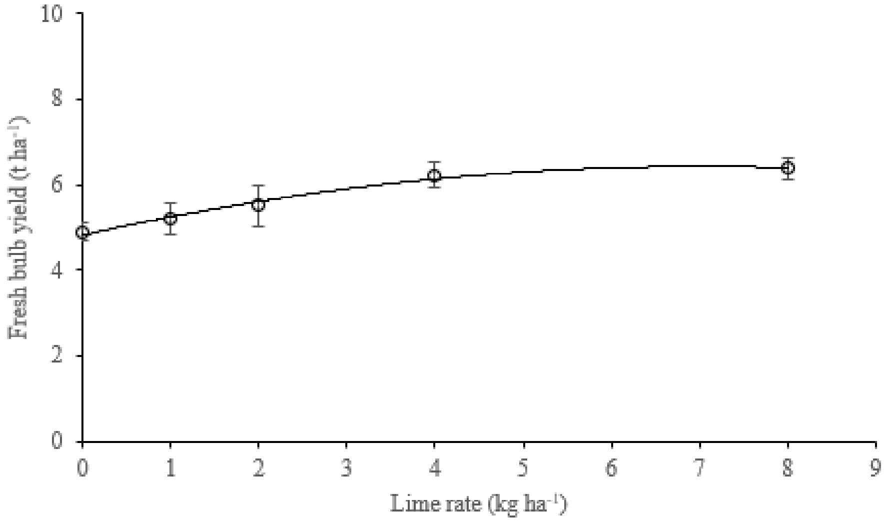

Figure 6.20. The means of fresh bulb yield in relation to different lime rates (all treatments also received 120 kg P, 200 kg N and 125 kg K ha^{-1}; error bars are the standard error, n = 4).

The application of P fertiliser increased the bulb yield, but the effect was greater when the plants also received lime (Figure 6.21). It shows that soil pH and P are a limiting factor in producing bulb yield in this soil type. The application of 120 kg P ha^{-1} without lime (T3) increased the bulb yields sharply by 58% above the control and addition 8 t ha^{-1} lime + 120 kg P ha^{-1} enhanced the fresh bulb yield by 105% compared with the control. However, the Bray1-P in this field trial was still lower than the optimal range (>28 mg P kg^{-1}) that contributed to the low yield in this experiment.

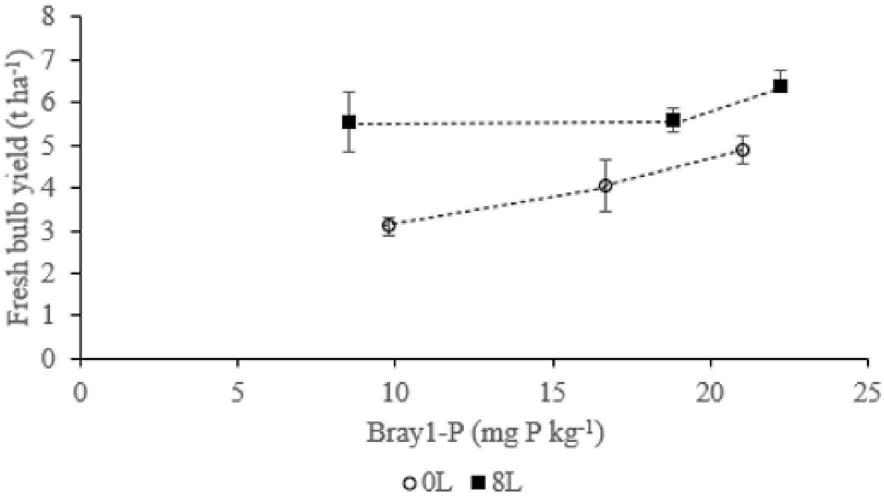

Figure 6.21. The means of fresh bulb yield in relation to different soil available-P (Bray1-P) The error bars are the standard error, n = 4.

Shallot bulb quality was assessed using measures of total soluble solids (TSS), volatile reducing substances (VRS), water content and protein content. A good quality of shallot bulbs could be determined by using those parameters. A high value of TSS and a low concentration of water indicated a longer life storage was likely. The volatile reducing substrate represented the pungency of the shallot and protein characteristics show the value of shallot as food enhancer. Treatments only had a significant effect on shallot bulb protein content (Table 6.11). The Nil-N Control treatment (T15) had the lowest protein content of all the treatments of 2.02%. The absence of N fertiliser input in this treatment is likely to have contributed the low protein. In comparison, the highest protein content of 3.06% was for T5, received 2 t lime, 120 kg p and 200 kg N ha^{-1}. Similarly, Fatideh and Asil (2012) reported that N improved the protein content in common onions. Neither the lime nor the P fertiliser treatments significantly increased protein content.

Table 6.11. The effect of treatments on shallot bulb quality (total soluble solids (%), sulphate content (ppm), water content (%) and protein (%)).

Treatment	TSS (%)	VRS (ppm)	Water Content (%)	Protein (%)
T1=0L+0P (Control)	21.5[ns]	137[ns]	77[ns]	2.63[ab]
T2=0L+60P	20.6	126	76	2.88[ab]
T3=0L+120P	22.1	133	77	2.90[ab]
T4=1L+120P	20.9	126	77	3.04[a]
T5=2L+120P	20.3	133	77	3.06[a]
T6=4L+120P	21.0	140	76	2.65[ab]
T7=8L+0P	21.1	133	76	2.97[a]
T8=8L+60P	21.2	137	76	2.92[ab]
T9=8L+120P	21.0	129	76	2.56[ab]
T14=1.0CaSup+120P	20.9	133	76	2.74[ab]
T15=0L+0P+0N (Nil-N Control)	21.2	130	76	2.02[b]
p-value	0.15	0.88	0.23	< 0.01
CV (%)	3.9	9.5	1.2	13.0

Note: Selected treatments shown in the table and results for all treatments are provided in the Appendix 6.7. CV=Coefficient of Variance; ns=not significance; Tukey's method for means comparison; means presenting the same letters are not significantly different at α =5%, TSS = total soluble solids; VRS = volatile reducing substances (sulphate).

Shallots, similar to common onions, require a high concentration of P due to their importance on plant growth, bulb initiation and total bulb yield (Aliyu et al., 2007). The root morphology of shallot and onion is shallow and hairless, and the root density is low, increasing the demand for high P content in the soil solution to get a better P diffusion uptake (Brewster, 2008). High P content in soil solution due to increasing P fertiliser rate increased root P content and affected shoot growth (Föhse et al., 1991). The highest P fertiliser rate, 120 kg P ha^{-1}, improved soil P availability, however the value was lower than Bray1-P that required in Field site 3 to achieve 10 t ha^{-1} fresh bulb yield, 28 mg P kg^{-1} (Chapter 4). Therefore, insufficient of soil P availability might contribute to the low yield that were achieved in this experiment.

6.4. Conclusions

The objectives of this research were to investigate the effects of lime and P fertiliser rates on soil fertility status, namely soil exchangeable acidic cations and available P, and on shallot growth and bulb yield. This was specifically for a smallholder farm on Category 1 land, located close to a village, with a long history of cropping in the Pacet District of West Java. At this site, soil exchangeable Al^{3+} and Bray1-P were at levels considered to be major limitations to shallot growth. The high initial soil exchangeable Al^{3+} required a lime (local lime; CCE 71%) rate of up to 4 t ha^{-1} to reduce exchangeable Al^{3+} and Al:Ca ratio to target levels (Exch. Al^{3+} <

0.5 and Al:Ca < 0.10). This is higher than the 2-3 t lime ha^{-1} predicated from the incubation study (Chapter 5), however, using a lime with a higher CCE% would reduce the quantity of lime required. In additional, the general recommendation of ~1 t lime per cmol (+) Al^{3+} kg^{-1}, would have underestimated lime requirements at this site, which required about double this rate of lime to achieve low exchangeable Al^{3+} levels. This demonstrates that while general recommendations are a useful guide, on-going soil testing of a farm to assess exchangeable Al^{3+} will be important for ensuring low exchangeable Al^{3+} levels are achieved and maintained from a liming programme. Soil available P status improved with increasing rates of P fertiliser. However, due to the very low initial Bray1-P levels at this farm site, the highest rate of P of 120 kg P ha-1 only increase Bray1-P to level just below the optimum range (> 28 mg P kg^{-1}). Therefore, without achieving soil available P levels well within the optimum range, it is not possible to confidently say that P availability was high enough to not be a limiting factor for shallot growth.

Overall shallot bulb yield was low (< 6.5 t ha^{-1}) in this experiment, being well below yields considered to be agronomically high (i.e., > 10 t ha^{-1}). In the absence of lime or P fertiliser (i.e., Control treatment) shallot bulb yield was very low (3.1 t ha^{-1}), in spite of high rates of N and K fertiliser being applied (200 kg N and 125 kg K ha^{-1}). Additions of lime increased shallot bulb yield and lime rates of up to 4 t lime ha^{-1} showed a trend of increasing shallot bulb yields. While the differences between lime rates were not large enough be statistically significant, the corresponding reductions in exchangeable Al^{3+}, support the benefit of lime rates of up 4 t lime to ensure that the risk of Al toxicity is low. An application of 120 kg P ha^{-1} without lime, significantly increased shallot bulb yield by 58%, compared to the Control treatment. When this P fertiliser rate was applied in combination with 4 t lime ha^{-1}, yield increase was 106%, compared to the Control treatment. These rates of P fertiliser and lime are considered capital rates, needed to build soil fertility status and, subsequently, lower rates will be needed once soil test levels are with the optimum range. The overall low yields observed in this experiment could have also been influenced by a combination of soil moisture limitations and pest and diseases incidence. Therefore, further evaluation of the benefits of P fertiliser and lime inputs in more favourable growing conditions would be useful to demonstrate the full benefits of the soil fertility improvements achieved.

Chapter 7

General Discussion and Conclusions

7.1. Introduction

Shallots are a major vegetable crop, used widely in Indonesian cuisine, and are an important source of income for smallholder farmers in West Java, Indonesia. Improving shallot production in the existing production areas is necessary to meet increased demand, driven by factors such as population growth. This need has recently been further accentuated by the Government's decision to prohibit the growing of short-term crops on more erosion prone areas (i.e., Category 3 land). Increased climate variability, because of Climate Change, is also expected to increase the challenges that farmers face with crop production. Smallholder farmers, who have small areas of land to cultivate, make up more than half of the country's farmers, therefore, they will play a central role in achieving improvements in shallot production. These farmers commonly have limited access to agronomic advice and crop inputs, such as soil testing, fertiliser, irrigation, and pesticides. In addition, the remote locations of many of these farms are another obstacle to gaining access to support and resources.

In West Java, the wide range of shallot bulb yields suggests that there is potential for improvements in productivity on some farms. Various factors contribute to low shallot bulb yield, including pest and diseases, climate, and a decline in soil fertility. About 12,600 ha (52%) of West Java's farmland is located in upland regions, characterised by strongly acidic soils. Like other *Allium* species, the shallot is characterised by shallow roots that are sensitive to soil acidity. Soil acidity negatively affects *Allium* growth and root biomass is reported as the most affected plant component by acidity (Brito et al., 2020; Rengel, 1992). Maintaining adequate soil fertility status is important to support plant growth and produce high bulb yields. However, there has been limited research previously conducted on the soil fertility requirements of shallots grown in strongly acidic soil conditions, which are common in the mid- and upland districts of West Java.

The main aim of this research was to improve the shallot productivity of smallholder farmers in West Java's acidic upland soils. To achieve this aim, the specific objectives were:

- To identify potential causes of low shallot yields in areas of West Java.

- To understand the effect of lime and fertilisers on shallot growth and bulb yield in strongly acidic soils.
- To determine the efficacy and cost-effectiveness of soil amendments on alleviating aluminium toxicity.
- To create specific recommendations for smallholder farmers for improving shallot bulb yield in acidic soils.

7.2. Shallot Production Systems in West Java: Survey of Current Farmer Practice (Chapter 3)

The survey of smallholder farmers in West Java, which included a questionnaire and soil testing, helped to ascertain the potential causes of shallot yield variation, and identified the district with the highest potential to improve yields. Of the four districts surveyed, the Pacet District had the lowest average bulb yield of 5.4 t ha^{-1}, with almost three-quarters of the farmers surveyed in this district having low bulb yields (i.e., < 7 t ha^{-1}). But importantly, farmers in this district had a wide range in yields (2.3 to 11.8 t ha^{-1}), which suggested that there was opportunity to improve yields.

There was evidence from the survey that pest and disease incidence is likely to be a factor contributing to lower bulb yields in the Pacet District. Of the farms surveyed, farms with low yielding shallot crops had slightly higher pest and disease damage, compared to medium to high yielding farms. Longer spray intervals of 7 days, and the types and rates of pesticide application, may have been contributing factors to the higher pest and disease incidence. Therefore, farmers should continue to review their spray programmes, such as opportunities to reduce the spray intervals, using the recommended rate and type of pesticide in order to improve pest and disease control methods.

Although Pacet farmers typically applied high rates of NPKS fertiliser, this did not result in a high yield for many farmers in this district. The two soil fertility constraints that were common among farmers in Pacet were low soil pH and low plant availability of soil P. Average soil pH was 4.8 for low yielding farms and 5.3 for high yielding farms (overall pH ranged from 4.1-6.1). In additions, farms that had been cropped the longest (> 80 years) typically had the lowest average soil pH (4.3). The soil P status also differed between the low and high yielding farms. The average soil Bray1-P was 11 mg P kg^{-1} for low yielding farms and 30 mg P kg^{-1} for high yielding farms. Pacet farmers do not commonly use lime due to a lack of understanding of its benefits and because of the large quantities of lime required on strongly acidic soils, which can be a constraint to its use because many farms are in remote areas with no vehicle access. In addition, Indonesian farmers do not commonly use soil testing and, therefore, fertiliser use is based more typically on a 'recipe' approach, which has also contributed to the lack of awareness about lime requirements.

This survey has highlighted that despite high inputs of insecticide, fungicide and fertiliser, low yields persist, and that better understanding and monitoring of soil fertility status is important to help identify limitations to plant productivity. In addition, P fertiliser application practices are not ideal for optimising the availability of fertiliser P for establishing shallot plants. Therefore, P fertiliser application practices for shallots also need further research to provide a recommendation for growers in the Pacet District.

This survey has made an important contribution in terms of benchmarking soil pH's, current fertiliser management and crop yields in the different regions. The data of this study could be used to improve shallot management in the future, especially on soil fertility and nutrient management. Adding high rate of fertiliser especially the ammonium fertiliser did not increase the yield due to soil acidity, otherwise, it was worsening the soil properties that led to phytotoxicity. Moreover, high rate of P fertiliser application that occurred in many regions might contribute to soil and water pollution. High rate of P was an inefficient input that increased the production cost and reduced the benefit. Using soil testing as a technique to gather the recommendation rate of lime and fertiliser would help the farmers to produce the shallot in sustainable way.

Overall, this survey supported that further research was required to better understand how soil fertility can be managed to improve shallot crop yield. Research needs to identify the benefits of improved lime and P fertiliser practices and how these can be implemented on farms in a way that overcome current constraints. This informed the basis of the subsequent experiments conducted in this study, the key findings of which are summarised in the following sections.

7.3. Field Trial 1: Lime and Phosphorus Fertiliser Strategies for Improving Shallot Bulb Yield (Chapter 4)

From the farmer survey, low soil pH and low soil available P were soil fertility factors identified as being likely to contribute to low shallot bulb yields on many farms in the Pacet District. As mentioned previously, Pacet farmers are mostly not familiar with the use of liming materials, as the high rates of lime required and the difficulties with its transportation being a deterrent to its use. Because the farm location can limit a farmer's ability to carry large quantities of lime on foot, it is worthwhile assessing whether the use of lower rates of lime (< 1 t ha^{-1}) can be beneficial for shallot yields. Therefore, it was important to assess the positive effects of lime and P fertiliser use on shallot productivity, in order to improve the economic returns from growing shallots. In addition, further specific quantitative information was required to identify the economic optimum soil fertility parameters, especially soil pH, exchangeable Al^{3+} and soil available-P, for farms in low yielding districts of West Java, like Pacet.

The objective of the first field trial was to determine the optimal amount of lime and P fertiliser rates for three different farm sites with strongly acidic soils in the Pacet District. The sites were categorised based on soil properties and land history. Field site 1 had been cultivated for more than 80 years and is located close to the village (Category 1 land). Field site 1 had an extremely low soil pH_{H2O}, very high soil exchangeable Al^{3+}, and low soil available-P. Field site 2 had been cultivated for more than 20 years and was located in a remote site (Category 2 land). Field site 2 had very low soil pH, high soil exchangeable Al^{3+} and moderate soil available-P status. Field site 3 had been cultivated for less than 20 years, was located in a remote site (Category 3 land), has a low soil pH and exchangeable Al^{3+} and has very low soil available-P.

Even though soil pH was very low at all three field trial sites, the addition of 1 t lime ha^{-1} only significantly increased shallot bulb yield at Field site 2. This rate of lime increased soil pH_{H2O} from 3.7, 4.1 and 4.7 to 4.0, 4.4 and 5.1 for Field sites 1, 2 and 3, respectively. Soil exchangeable Al^{3+} helped to explain the yield responses at the three sites. At Field site 1, exchangeable Al^{3+} remained high for the 1 t lime ha^{-1} treatment, which decreased exchangeable Al^{3+} from 1.60 to 1.16 cmol (+) kg^{-1}. At this site shallot bulb yield was low (6.2 t ha^{-1}) for the nil lime treatments on average and remained low after the lime treatment. At Field site 2, the exchangeable Al^{3+} was high (1.13 cmol (+) kg^{-1}) for the nil lime treatment and 1 t lime ha^{-1}

treatment decreased exchangeable Al^{3+} to a moderate level of 0.65 cmol (+) kg^{-1}. At this site, the 1 t lime ha^{-1} treatment increased shallot bulb yield from 7.7 to 10.6 t ha^{-1}. At Field site 3, exchangeable Al^{3+} was low (0.27 cmol (+) kg^{-1}) for the nil lime treatment and, therefore, there was only a small further reduction achievable from lime application. At this site shallot bulb yield was high (9.5 t ha^{-1}) for the nil lime treatment and lime treatment did not significantly further increase yield. Thus, the general approach of determining lime rates from exchangeable Al^{3+} showed promise for use when growing shallots on highly acidic soils, helping to achieve high yields while minimising the use of lime. This is particularly important for those more remote sites, such as Field sites 2 and 3, where poor site access limits the use of large quantities of lime. Overall, greater likelihood of high yields was observed when exchangeable Al^{3+} is < 0.5 cmol (+) kg^{-1} and low to moderate rates of lime (≤ 1 t lime ha^{-1}) were adequate for high shallot yields when exchangeable Al^{3+} < 1.2 cmol (+) kg^{-1}. For farms with high exchangeable > 1.2 cmol (+) kg^{-1}, then higher rates of lime are likely required to improve shallot yields. For those farms located closer to village with better site access, such as Field site 1, there may be greater potential to use higher rates of lime but having information on the optimum lime rate was needed to ensure efficient use of inputs.

The application of P fertiliser significantly increased shallot bulb yield at Field sites 1 and 3, but not a Field site 2. At Field site 1, only the highest rate of P fertiliser (150 kg P ha^{-1}) increased bulb yield compared to the nil P fertiliser treatments on average. This rate of P addition increased bulb yield from 5.9 to 6.8 kg ha^{-1}, which coincided with an increase in Bray1-P of from 22 to 35 mg P/kg. However, there was only a small marginal increase in yield for the 150 kg P ha^{-1} treatment compared to the 100 kg P ha^{-1} treatment, which had a Bray1-P value of 25 mg P/kg. In addition, the highest yield achieved at this site was still at a level considered low, which is likely, in part, due to the effect of high exchangeable Al^{3+} limiting the yield response. At Field site 2, the nil P fertiliser treatments on average had a Bray1-P value of 28 mg P/kg. This level of soil available P may have been sufficient to ensure the P availability was not yield limiting. At Field site 3, which had a low average Bray1-P of 12 mg P kg^{-1} soil for the nil P fertiliser treatments, P fertiliser addition of up to 100 kg ha^{-1} increased Bray1-P to 28 kg mg P/kg and significantly increased bulb yield from 8.7 to 10.5 t ha^{-1}. Overall, there was evidence to support that high shallot bulb yield (>10 t ha^{-1}) is achievable when Bray1-P was ≥ 28 mg P kg^{-1}. This agrees well with the finding in the farmer survey (Chapter 3), that the average Bray1-P value for high yielding farms was 30 mg P kg^{-1}. Therefore, increasing soil P status to at or above approximately 28 mg P kg^{-1} is expected to minimise the risk of P availability limiting bulb yield potential. For farms with low soil P status, like Field site 3, this will require capital fertiliser P inputs. Once optimal soil P status is obtained then only maintenance rates of P fertiliser are needed. In this field trial, P fertiliser was broadcast and incorporated into the soil before planting. This method of P fertiliser application is expected to result in less spatial variation in the Bray1-P soil test and improve soil P recovery by shallots, compared to the more typical placement method of adding P fertiliser to shallow impressions in soil surface. In addition, the surface application of P fertiliser can also increase the risk of surface runoff P, which can contribute to enrichment of rivers and lakes. However, further research is required to compare P placement methods.

The results at Field sites 2 and 3 also demonstrated that high shallot yields could be achieved at N fertiliser rates of up to 200 kg N ha^{-1}. This is lower than the average N rate used by farmers surveyed in the Pacet District (Chapter 3) of 258 kg N ha^{-1}. Therefore, there is potential for some farmers to decrease N fertiliser rates without appreciably influencing crop productivity. The overuse of N fertiliser by some farmers could be an attempt to overcome low yields potentially caused by other soil fertility limitations (i.e., soil acidity) and also due to the relatively low cost of N fertiliser, compared to other nutrients and other crop inputs (refer to Section 7.6 for costs). High N fertiliser rates contribute to increased nitrate leaching and, like with P, can lead to ground and surface water enrichment and eutrophication of rivers and lakes. Buckland et al. (2013) observed that reducing N fertiliser inputs in onion systems decreased the risk of NO_3^- leaching and reduced thrip pest incidence. The Pacet District is in the upper Citarum River basin, which is highly enriched with nutrients and considered to be the most polluted river in West Java. Therefore, improvements in the management of N fertilisers will reduce the negative impact that the agricultural sector is having on water quality. High N fertiliser use, and the excessive leaching of nitrate can also lead to a greater level of soil acidity being left behind in the soil. Assisting farmers increase yields, using lime and ensuring Bray-P levels are optimum and more spatially uniform, will help to reduce the overuse of N fertiliser and, as a consequence, reduce the environmental impact of these farming systems.

7.4. Incubation Experiment: Effect of Liming Materials and Selected Soil Amendments on Chemical Properties of An Extremely Acidic Soil (Chapter 5)

At Field site 1, which has an extremely acidic soil with high exchangeable Al^{3+}, the application of 1 t lime ha^{-1} was insufficient to decrease exchangeable Al^{3+} to a low level. Consequently, yields remained low in spite of high fertiliser inputs. This field site also has low soil cation exchange capacity (CEC) due to it being used for long-term cropping systems, which reduces soil organic matter and the soil's ability to store cation nutrients in an exchangeable form. Biochar and zeolite are soil amendments that have been shown to improve the CEC of soils. In addition, some biochar increase soil pH as they can have a liming effect. This farm site is located close to the village with good access (i.e., Category 1 land), therefore, there are fewer constraints to using high rates of limes or other soil amendments, compared to more remote farms. This laboratory incubation experiment aimed to quantify the effect of high lime rates, rice husk biochar and zeolite on soil pH, exchangeable Al^{3+} and CEC of the soil from Field site 1.

The soil used in this experiment had an initial pH_{H2O} of 4.2, exchangeable Al^{3+} of 1.5 cmol (+) $kg^{-1}$and CEC of 12 cmol (+) kg^{-1}. Of the lime materials evaluated in this experiment, Calcium Super was the most effective at increasing soil pH and reducing exchangeable Al^{3+}. These results reflect its high calcium carbonate equivalent (CCE) value of 108% and fine particle size. This compares to a CCE of only 71% for local lime. However, overall, the local lime is a much more cost-effective material for famers to use, because of the large price deferential compared to Calcium Super.

It is estimated from the experiment that at least 3 t ha^{-1} of local lime is required to achieve the soil pH target of 4.8 for soil from Field site 1, which is a level of soil acidity where exchangeable Al^{3+} is expected to be low. This rate of lime is equivalent to 2.0 times of exchangeable Al^{3+}. Based on the findings from the first field trial (Chapter 4), this is predicted to help minimise the potential for soil properties, particularly exchangeable Al^{3+}, to be limiting shallot yield potential.

The use of rice husk biochar and zeolite applied at high rates, of up to 20 t ha^{-1}, did not significantly affect soil pH, exchangeable Al^{3+} or CEC. While there has been evidence from other studies of improved effectiveness from griding biochar to smaller particle sizes, this is an expensive additional processing step and likely to be cost-prohibitive for farmers to use. Therefore, it is not recommended that farmers use the types of biochar and zeolite evaluated in this experiment.

7.5. Field Trial 2: The Effect of Liming and Phosphorus Fertiliser Application on Alleviating Acidic Cation Toxicity and Improving the Shallot Bulb Yield on An Extremely Acidic Soil (Chapter 6)

The first field trial in this study (Chapter 4) showed that for Field site 1 a lime rate of 1 t ha^{-1} was insufficient to reduce exchangeable Al^{3+} to a low level (< 0.5 cmol (+) kg^{-1}). Based on the incubation study (Chapter 5), it was estimated that at least 3 t ha^{-1} of local lime is likely required to reduce soil exchangeable Al^{3+} to low level at this field site. Also, during the first field trial at this field site there was a small but significant influence of P fertiliser on yield response, but this response may have been limited by the high exchangeable Al^{3+}. Therefore, further research was also required to determine the response of shallot bulb yield to P fertiliser when exchangeable Al^{3+} had been decreased to a low level through the use of higher rates of lime. The trial investigated the effects of lime and P fertiliser rates on a number of soil properties, including exchangeable Al^{3+} and Bray1-P, at Field site 1 (i.e., Category 1 land with high soil exchangeable Al^{3+}) to determine their effects on soil fertility and on shallot growth and bulb yield.

In the second field trial the Control treatment had a very low soil pH_{H2O} of 4.1, high exchangeable Al^{3+} of 1.9 and a low Bray1-P of 10 mg P kg^{-1}. An application of 4 t lime + 120 kg P ha^{-1} increased soil pH_{H2O} to 4.7, reduce exchangeable Al^{3+} to 0.44 cmol (+) kg^{-1}, and increased Bray1-P to 25 mg P kg^{-1}. Increasing the lime rate to 8 t lime + 120 kg P ha^{-1} increased pH_{H2O} further to 5.5 and decreased exchangeable Al^{3+} to zero. The highest rate of P fertiliser, 120 kg P ha^{-1}, only increased the soil available P levels to up to just below 28 mg P kg^{-1}, which was identified as a potential optimum level in the first field trial. Therefore, at this site a higher rate of P fertiliser is required to bring the soil P status to a level that is considered to minimise the potential for P to be plant growth limiting. On average, a rate of about 9 kg P ha^{-1} was required for a 1 mg P kg^{-1} change in Bray1-P during this trial. Therefore, increasing the Bray1-P by a total of 18 mg P kg^{-1}, from the initial value of 10 mg P kg^{-1} would require an estimated 162 kg P ha^{-1} on average.

The bulb yield for the Control treatment, without lime or P fertiliser addition, was only 3.10 t ha^{-1} despite this treatment receiving high rates of N and K fertiliser. The application of 8 t lime + 120 kg P ha^{-1} doubled the shallot bulb yield compared to the Control treatment, but was not significantly different from applying only 4 t lime with the same rate of P. Overall yields in this trial were low (i.e., < 7 t ha^{-1}) and there was a relatively flat response to Bray1-P. This suggests that there was likely something else that was potentially more plant growth limiting in this field trial, with soil moisture and pest and diseases incidence being likely factors based on field observations.

7.6. An Assessment of The Economic Returns for Smallholder Shallot Growers from Improved Soil Fertility

Smallholder farmers require relatively low-risk options to increase production capacity and provide adequate short-term returns on investment (Vanlauwe et al., 2014). Farmers in the Pacet District typically have limited access to soil testing and agronomic advice. The lack of soil testing information is likely to have resulted in key soil fertility limitations going undetected and, therefore, not corrected with current nutrient management practices. In particular, alleviating the aluminum toxicity through liming is a crucial step for increasing shallot production on farms with very acidic soils. In addition, famers also not knowing their soil P status has likely led to some farmers to use higher rates of P fertiliser than required, while other farmers are unaware that soil available P is limiting crop productivity and, therefore, they require capital P fertiliser inputs.

Shallots are an expensive crop to grow, with the total cost (excluding the cost of land) of growing a hectare of shallot in the Pacet District estimated to be approximately NZ$10,262 (Table 7.1). The three largest costs are pesticides (38.3%), labour (37.6%) and planting bulbs (19.1%). Although high rates of fertilisers are used on average, they only represent about 4.9% of total costs. Therefore, fertiliser costs are unlikely to be a constraint to their use, and in some cases may lead to their overuse, especially for cheaper nutrients like N.

The average shallot yield for the farmers surveyed in the Pacet District (Chapter 3) was a low yield of 5.4 t ha^{-1}. At this yield, total revenue is estimated to be NZ$12,150/ha, which results in a net revenue of NZ$1,296/ha. This net revenue is only 12% of total cost, which is low considering that the cost of land (i.e., return on capital) has not been accounted for in this value. In comparison, for a high yielding crop of 10 t ha^{-1} the total revenue is NZ$22,500/ha and the net revenue is NZ$11,301/ha. This net revenue is 100% higher than the total cost of growing shallots, which highlights that shallot can provide very good financial returns when yields are high. In this case, a yield of 10 t ha^{-1} provide net revenue that is about 7.7 times higher than for an average yield of 5.4 t ha^{-1}. It is assumed that cost of an average yielding crop and high yielding crop are similar, including for fertiliser, because from the farmer survey (Chapter 3) there was no clear relationship between fertiliser use and yield. The large net revenue differences between the low average yields achieved in the Pacet District with what famers can earn from high yields, highlight the importance for farmers to improve crop yields to be more financially sustainable.

Table 7.1. Examples of per hectare revenue and costs for shallot farming in Pacet District, Kabupaten Bandung.

	NZ$ Per Unit	**Pacet average yield***		**High yield example**	
		Unit/ha	**Value (NZ$)**	**Unit/ha**	**Value (NZ$)**
Revenue					
Selling price ($ kg^{-1})	2.25				
Yield (kg ha-1)*		5,400		10,000	
Total Revenue			**12,150**		**22,500**
Costs					
Shallot bulbs ($ kg $bulb^{-1}$)	2.81	700	1,967	700	1,967
Fertiliser ($ kg $nutrient^{-1}$)*					
N (kg ha^{-1})	0.47	258	121	258	121
P (kg ha^{-1})	1.60	135	216	135	216
K (kg ha^{-1})	2.22	120	266	120	266
Pesticide (eq.1 kg antracol/ha)	13.70	287	3,932	287	3,932
Labour ($/labour unit/day)	5.62	686	3,855	686	3,855
Bulb transport cost (per kg)**	0.075	6,100	458	10,700	803
Fertiliser transport cost (per kg)	0.075	513	38	513	38
Total Cost			**10,854**		**11,199**
Net Revenue			**1,296**		**11,301**
Revenue/Cost ratio			**1.12**		**2.01**

*Yield, fertiliser rates and transport cost based on average rates for the Pacet District obtained from the farmer survey (Chapter 3). **Bulb transport cost is for planting bulbs and harvested bulbs

Although, on average, farmers in the Pacet District are using high rates of major fertiliser nutrients, the results for the first field trial (Chapter 4) showed the potential for individual farms to increase yield by better understanding their soil fertility status from soil test results, in particular soil pH, exchangeable Al^{3+} and plant available P. At Field site 2, soil testing showed that that the soil had a very low pH_{H2O} of 4.1, a high exchangeable Al^{3+} of 1.13 cmol (+) kg^{-1} and an optimum Bray1-P of 28 mg P kg^{-1}. The application of 1 t lime ha^{-1} treatment decreased exchangeable Al^{3+} to a moderate level of 0.65 cmol (+) kg^{-1} and increased shallot bulb yield from 7.7 to 10.6 t ha^{-1}. This yield increase equates to \$6,060 ha^{-1} additional income, which is a 35% increase (Table 7.2). Applying 1 t lime ha^{-1} at this site is estimated to cost an additional NZ\$175 ha^{-1}. This cost consists of lime cost of NZ\$75 t^{-1} and the labour cost for transporting and spreading lime of NZ\$100 t^{-1}. Therefore, for a relatively small additional cost this farm was able to achieve a high return in revenue, which translated into an increase in net revenue of 100%.

Table 7.2. Estimated per hectare revenue and costs for shallot farming in Field site 2 (Field trial 1) Pacet District, Bandung Regency.

	NZ\$ Per Unit	**No lime treatment yield**		**1 t lime ha^{-1} treatment yield**	
		Unit/ha	**Value (NZ\$)**	**Unit/ha**	**Value (NZ\$)**
Revenue					
Selling price (\$ kg^{-1})	2.25				
Bulb yields (kg ha^{-1})		7,700		10,600	
Total Revenue			17,325		23,850
Costs					
Shallot bulb seeds (\$ kg $bulb^{-1}$)	2.81	700	1967	700	1967
Fertiliser (\$ kg $nutrient^{-1}$)					
N (kg ha^{-1})	0.47	200	94	200	94
P (kg ha^{-1})	1.60	100	160	100	160
K (kg ha^{-1})	2.22	160	355	160	355
Pesticide (eq. 1 kg antracol/ha)	13.7	287	3932	287	3932
Lime (t ha^{-1})	75	0	0	1	75
Labour (\$/labour unit/day)	5.62	686	3855	686	3855
Bulb transport cost (per kg)*	0.10	8400	840		1130
Fertiliser transport cost (per kg)	0.10	410	41	410	41
Lime transport cost (per kg)	0.10	0	0	1000	100
Total Cost			11,249		11,714
Net Revenue			6076		12,136
Revenue/Cost ratio			1.54		2.04

*Bulb transport cost is for planting bulbs and harvested bulbs

Farmers can pay many of their crop production costs (e.g., planting bulbs, fertiliser, pesticides and harvest labour costs) after harvest when they have received their crop income. However, it is more challenging financially for them to pay for labour costs associated with the early stages of the crop, such as the cost of labour to help transport lime to their farm site. Therefore, while the overall cost of lime use may be relatively small, compared to total crop costs, farm cashflow can still limits its use. Also, this highlights the importance of soil testing to ensure that farmers only use lime if it is needed and use adequate rates to achieve a yield response. The cost of soil testing for pH, exchange Al^{3+} and Bray1-P is approximately \$NZ11 per sample, therefore, represents a very minor cost compared the financial benefits that famers can gain from improved soil fertility status. However, access to soil testing and nutrient management recommendations will also be limited by the availability of agriculture field officers to collect soil samples and provide interpretation of results, which is especially a constraint for smallholder farmers.

At Field site 3, which had a soil pH_{H2O} of 4.7 and an exchangeable Al^{3+} of 0.27 cmol (+) kg^{-1}, the Bray1-P test value for the nil P fertiliser treatment was a low value of 12 kg mg P/kg (Chapter 4). The application of 100 kg P ha^{-1} increased Bray1-P to 28 kg mg P/kg and significantly increased bulb yield from 8.7 to 10.5 t ha^{-1}. This yield increase provides further income of NZ$3,700 ha^{-1}, which is a 19% in total revenue. The application of P fertiliser at a rate of 100 kg P ha^{-1} is estimated to cost NZ$170 ha^{-1} (NZ$160 material cost + NZ$10 transport cost). As with the previous example, a relatively small increase in input costs has resulted in a large increase in revenue, which is an even greater increase in net revenue.

During the second field trial (Chapter 6), Field site 1 had a very low soil pH_{H2O} of 4.1, high exchangeable Al^{3+} of 1.9 and a low Bray1-P of 10 mg P kg^{-1}. The bulb yield for the treatment that received a moderate rate of P of 60 kg P ha^{-1}, without lime addition, was very low at 4.0 t ha^{-1}. An application of 4 t lime + 120 kg P ha^{-1} increased soil pH_{H2O} to 4.7, reduced exchangeable Al^{3+} to 0.44 cmol (+) kg^{-1}, and increased Bray1-P to 25 mg P kg^{-1}. This treatment increased bulb yield to 6.2 t ha^{-1}, which is 55% higher than the aforementioned treatment with a lower rate of P and no lime. Therefore, these capital rates of P fertiliser and lime provided an estimated NZ$4,241 ha^{-1} increase in revenue. The additional cost of 4 t lime and an additional 60 kg P ha^{-1} is estimated to be NZ$599 ha^{-1} (lime $500; P fertiliser $99, NZ$96 for P material cost and NZ$3 for P transport cost). The increase in yield attributed to only the lime addition, was estimated to be 1.3 t ha^{-1}, which is a revenue increase of NZ$2,360 ha^{-1} or a 7-fold improvement in net revenue compared to the no lime treatment with the same rate of P fertiliser (120 kg P ha^{-1}; Table 7.3). Overall, the yields achieved at this site were low, which may have reflected soil moisture limitations and pest and disease incidence. Therefore, overall yield and revenue is expected be higher in a year when these factors are less limiting. However, in spite of these limitations, the use of lime greatly improved the financial returns of growing shallots at this site. In addition, the higher rate of lime used at this site includes a capital component and, therefore, annual maintenance rates are expected to be lower than this. Therefore, the cost of maintenance lime use on an annual basis is also expected to be lower.

Table 7.3. Estimated per hectare revenue and costs for shallot farming in Field site 1 (Field trial 2) Pacet District, Bandung Regency.

	NZ$ Per Unit	No lime treatment yield		4 t lime ha^{-1} treatment yield	
		Unit/ha	Value (NZ$)	Unit/ha	Value (NZ$)
Revenue					
Selling price ($ kg^{-1})	2.25				
Bulb yields (kg ha^{-1})		4,900		6,200	
Total Revenue			**11,025**		**13,950**
Costs					
Shallot bulb seeds ($ kg $bulb^{-1}$)	2.81	700	1967	700	1967
Fertiliser ($ kg $nutrient^{-1}$)					
N (kg ha^{-1})	0.47	200	94	200	94
P (kg ha^{-1})	1.60	120	160	120	160
K (kg ha^{-1})	2.22	160	355	160	355
Pesticide (eq. 1 kg antracol/ha)	13.7	287	3932	287	3932
Lime (t ha^{-1})	75	0	0	4	0
Labour ($/labour unit/day)	5.62	686	3855	686	3855
Bulb transport cost (per kg)*	0.05	5600	280	6900	345
Fertiliser transport cost (per kg)	0.05	480	24	480	24
Lime transport cost (per kg)	0.05	0	0	4000	200
Total Cost			**10,699**		**11,264**
Net Revenue			**326**		**2,686**
Revenue/Cost ratio			**1.03**		**1.24**

*Bulb transport cost is for planting bulbs and harvested bulbs

7.7. Conclusions

The research in this study has contributed to the understanding of how improvements in shallot productivity can be achieved by smallholder farmers who are farming acidic upland soils in West Java. Even though shallot farmers typically use high amounts of inputs low yields are common, especially in the Pacet District, which is be due to key soil fertility constraints. The use of soil testing and better understanding of how soil fertility can be managed to improve shallot crop yield, are critical requirements for improving yields and financial returns. This study has quantified the benefits of improved lime and P fertiliser practices and identified constraints to their implementation.

The research results support that shallot yields in the Pacet District are commonly limited by very low soil pH and high exchangeable Al^{3+} levels. Therefore, farmers should aim to ensure that soil exchangeable Al^{3+} levels are maintained < 0.5 cmol (+) kg^{-1}, which will be at soil pH levels of approximately > 4.7. Monitoring soil P status through soil testing and achieving

Bray1-P levels above 28 kg ha^{-1} also improves the likelihood of achieving high yields. Where soil pH and Bray 1-P soil test levels are below optimum, capital rates of lime and P fertiliser should be evenly broadcast and incorporated into the topsoil to achieve uniform improvements in soil fertility.

Favorable financial returns can be achieved from high yielding shallot crops, and, in comparison, the costs associated with soil testing and lime and P fertiliser use are relatively minor. Therefore, cost alone is not expected to be a limitation to implementing the above recommendations. However, farmers need better access to the services of agricultural field officers to conduct and interpret soil testing results and adequate cashflows at the time of crop preparation to allow them to cover the labour cost associated with transporting lime to farm sites.

The use of improved agronomic practices, identified in this study and previously discussed, and the resulting improved financial benefits, also have wider social, economic and environmental outcomes. Improving shallot productivity of farms increases food security and helps to alleviate the pressures on deforestation and the use of margin land that is more erosion prone. In addition, the use of soil testing and optimum target levels, including those established from this study, support more economically and environmentally sustainable use of fertilisers and lime, because excessive use of nutrients is both costly and detrimental to water quality.

Chapter 8.

Limitations and Recommended Future Research

8.1. Limitations

The scope of the study was limited to the climatic and soil conditions of the sites where the field studies were located and the seasons in which they were conducted. In addition, pest and disease incidence had a bearing on the results of the study results. Therefore, further field studies over more sites, in different regions, over multiple seasons and where there is improved control of pests and diseases would allow the results of this study to be further refined and used more widely for recommendations.

8.2. Recommendations

From the findings of this thesis, the following areas of future research have been identified to help assist improvements in shallot production in Indonesia's upland regions:

- Research needs to be conducted on how farmers can gain better access to soil testing services and soil test recommendations. For example, whether simplified services located closer to farmers providing rapid soil pH and available soil P tests would help improve availability to farmers.
- In this study the P fertiliser application method was different to the more typical practice used by farmers in the Pacet District. The common method of P fertiliser placement is to apply P fertiliser to shallow impressions in the soil surface. Therefore, research is required to better understand the effect of farmers' current practices on the spatial variability of available soil P and on the the risk of P surface runoff.
- Lime can have long-term effects on improving soil chemical and biological properties, which can also have benefits for subsequent crops. Therefore, more research is required to understand the overall benefits of liming including the crop rotation for example chili and legumes and how frequently lime needed to reapply to maintain these benefits in the upland districts of West Java.
- An evaluation of the effectiveness of farmer demonstration trials on farmer adoption of lime use.
- Excessively high rates of N fertiliser increase the risk of nitrate leaching and accelerate soil acidification. More research is required to help quantify the optimum N fertiliser rates for shallot production on the upland districts of West Java.

- Pest and disease incidence was also identified as affecting shallot yields. Therefore, further research is required to help improve pest and disease control in the Pacet District.
- These are additional indicators that could also be studied to better address the sustainability issues of smallholder farmers. Examples of these include farm productivity, soil biological activity, agrobiodiversity and pesticide residues in soil and water.

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Appendix 3.1. Pests and diseases of shallot

PESTS (Hama)

Ulat bawang merah (*Spodoptera exigua*)

Ulat grayak (*Spodoptera litura*)

Lalat pengorok daun

(Liriomyza chinensis)

Armyworm (*Spodoptera mauritia*)

Thrips tabaci

Orong-orong (*Grylotallpa* sp)

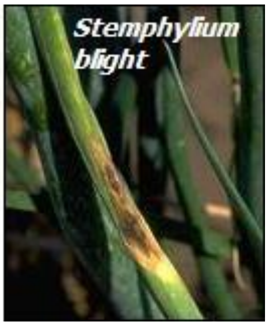
DISEASES (Penyakit)


Purple blotch *(Alternaria porii*)


Anthracnose (Colletotrichum)


Downy mildew (Peronospora)


Twisting disease (Fusarium)



Stemphylium leaf blight


Cercospora leaf spot

Appendix 3.2. Questionnaire

Part 1. Selection of respondent

1. Do you plant shallot in the last rainy season (October 2016-March 2017)?
    a. Yes
    b. No
2. How do you practice crop rotation?

	2016					2017											
	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12
Month																	
Crops																	

Experience of Growing Shallot					
Season	Planting time-Harvesting time	Harvested Area (ha)	Seed Bulb (t)	Bulb Yield (t)	Productivity (t/ha)
Dry season 1					
Dry season 2					
Rainy season 1					
Rainy season 2					

Part 2. Identify of respondent

1	Name	:			
2	Location	:	a. Village: ………………………. b. Sub Regency: …………….. c. Regency: …………………….		
3	Altitude	:	a. Low-land b. High-land		
4	Experience in shallot production	:	a. Bellow 5 years b. Five until ten years c. Above ten years		
5	Land area total	:			
6	Land for shallot	:			
7	Land for other crops	:			
8	Land status	:	a. Owner b. Rent c. Owner and rent		
9	Land owned from 2016 until now				
Soil type	Land status (m^2)				
	Own	Rent	Profit-sharing	*Bengkok*	Total
a. Paddy field					
b. Dryland					
10	Which farmland for shallot in the dry season?	:			

11	Which farmland for shallot in the rainy season?	:	

Part 3. Shallot cultivation

3.1. The Dry Season

A. SEED			
1	The last planting time	:	Week ….. Month ….. Year ……
	The last harvest time	:	Week ….. Month …… Year …….
2	Varieties	:	a.
		:	b.
3	How many?	:	……………………….. (kg)
4	Planting area	:	……………………….. m^2
5	Seed bulb size	:	a. Small (< 2.5 g) b. Medium (2.5- 5 g) c. Large (> 5 g)
6	Planting space	:	………… X ……………. cm
7	How many bulbs per hole	:	………………………….. bulb

B. Fertiliser					
1	Lime application	Time of application	Fertiliser	Rate	Method
2	Manure				
3	Basic Fertiliser				
4	Supplementary Fertiliser I				
5	Supplementary Fertiliser II				
6	Supplementary Fertiliser III				

3.2. The Rainy Season

A. SEED			
1	The last planting time	:	Week ….. Month ….. Year ……
	The last harvest time	:	Week ….. Month …… Year …….
2	Varieties	:	a.
		:	b.
3	How many?	:	……………………….. (kg)
4	Planting area	:	……………………….. m^2
5	Seed bulb size	:	d. Small (< 2.5 g) e. Medium (2.5- 5 g) f. Large (> 5 g)
6	Planting space	:	………… X ……………. cm
7	How many bulbs per hole	:	………………………….. bulb

B. Fertiliser					
1	Lime application	Time of application	Fertiliser	Rate	Method
2	Manure				
3	Basic Fertiliser				
4	Supplementary Fertiliser I				

5	Supplementary Fertiliser II				
6	Supplementary Fertiliser III				

Part 4. Pests and Diseases

No	Pests and Diseases	% Plant infected		% Yield loss	
		Dry season	Rainy Season	Dry season	Rainy Season
1	Pests				
	Armyworm *Spodoptera exigua*				
	Spodoptera litura				
	Liriomyza Chinensis				
	Thrips				
	Grlotallpa sp.				
2	Diseases				
	Purple Blotch *Alternaria porii*				
	Anthracnose *Colletotrichum*				
	Downy Mildew *Peronospora*				
	Fusarium				
	Leaf blight *Stemphylium*				
	Cercospora				

Part 5. The Controlling of Pests and Diseases

5.1. Dry Season

1	Do you reduce the pH of water used to control pests and diseases?		yes	no
2	Hand control	:	a. Yes b. No	
5	How many times did you control by hand?	:	…………… times	
6	Pesticide sprayer	:	a. Calendar system b. Based on observation	
7	The first-time pesticide application	:		
8	Interval (days)	:		
9	The last time pesticide application	:		
10	Do you mix the pesticide	:	a. Yes b. No	
11	Explain how you apply pesticide to your crop			
	First formulation:			Dose/tank 1 tank = …. liter

	Number of insecticides	:	………………………	
	Name of insecticide and rate	:	1…………………………..	………… g/cc
			2…………………………..	………… g/cc
			3…………………………..	………… g/cc
			4……………………………	………… g/cc
			5…………………………..	………… g/cc
	Number of fungicides	:	……………………..	
	Name of fungicide and rate	:	1…………………………..	……….. g/cc
			2…………………………..	……….. g/cc
			3……………………………	……….. g/cc
	Name of adhesive and rate	:	………………………………	……….. g/cc
	Foliar fertiliser	:	………………………………	……….. cc
	Do you repeat this formulation?	:	a. yes	b. no
	Intervals for this formulation	:	…………. days	
	How many times did you use this formulation?	:	…………. times	
	Second formulation:			Dose/tank 1 tank = …. liter
	Number of insecticides	:	………………………	
	Name of insecticide and dose	:	1…………………………..	………… g/cc
			2…………………………..	………… g/cc
			3…………………………..	………… g/cc
			4……………………………	………… g/cc
			5…………………………..	………… g/cc
	Number of fungicides	:	……………………..	
	Name of fungicide and dose	:	1…………………………..	……….. g/cc
			2…………………………..	……….. g/cc
			3……………………………	……….. g/cc
	Name of adhesive and dose	:	………………………………	……….. g/cc
	Foliar fertiliser	:	………………………………	……….. cc
	Do you repeat this formulation?	:	c. yes	d. no
	Intervals for this formulation	:	…………. days	
	How many times did you use this formulation?		…………. times	
	Third formulation:			Dose/tank 1 tank = …. liter
	Number of insecticides	:	………………………	
	Name of insecticide and dose	:	1…………………………..	………… g/cc
			2…………………………..	………… g/cc
			3…………………………..	………… g/cc
			4……………………………	………… g/cc
			5…………………………..	………… g/cc
	Number of fungicides	:	……………………..	
	Name of fungicide and dose	:	1…………………………..	……….. g/cc
			2…………………………..	……….. g/cc
			3……………………………	……….. g/cc
	Name of adhesive and dose	:	………………………………	……….. g/cc
	Foliar fertiliser	:	………………………………	……….. cc
	Do you repeat this formulation?	:	a. yes	b. no
	Intervals for this formulation	:	…………. days	
	How many times did you use this formulation?		…………. times	

5.2. Rainy Season

1	Do you reduce the pH of water used to control pests and diseases?		yes	no
2	Hand control	:	c. Yes d. No	
5	How many times did you control by hand?	:	…………… times	
6	Pesticide sprayer	:	c. Calendar system d. Based on observation	
7	The first-time pesticide application	:		
8	Interval (days)	:		
9	The last time pesticide application	:		
10	Do you mix the pesticide	:	c. Yes d. No	
11	Explain how you apply pesticide to your crop			
	First formulation: Number of insecticides Name of insecticide and rate Number of fungicides Name of fungicide and rate Name of adhesive and rate Foliar fertiliser	 : : : : : :	 ……………………… 1………………………….. 2………………………….. 3………………………….. 4…………………………… 5………………………….. …………………….. 1………………………….. 2………………………….. 3…………………………… ……………………………… ………………………………	Dose/tank 1 tank = …. liter ………… g/cc ………… g/cc ………… g/cc ………… g/cc ………… g/cc ……….. g/cc ……….. g/cc ……….. g/cc ……….. g/cc ……….. cc
	Do you repeat this formulation?	:	e. yes	f. no
	Intervals for this formulation	:	…………. days	
	How many times did you use this formulation?	:	…………. times	
	Second formulation: Number of insecticides Name of insecticide and dose Number of fungicides Name of fungicide and dose Name of adhesive and dose Foliar fertiliser	 : : : : : :	 ……………………… 1………………………….. 2………………………….. 3………………………….. 4…………………………… 5………………………….. …………………….. 1………………………….. 2………………………….. 3…………………………… ……………………………… ………………………………	Dose/tank 1 tank = …. liter ………… g/cc ………… g/cc ………… g/cc ………… g/cc ………… g/cc ……….. g/cc ……….. g/cc ……….. g/cc ……….. g/cc ……….. cc
	Do you repeat this formulation?	:	g. yes	h. no
	Intervals for this formulation	:	…………. days	
	How many times did you use this formulation?		…………. times	
	Third formulation:			Dose/tank 1 tank = …. liter

	Number of insecticides Name of insecticide and dose	: :	……………………… 1………………………….. 2………………………….. 3………………………….. 4…………………………… 5…………………………..	 ………… g/cc ………… g/cc ………… g/cc ………… g/cc ………… g/cc
	Number of fungicides Name of fungicide and dose	: :	…………………….. 1………………………….. 2………………………….. 3……………………………	 ……….. g/cc ……….. g/cc ……….. g/cc
	Name of adhesive and dose Foliar fertiliser	: :	……………………………… ………………………………	……….. g/cc ……….. cc
	Do you repeat this formulation?	:	c. yes	d. no
	Intervals for this formulation	:	…………. days	
	How many times did you use this formulation?		…………. times	

Appendix 3.3. Nitrogen, phosphorus, potassium, and sulphur sources in all districts

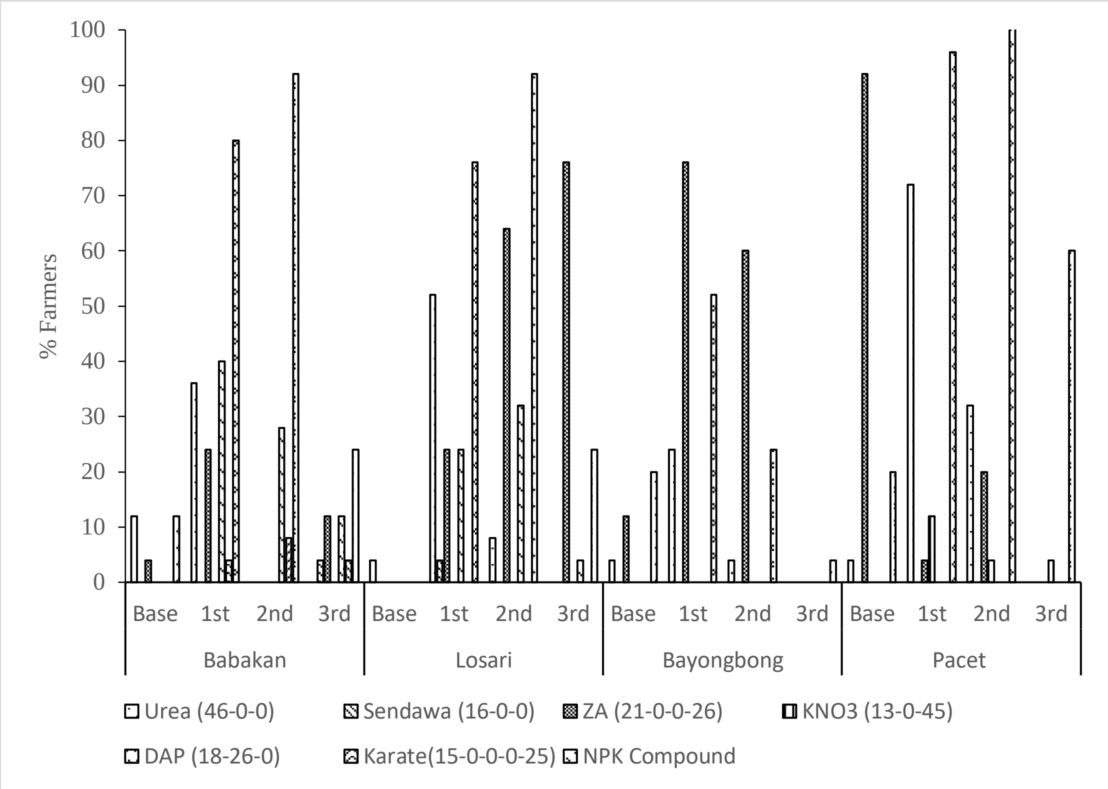


Figure 1. Nitrogen sources in all districts.

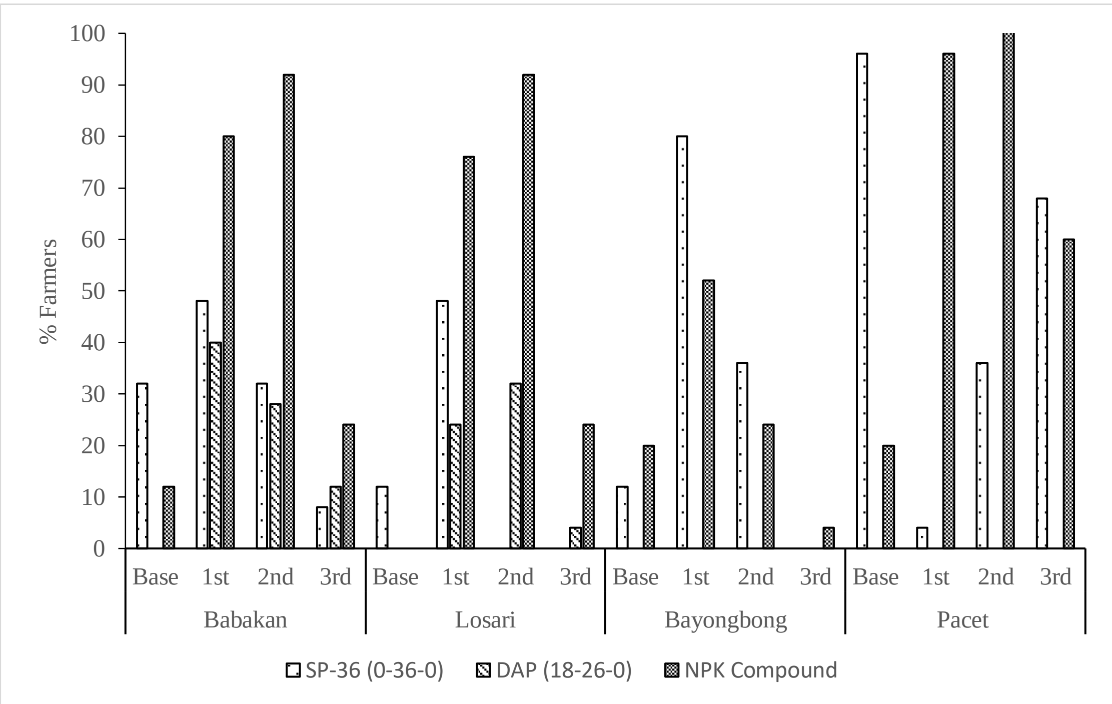


Figure 2. Phosphorus sources in all districts.

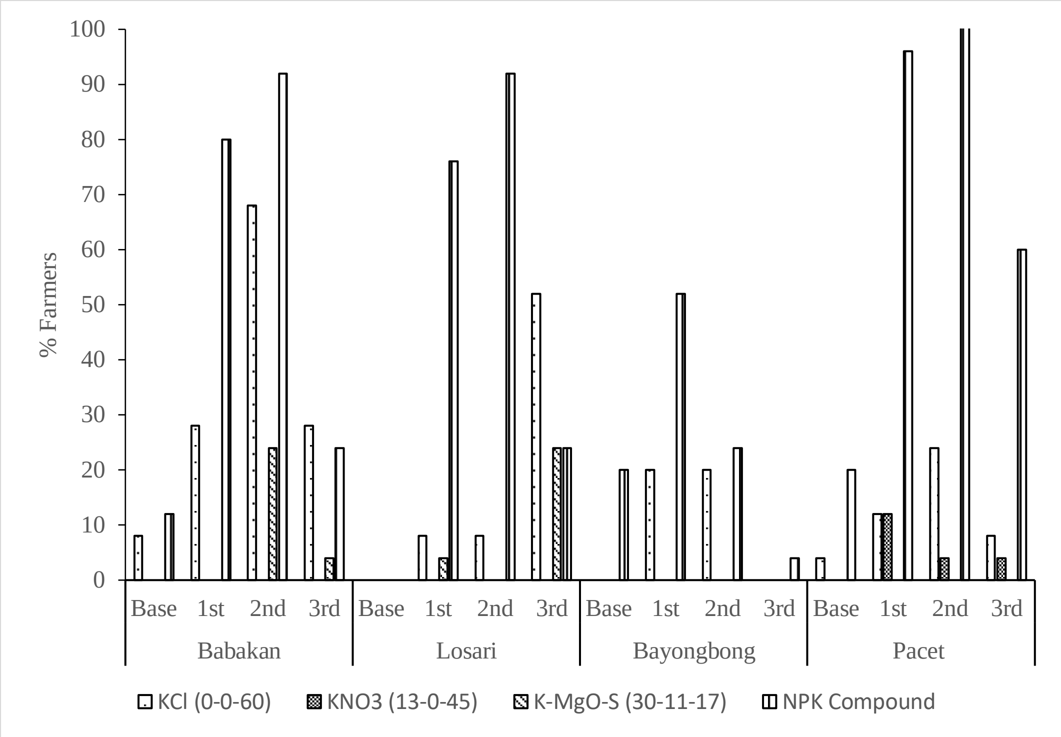


Figure 3. Potassium sources in all districts.

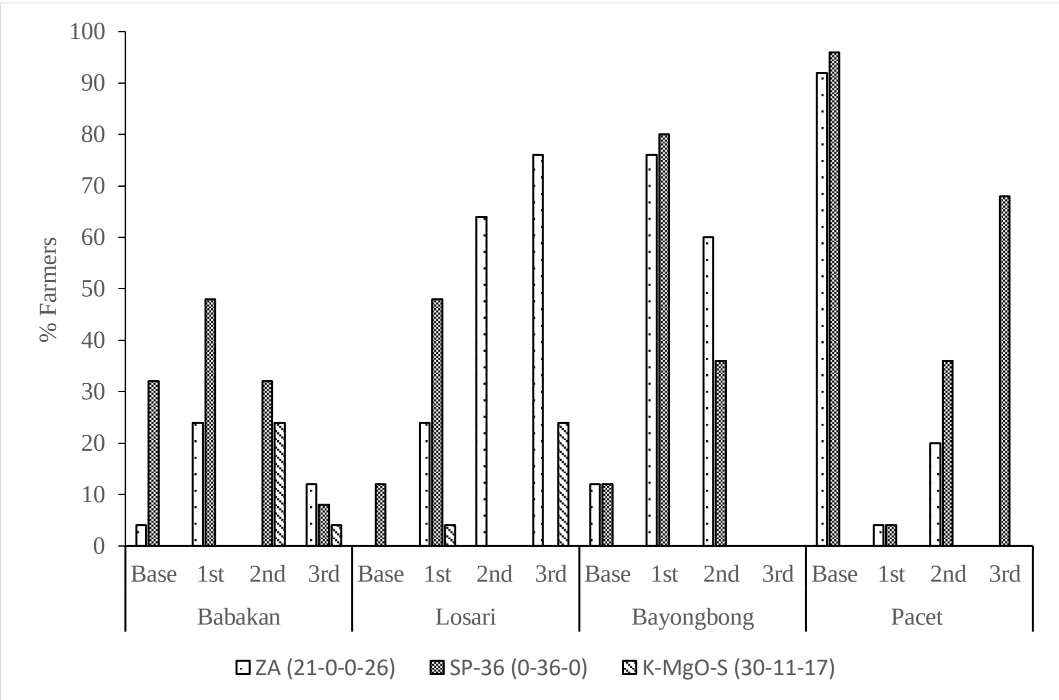


Figure 4. Sulphur sources in all districts

Appendix 3.4. The comparison of each fertiliser application in each district

Variables		Babakan-Cirebon	Losari-Cirebon	Bayongbong-Garut	Pacet-Bandung
Lime		128.66±35.11	184.37±71.20	89.54±43.39	17.54±17.54
		0.00-1071.43	0.00-1000.00	0.00-1094.49	0.00-438.60
Basic fertiliser	N (kg/ha)	13.38±5.52	6.13±6.13	36.88±15.05	54.42±4.14
		0.00±83.71	0.00-153.33	0.00-271.29	8.14-97.72
	% of farmers	25	4	24	100
	P (kg/ha)	14.31±4.51	6.73±3.91	14.66±6.99	41.87±2.97
		0.00-62.84	0.00-78.55	0.00-132.26	9.93-70.24
	% of farmers	40	12	20	100
	K (kg/ha)	7.76±4.86	-	12.06±5.16	6.86±3.86
		0.00-100.23		0.00-89.85	0.00-89.69
	% of farmers	12	0	20	20
	S (kg/ha)	7.31±2.86	-	30.58±14.83	55.66±4.69
		0.00±61.25		0.00-303.16	0.00±101.67
	% of farmers	36	0	20	96
	CaO (kg/ha)	0.45±0.45	-	-	0.98±0.71
		0.00-10.71			0.00-15.93
	% of farmers	4	0	0	8
	MgO (kg/ha)	0.03±0.03	-	-	0.08±0.06
		0.00-0.89			0.00-1.33
	% of farmers	4	0	0	8
First fertiliser	N (kg/ha)	55.54±5.80	88.180±15.44	146.50±23.71	112.26±12.27
		0.00-101.00	16.40-409.00	0.00±436.34	9.15-217.55
	% of farmers	92	100	96	100
	P (kg/ha)	71.64±10.36	56.87±7.35	107.13±24.20	30.85±3.93
		0.00-191.75	10.17-136.14	0.00-536.86	0.00-97.29
	% of farmers	96	100	88	92
	K (kg/ha)	28.09±6.26	22.66±5.00	36.40±9.27	26.21±14.42
		0.00-102.28	0.00-76.37	0.00-93.11	0.00-374.86
	% of farmers	72	72	64	96
	S (kg/ha)	20.35±4.19	23.88±7.36	130.56±26.04	29.88±4.84
		0.00±65.48	0.00-170.00	10.87-520.98	0.00-105.72
	% of farmers	88	84	100	88
	CaO (kg/ha)	4.81±1.31	2.95±0.83	0.04±0.04	0.83±0.56
		0.00±26.00	0.00-12.00	0.00-1.08	0.00-12.91
	% of farmers	52	40	4	12
	MgO (kg/ha)	0.49±0.15	1.63±0.92	0.00±0.00	0.07±0.05
		0.00±2.80	0.00-23.00	0.00-0.09	0.00-1.08
	% of farmers	48	52	4	12
Second fertiliser	N (kg/ha)	37.25±4.80	71.63±8.99	71.06±16.67	83.10±13.26
		0.00-74.00	17.14-190.83	0.00±372.49	31.77-326.32
	% of farmers	88	100	68	100
	P (kg/ha)	27.45±5.07	27.24±4.67	19.00±5.03	32.78±5.18
		0.00-85.20	0.00-91.85	0.00±86.16	0.00-119.06
	% of farmers	92	92	44	96
	K (kg/ha)	61.43±8.32	35.85±2.59	24.94±7.58	73.58±26.54
		0.00-177.88	0.00-99.61	0.00-108.01	0.00-380.16
	% of farmers	92	92	44	96
	S (kg/ha)	24.83±3.22	42.22±6.89	77.15±18.60	36.18±4.22
		0.00-58.00	0.00-120.00	0.00-429.80	0.00-83.17
	% of farmers	92	88	68	96
	CaO (kg/ha)	8.80±1.70	4.31±1.17	-	3.51±1.31

		0.00-32.00	0.00-19.67		0.00-21.31
	% of farmers	80	48	0	28
	MgO (kg/ha)	3.32±0.97	3.38±1.15	-	0.29±0.11
		0.00±16.43	0.00±26.00		0.00-1.78
	% of farmers	88	84	0	28
Third fertiliser	N (kg/ha)	13.78±4.64	55.54±9.66	0.43±0.43	21.20±5.57
		0.00±72.86	0.00-230	0.00-10.84	0.00-110.09
	% of farmers	32	80	4	48
	P (kg/ha)	7.09±2.58	6.98±3.50	0.36±0.36	83.15±6.17
		0.00±43.64	0.00-85.10	0.00-4.73	0.00-112.21
	% of farmers	32	36	4	84
	K (kg/ha)	19.58±6.47	71.69±10.03	0.36±0.36	24.27±5.57
		0.00±90.42	0.00-166.02	0.00-9.00	0.00-91.39
	% of farmers	28	76	4	56
	S (kg/ha)	6.52±3.30	56.22±9.13	-	19.98±2.85
		0.00±57.14	0.00-162.5		0.00-39.56
	% of farmers	24	80	0	24
	CaO (kg/ha)	3.27±1.26	1.93±1.28	-	2.79±1.14
		0.00±26.00	0.00-30.00		0.00-21.31
	% of farmers	28	12	0	24
	MgO (kg/ha)	0.59±0.44	6.00±2.37	-	0.23±0.10
		0.00±10.71	0.00-42.85		0.00-1.78
	% of farmers	24	40	0	76
Total	N (kg/ha)	119.94±9.15	221.48±31.85	255.63±30.55	270.97±22.83
		48.57±191.43	64.21±829.00	15.92-744.99	109.36-608.77
	P (kg/ha)	86.52±10.90	70.84±12.25	90.17±14.87	134.58±10.39
		38.35±351.96	6.98±264.02	0.00-282.24	9.93-223.90
	K (kg/ha)	116.89±10.76	130.20±14.04	73.76±13.95	154.58±30.32
		13.28±225.31	19.09-307.14	0.00-212.85	15.83±773.87
	S (kg/ha)	59.00±7.20	122.32±18.47	238.89±38.40	141.72±11.37
		7.14±134.52	24.00±452.5	22.20-919.29	0.00-239.43
	CaO (kg/ha)	17.27±2.72	9.19±2.37	0.04±0.04	8.11±2.25
		0.00-58.00	0.00±45.00	0.00-1.07	0.00-42.62
	MgO (kg/ha)	4.44±0.99	11.02±2.79	0.00±0.00	0.44±0.12
		0.45-16.43	0.00±53.57	0.00-0.09	0.00-2.03

Appendix 3.5. The comparison of pests and diseases incidence in each district

Variables:	Babakan-Cirebon	Losari-Cirebon	Bayongbong-Garut	Pacet-Bandung
Pests:				
Spodoptera exigua	2.08±0.69	9.00±3.05	19.24±4.38	22.68±3.93
	0.00-10.00	0.00-50.00	0.00-50.00	0.00-80.00
Spodoptera litura	1.04±1.04	0.20±0.20	2.40±0.98	2.80±1.23
	0.00-25.00	0.00-5.00	0.00-10.00	0.00-20.00
Liriomyza chinensis	0.08±0.06	-	1.80±1.57	-
	0.00-1.00		0.00-10.00	
Thrips	0.67±0.62	0.20±0.20	2.02±1.36	-
	0.00-15.00	0.00-5.00	0.00-20.00	
Agrotis ipsilon	-	-	8.98±4.04	4.80±1.81
			0.00-50.00	0.00-30.00
Diseases:				
Alternaria porii	4.58±1.49	0.76±0.44	21.88±5.81	14.88±3.28
	0.00-30.00	0.00-10.00	0.00-80.00	0.00-50.00
Antrachnose	1.17±0.42	6.20±2.76	14.04±5.04	6.20±2.20
	0.00-5.00	0.00-50.00	0.00-60.00	0.00-40.00
Fusarium	4.29±1.89	5.08±1.42	4.00±1.70	0.08±0.08
	0.00-45.00	0.00-30.00	0.00-25.00	0.00-2.00
Peronospora	1.17±0.42	-	5.20±3.77	2.00±1.15
	0.00-5.00		0.00-30.00	0.00-20.00
Cercospora	0.50±0.42	1.60±0.95	2.60±1.70	3.00±1.47
	0.00-10.00	0.00-20.00	0.00-30.00	0.00-25.00

Appendix 3.6. Control of pests and diseases

Table 1. The comparison of pesticide application in each location

Variables:	Babakan-Cirebon	Losari-Cirebon	Bayongbong-Garut	Pacet-Bandung
Interval of pesticide application	2.92±0.20 2.00-5.00	2.76±0.08 2.00-3.00	5.32±0.54 3.00-15.00	6.64±0.42 3.00-14.00
First sprayer (dap)	11.56±0.51 7.00-15.00	9.20±0.53 5.00-15.00	14.60±0.83 5.00-20.00	22.36±1.02 15.00-30.00
Last sprayer (dap)	51.40±0.61 47.00-58.00	48.72±0.73 40.00-57.00	56.00±1.04 50.00-70.00	71.84±1.98 50.00-90.00
Number of sprayers	15.20±0.94 8.00-23.00	14.70±0.72 10.00-25.00	8.52±0.33 5.00-10.00	8.56±0.70 4.00-17.00
Number of types of insecticide was used in one sprayer	2.48±0.32 0.00-7.00	1.76±0.16 0.00-4.00	1.96±0.27 1.00-7.00	2.00±0.14 1.00-3.00
Number of types of fungicide was used in one sprayer	2.44±0.22 1.00-5.00	2.76±0.19 1.00-5.00	3.36±0.31 1.00-8.00	4.20±0.26 1.00-7.00

Table 2. The list of insecticide name and the percentage farmers used in each location

No	Babakan-Cirebon		Losari-Cirebon		Bayongbong-Garut		Pacet-Bandung	
	Name	(%)	Name	(%)	Name	(%)	Name	(%)
1	Buldok	68	Dursban	48	Dursban	44	Spontan	32
2	Arjuna	44	Arjuna	44	Metindo	44	Arrivo	28
3	Regent	16	Buldok	16	Gordon	32	Endure	24
4	Dursban	16	Agrimec	12	Endure	20	Acrobat	16
5	Metindo	12	Trigard	8	Lannate	12	Bestfast	16
6	Tumpas	12	Talent	8	Prevathon	8	Neo Rocker	16
7	Emma	8	Meotrin	8	Curacron	4	Sidametrin	16
8	Remazol	8	Akositrin	4	Buldok	4	Dursban	12
9	Trigard	8	Ekrim	4	Agrofos	4	Curacron	8
10	Sagri bit	8	Bay Carb	4	Sagri Jos	4	Lannate	4
11	Rizetin	4	Temagon	4	Rufino	4	Meotrin	4
12	Plektora	4	Aben	4	Hamadon	4	Prevathon	4
13	Decis	4	Marshal	4	Sildog	4	Ponce	4
14	Limofast	4	Sagri Jos	4	Alika	4		
15	Rosco	4			Ponce	4		
16	Pletra	4						
17	Sumo	4						
18	Amazon	4						
19	Demolis h	4						

Table 3. The rate of insecticide application in each location per tank (16 l)

No	Babakan-Cirebon		Losari-Cirebon		Bayongbong-Garut		Pacet-Bandung	
	Name	g/ml	Name	g/ml	Name	g/ml	Name	g/ml
1	Buldok	21.4±2	Dursban	22.5±2	Dursban	6.1±1	Spontan	9.4±2
2	Arjuna	41.6±4	Arjuna	29.5±3	Metindo	8.9±1	Arrivo	21.4±7
3	Regent	43.1±19	Buldok	17.5±2	Gordon	8.8±1	Endure	11.7±2
4	Dursban	36.7±12	Agrimec	6.3±1	Endure	7.0±1	Acrobat	6.9±2
5	Metindo	13.8±9	Trigard	3.75±1	Lannate	10.0±0	Bestfast	25.0±0
6	Tumpas	40.8±12	Talent	30.0±1	Prevathon	10.0±0	Neo Rocker	12.5±4
7	Emma	56.3±6	Meotrin	15.0±2	Curacron	10.0±0	Sidametrin	10.0±0
8	Remazol	22.5±3	Akositrin	5.0±0	Buldok	5.0±0	Dursban	11.7±2
9	Trigard	31.3±19	Ekrim	25.0±0	Agrofos	10.0±0	Curacron	8.3±1
10	Sagri bit	7.5±0	Bay Carb	30.0±0	Sagri Jos	5.0±0	Lannate	15.0±0
11	Rizetin	25.0±0	Temagon	10.0±0	Rufino	5.0±0	Meotrin	25.0±0
12	Plektora	40.0±0	Aben	5.0±0	Hamadon	10.0±0	Prevathon	5.0±0
13	Decis	10.0±0	Marshal	25.0±0	Sildog	10.0±0	Ponce	10.0±0
14	Limofast	30.0±0	Sagri Jos	17.5±0	Alika	10.0±0		
15	Rosco	5.0±0			Ponce	10.0±0		
16	Pletra	32.5±0						
17	Sumo	50.0±0						
18	Amazon	20.0±0						
19	Demolish	15.0±0						

Table 4. The list of fungicide name and the percentage farmers used in each location

No	Babakan-Cirebon		Losari-Cirebon		Bayongbong-Garut		Pacet-Bandung	
	Name	(%)	Name	(%)	Name	(%)	Name	(%)
1	Antracol	88	Dithane	84	Daconil	92	Daconil	84
2	Dithane	40	Rovral	48	Rovral	48	Antracol	76
3	Score	20	Antracol	44	Antracol	40	Rovral	68
4	Vandozeb	16	Daconil	24	Delsene	20	Dithane	56
5	Remazol	16	Delsene	24	Calicron	20	Folicur	52
6	Topsin	12	Amistartop	16	Folicur	16	Amistartop	24
7	Delsene	8	Vandozeb	12	Pyramid	16	Score	20
8	Amistartop	8	Larvin	8	Nativo	8	Besromil	4
9	Trivia	8	Folicu	4	Carbio Top	8	Delsene	4
10	Infinito	8	Alvamet	4	Surjit Equation	8		
11	Folicur	8	Golek	4	Dithane	4		
12	Vitazep	4	Manzeb	4	Natural	4		
13	Deltazep	4			Saromyl	4		
14	Ridomil	4			Curzate	4		
15	SAF	4			Tridex	4		
16	Dense	4			Victory	4		
17	Lenlok	4			Phytoclor	4		
18	Mancozeb	4			Zumilev	4		
19	Rovral	4			Pizaro	4		
20	Makoban	4			Synergy	4		
21	Hatake	4			Amistartop	4		
22	Daconil	4						

Table 5. The rate of fungicide application in each location per tank (16 l)

No	Babakan-Cirebon		Losari-Cirebon		Bayongbong-Garut		Pacet-Bandung	
	Name	g/ml	Name	g/ml	Name	g/ml	Name	g/ml
1	Antracol	23.9±7	Dithane	11.9±1	Daconil	11.2±1	Daconil	14.3±2
2	Dithane	22.3±11	Rovral	5.0±0	Rovral	5.6±1	Antracol	13.9±1
3	Score	27.5±9	Antracol	10.5±0	Antracol	11.0±1	Rovral	9.4±1
4	Vandozeb	37.5±29	Daconil	5.7±0	Delsene	11.0±2	Dithane	17.7±4
5	Remazol	31.6±3	Delsene	8.3±1	Calicron	8.0±1	Folicur	6.3±1
6	Topsin	48.3±38	Amistartop	5.0±0	Folicur	7.5±1	Amistartop	11.7±3
7	Delsene	36.3±26	Vandozeb	15.0±0	Pyramid	1.0±0	Score	11.0±4
8	Amistartop	16.3±1	Larvin	20.0±0	Nativo	2.5±0	Besromil	10.0±0
9	Trivia	31.3±0	Folicur	5.0±0	Carbio Top	12.5±3	Delsene	15.0±0
10	Infinito	17.5±3	Alvamet	5.0±0	Surjit Equation	7.5±1		
11	Folicur	36.3±26	Golek	5.0±0	Dithane	10.0±0		
12	Vitazep	2.5±0	Manzeb	10.0±0	Natural	10.0±0		
13	Deltazep	5.0±0			Saromyl	10.0±0		
14	Ridomil	10.0±0			Curzate	10.0±0		
15	SAF	10.0±0			Tridex	15.0±0		
16	Dense	62.5±0			Victory	15.0±0		
17	Lenlok	25.0±0			Phytoclor	15.0±0		
18	Mancozeb	10.0V0			Zumilev	5.0±0		
19	Rovral	25.0±0			Pizaro	10.0±0		
20	Makoban	10.0±0			Synergy	10.0±0		
21	Hatake	100.0±0			Amistartop	5.0±0		
22	Daconil	10.0±0						

Table 6. The list of pesticide adhesive brand and the percentage farmers used in each location

No	Babakan-Cirebon		Losari-Cirebon		Bayongbong-Garut		Pacet-Bandung	
	Name	(%)	Name	(%)	Name	(%)	Name	(%)
1	Dustik	40	Dustik	24	Apsa	16	Apsa	52
2	Besmol	20	Triton	16	Agristik	12	Agristik	8
3	Apsa	16	Agristik	4	Brand white	12		
4	Triton	12			Lantis	12		
5	Super stick	4			Bernuel	4		
6	Ultra-stick	4						
7	Khanza	4						

Table 7. The dose of pesticide adhesive application in each location per tank (16 l)

No	Babakan-Cirebon		Losari-Cirebon		Bayongbong-Garut		Pacet-Bandung	
	Name	g/ml	Name	g/ml	Name	g/ml	Name	g/ml
1	Dustik	24.0±3	Dustik	29.2±2	Apsa	6.3±1	Apsa	10.8±2
2	Besmol	13.0±5	Triton	6.3±0	Agristik	8.3±2	Agristik	10.0±0
3	Apsa	5.5±1	Agristik	7.5±0	Brand white	10.0±0		
4	Triton	15.0±5			Lantis	13.3±3		
5	Super stick	10.0±0			Bernuel	15.0±0		
6	Ultra-stick	15.6±0						
7	Khanza	5.0±0						

Table 8. The list of liquid fertiliser brand and the percentage farmers used in each location

No	Babakan-Cirebon		Losari-Cirebon		Bayongbong-Garut		Pacet-Bandung	
	Name	(%)	Name	(%)	Name	(%)	Name	(%)
1	Magic green	12	Borer	44	Vitoclor	12	Atonik	48
2	Progib	8	Bigest	20	Super grow	8	Supergrow	24
3	Astonish	8	Trubus	12	Atonik	8	Doping	16
4	Boom Flower	8	Triple	4	NPK Tawon	4	Gandasil	16
5	Trigold	4			Progib	4	Rabbit urine	4
6	Bigest	4						
7	Atonik	4						
8	Trubus	4						
9	Vormax	4						

Table 9. The dose of liquid fertiliser application in each location per tank (16 l)

No	Babakan-Cirebon		Losari-Cirebon		Bayongbong-Garut		Pacet-Bandung	
	Name	g/ml	Name	g/ml	Name	g/ml	Name	g/ml
1	Magic green	93.3±32	Borer	10.9±2	Vitoclor	8.3±2	Atonik	18.3±3
2	Progib	2.0±0	Bigest	24.0±8	Super grow	25.0±3	Supergrow	13.3±3
3	Astonish	22.5±3	Trubus	20.0±1	Atonik	25.0±3	Doping	15.0±4
4	Boom Flower	80.0±20	Triple	5.0±0	NPK Tawon	200.0±0	Gandasil	15.0±1
5	Trigold	7.5±0			Progib	15.0±0	Rabbit urine	250.0±0
6	Bigest	12.5±0						
7	Atonik	27.5±0						
8	Trubus	30.0±0						
9	Vormax	50.0±0						

Appendix 3.7. The comparison of the other variables in each location

Variables:	Babakan-Cirebon	Losari-Cirebon	Bayongbong-Garut	Pacet-Bandung
Variety	Bima	Bima	Tuk-tuk	Sumenep
Harvested area	10245.41±2364.08	2534.65±310.15	2689.42±354.47	1639.75±168.11
(m^2)	2028.00-80000.00	400.00-7920.00	210.42-9798.62	560.84-3486.95
Seed bulb (kg/ha)	1899.68±72.66	1525.29±122.89	1555.76±67.31	613.53±25.59
	1396.45-3990.98	200.00-2799.64	807.91-2576.27	354.22-857.07
Bulb seed: yield	6.69±0.31	8.49±0.53	5.06±0.29	9.10±0.75
ratio	3.04-14.00	3.33-13.62	2.00-11.76	3.75-17.65
Plant spacing	15.48±0.12	14.24±0.49	19.60±0.49	22.40±0.59
(cm) one	15.00-17.00	7.00-18.00	10.00-25.00	20.00-30.00
Plant spacing	12.65±0.60	14.24±0.55	18.20±0.91	22.20±0.65
(cm) two	10.00-20.00	7.00-20.00	10.00-25.00	15.00-30.00
Harvested time	54.15±0.43	53.36±0.87	65.56±0.92	90.4±0.4
(dap)	50.00-60.00	50.00-70.00	60.00-80.00	90.00-100.00
Organic fertilizer	203.43±46.70	234.16±95.01	9770.50±636.76	10266.18±806.87
(kg/ha)	0.00-400.00	0.00-2000.00	2397.00-19009.60	2905.63-21097.54
Nematicide	15.78±2.87	29.85±5.40	11.15±2.85	8.29±2.91
(kg/ha)	0.00-96.00	0.00-100.00	0.00-71.86	0.00±40.17
Basic fertilizer	-2.56±0.57	-5.00±1.41	-3.44±1.17	0.00±0.00
(dap)	-7.00-0.00	-10.00-0.00	-7.00-0.00	0.00
First fertilization	10.29±0.82	10.08±1.41	16.72±1.24	22.76±0.88
(dap)	2.00-15.00	6.00-25.00	7.00-30.00	14.00-30.00
Second fertilizer	22.71±0.92	21.24±0.91	31.0±1.70	45.00±1.91
(dap)	12.00-30.00	15.00-35.00	20.00-45.00	25.00-60.00
Last fertilization	28.20±0.44	30.55±0.56	-	66.52±1.98
(dap)	25.00-30.00	25.00-35.00		42.00-80.00

Appendix 4.1. Insecticide and fungicide application during Field Trial 1

Plant age (DAP)	Insecticides			Fungicides		
	Brands	Active Ingredients	Rate (ml l^{-1})	Brands	Active Ingredients	Rate (g l^{-1})
20	Sidamethrin	Sipermetrin	2.0-4.0	Antracol 70WP	Propineb	2.0
	50EC			Daconil 75WP	Chlorothalonil	1.1
				Benlox 50WP	Benomyl 50%	0.5
27	Sidamethrin	Sipermetrin		Antracol 70WP	Propineb	2.0
	50EC			Daconil 75WP	Chlorothalonil	1.1
				Benlox 50WP	Benomyl 50%	0.5
35	Prevathon	Chlorantraniliprole	2.0	Mancobat 82WP	Mancozeb	1.0
		5%		Daconil 75WP	Chlorothalonil	1.1
	Sidamethrin	Sipermetrin	2.0-4.0	Topsin 500SC	Methyl	1.0
	50 EC				thiophanate	
				Score 250EC	Difenoconazole	0.5(ml l^{-1})
42	Endure 120SC	Spinoteram	0.5-1.0	Daconil 75 WP	Chlorothalonil	1.1
				Topsin 500 SC	Methyl	1.0
				Score 250EC	thiophanate	
					Difenoconazole	0.5(ml l^{-1})
50	Prevathon	Chlorantraniliprole	2.0	Daconil 75 WP	Chlorothalonil	1.1
		5%		Topsin 500 SC	Methyl	1.0
	Sidamethrin	Sipermetrin	2.0-4.0	Score 250EC	thiophanate	
	50EC				Difenoconazole	0.5(ml l^{-1})
57	Prevathon	Chlorantraniliprole	2.0	Daconil 75 WP	Chlorothalonil	1.1
		5%		Topsin 500 SC	Methyl	1.0
	Sidamethrin	Sipermetrin	2.0-4.0	Score 250EC	thiophanate	
	50EC				Difenoconazole	0.5(ml l^{-1})
63	Prevathon	Chlorantraniliprole	2.0	Daconil 75 WP	Chlorothalonil	1.1
		5%		Topsin 500 SC	Methyl	1.0
	Sidamethrin	Sipermetrin	2.0-4.0	Score 250EC	thiophanate	
	50EC				Difenoconazole	0.5(ml l^{-1})
70	Prevathon	Chlorantraniliprole	2.0	Daconil 75 WP	Chlorothalonil	1.1
		5%		Topsin 500 SC	Methyl	1.0
	Sidamethrin	Sipermetrin	2.0-4.0	Score 250EC	thiophanate	
	50EC				Difenoconazole	0.5(ml l^{-1})
77	Prevathon	Chlorantraniliprole	2.0	Daconil 75 WP	Chlorothalonil	1.1
		5%		Topsin 500 SC	Methyl	1.0
	Sidamethrin	Sipermetrin	2.0-4.0	Score 250EC	thiophanate	
	50EC				Difenoconazole	0.5(ml l^{-1})

Appendix 4.2. Effect of lime and P fertiliser levels on soil properties in each site

Table 1. The interaction of lime and P fertiliser on soil pH_{H2O}, Al^{3+} and KCl titratable acidity.

Lime ($t\ ha^{-1}$)	P-fertiliser ($kg\ ha^{-1}$)	Field site 1				Field site 2				Field site 3			
		pH_{H2O}	pH_{KCl}	Al^{3+}	EA	pH_{H2O}	pH_{KCl}	Al^{3+}	EA	pH_{H2O}	pH_{KCl}	Al^{3+}	EA
0	0	3.57^{ns}	3.24ns	1.45^{ns}	1.88^{ns}	4.02^{ns}	3.25^{ns}	1.48^{ns}	1.83^{ns}	4.64^{ns}	3.75^{ns}	0.31^{ns}	0.43^{ns}
	50	3.51	3.27	1.40	1.82	4.02	3.23	1.05	1.41	4.76	3.77	0.31	0.45
	100	3.84	3.31	1.47	2.10	4.11	3.42	0.84	1.09	4.69	3.84	0.20	0.55
	150	3.81	3.30	1.45	1.95	4.26	3.26	1.15	1.37	4.56	3.67	0.27	0.42
0.5	0	3.82	3.31	1.44	1.82	4.11	3.42	0.95	1.19	4.48	3.81	0.33	0.44
	50	3.90	3.30	1.43	1.85	4.24	3.29	1.24	1.47	4.44	3.86	0.34	0.55
	100	3.87	3.28	1.50	2.02	4.28	3.34	1.11	1.38	4.82	3.98	0.11	0.31
	150	3.97	3.35	1.39	1.69	4.35	3.47	0.71	0.84	4.83	3.98	0.20	0.30
1.0	0	3.95	3.41	1.26	1.28	4.36	3.53	0.86	0.99	5.23	4.34	0.05	0.16
	50	3.93	3.38	1.36	1.67	4.33	3.36	0.66	0.83	5.05	4.19	0.05	0.16
	100	4.26	3.48	1.28	1.41	4.39	3.57	0.47	0.71	5.06	4.16	0.07	0.17
	150	3.99	3.38	1.22	1.20	4.49	3.65	0.62	0.79	5.22	4.35	0.00	0.14
p-value	0.33	0.59	0.39	0.82	0.83	0.96	0.26	0.38	0.37	0.13	0.25	0.90	0.92
CV (%)	2.2	6.0	2.2	9.6	24.3	4.3	3.9	44.5	38.3	5.0	4.4	77.3	81.7

EA= KCl titratable acidity (sum of Al+3 + H+)

Table 2. Influence of lime and P fertiliser on organic-C, N-Kjeldahl and C/N ratio.

Lime ($t\ ha^{-1}$)	P-fertiliser ($kg\ ha^{-1}$)	Field site 1			Field site 2			Field site 3		
		Organic-C	Kjeldahl-N	C/N	Organic-C	Kjeldahl-N	C/N	Organic-C	Kjeldahl-N	C/N
0	0	1.46^{ns}	0.16^{ns}	9^{ns}	1.22^{ns}	0.15^{ns}	9^{ns}	2.58^{ns}	0.26^{ns}	10^{ns}
	50	1.55	0.17	9	1.25	0.15	8	2.47	0.24	10
	100	1.45	0.16	9	1.29	0.14	10	2.36	0.23	10
	150	1.46	0.16	9	1.20	0.15	8	2.46	0.25	10
0.5	0	1.52	0.17	9	1.37	0.15	9	2.19	0.22	10
	50	1.47	0.16	9	1.25	0.14	9	2.14	0.23	9
	100	1.46	0.16	9	1.31	0.15	9	2.64	0.26	10
	150	1.51	0.16	9	1.33	0.15	9	2.52	0.25	10
1.0	0	1.51	0.17	9	1.36	0.15	9	2.50	0.25	10
	50	1.49	0.18	9	1.32	0.15	9	2.57	0.25	10
	100	1.57	0.17	9	1.30	0.15	9	2.56	0.25	10
	150	1.61	0.17	10	1.38	0.14	10	2.40	0.25	10
p-value		0.56	0.97	0.91	0.94	0.68	0.22	0.42	0.42	0.28
CV (%)		7.6	10.8	7.3	13.3	10.9	10.2	14.3	11.8	5.3
Average across the lime (L) and P levels										
0L		1.48^{ns}	0.16^{ns}	9^{ns}	1.24^{ns}	0.14^{ns}	9^{ns}	2.47^{ns}	0.24^{ns}	10^{ns}
0.5L		1.49	0.16	9	1.32	0.15	9	2.37	0.24	10
1.0L		1.55	0.17	9	1.34	0.15	9	2.51	0.25	10
P-value		0.22	0.43	0.80	0.23	0.93	0.38	0.54	0.55	0.82
0P		1.50^{ns}	0.17^{ns}	9^{ns}	1.31^{ns}	0.15^{ns}	9^{ns}	2.42^{ns}	0.24^{ns}	10^{ns}
50P		1.51	0.17	9	1.27	0.14	8	2.39	0.24	10
100P		1.50	0.16	9	1.30	0.14	9	2.52	0.25	10
150P		1.53	0.16	9	1.30	0.15	9	2.46	0.25	10
p-value		0.87	0.68	0.40	0.95	0.84	0.92	0.83	0.79	0.66

Table 3. The interaction of lime and P fertiliser on Ca^{2+} and total base cations (TBC, cmol (+) kg^{-1}).

Lime ($t\ ha^{-1}$)	P-fertiliser ($kg\ ha^{-1}$)	Field site 1			Field site 2			Field site 3		
		Ca^{2+}	TBC	Al:Ca	Ca^{2+}	TBC	Al:Ca	Ca^{2+}	TBC	Al:Ca
0	0	3.13	5.21	0.52[ns]	3.98[ns]	6.01	0.33[ns]	5.48	8.39	0.07[ns]
	50	3.68	5.65	0.43	3.99	5.91	0.35	5.33	7.99	0.07
	100	3.03	5.20	0.62	4.50	6.79	0.20	5.37	8.02	0.14
	150	3.50	5.53	0.47	4.57	6.65	0.15	5.89	8.77	0.05
0.5	0	3.12	4.97	0.51	3.96	6.00	0.25	5.47	8.54	0.08
	50	3.65	5.67	0.44	4.57	6.69	0.22	6.03	8.93	0.13
	100	3.56	6.64	0.45	4.48	6.42	0.32	6.68	9.56	0.03
	150	3.87	5.77	0.40	5.25	7.39	0.26	6.94	9.88	0.03
1.0	0	3.97	6.09	0.28	5.43	7.68	0.16	8.81	11.67	0.01
	50	3.97	5.87	0.36	5.56	7.65	0.15	7.65	10.50	0.01
	100	4.22	6.24	0.29	5.21	7.10	0.09	7.29	10.08	0.01
	150	4.90	6.93	0.36	6.11	8.11	0.11	10.30	13.24	0.00
p-value		0.19	0.28	0.60	0.79	0.36	0.75	0.15	0.24	0.64
CV (%)		18.7	14.4		15.2	11.2		17.1	12.9	

Table 4. Influence of lime and P fertiliser on Mg^{2+}, K^+ and Na^+ (cmol (+) kg^{-1}).

Lime ($t\ ha^{-1}$)	P-fertiliser ($kg\ ha^{-1}$)	Field site 1			Field site 2			Field site 3		
		Mg^{2+}	K^+	Na^+	Mg^{2+}	K^+	Na^+	Mg^{2+}	K^+	Na^+
0	0	0.94	1.06	0.09	1.05[ns]	0.94[ns]	0.05[ns]	1.65[ns]	1.17[ns]	0.10
	50	0.97	1.92	0.08	1.04	0.84	0.05	1.62	0.95	0.10
	100	0.92	1.17	0.08	1.23	1.01	0.05	1.63	0.95	0.08
	150	0.99	0.96	0.08	1.15	0.87	0.06	1.63	1.16	0.09
0.5	0	0.80	0.97	0.07	1.19	0.77	0.05	1.47	1.51	0.09
	50	0.90	1.04	0.08	1.06	1.01	0.05	1.49	1.32	0.09
	100	0.94	1.05	0.09	1.16	0.73	0.05	1.53	1.24	0.11
	150	0.88	0.94	0.08	1.25	0.85	0.04	1.65	1.18	0.10
1.0	0	0.99	1.04	0.08	1.25	0.97	0.04	1.67	1.11	0.08
	50	0.89	0.93	0.08	1.13	0.91	0.06	1.63	1.13	0.08
	100	1.02	0.93	0.08	1.20	0.63	0.06	1.70	1.00	0.09
	150	0.95	1.02	0.08	1.24	0.71	0.05	1.68	1.16	0.10
P-value		0.56	0.56	0.72	0.78	0.38	0.64	0.85	0.87	0.41
CV (%)		13.9	18.0	13.4	13.5	29.5	30.5	9.3	27.7	17.4
0L		0.96	1.03	0.08	1.12	0.92	0.05	1.63[ab]	1.06[b*]	0.09
0.5L		0.88	1.00	0.08	1.16	0.84	0.05	1.54[b]	1.31[a]	0.10
1.0L		0.96	0.98	0.08	1.20	0.80	0.05	1.67[a]	1.10[ab]	0.09
P-value		0.18	0.77	0.51	0.30	0.44	0.79	0.05	0.07	0.36
0P		0.91	1.03	0.08	1.16	0.89	0.04	1.59	1.26	0.09
50P		0.92	0.96	0.08	1.07	0.92	0.05	1.58	1.13	0.09
100P		0.96	1.05	0.08	1.20	0.79	0.05	1.62	1.06	0.09
150P		0.93	0.97	0.08	1.21	0.81	0.05	1.65	1.17	0.10
P-value		0.81	0.58	0.76	0.14	0.51	0.41	0.64	0.50	0.56

Table 5. The interaction of lime and P fertiliser on CEC (cmol (+) kg^{-1}) and BS (%).

Lime (t ha^{-1})	P-fertiliser (kg ha^{-1})	Field 1		Field 2		Field 3	
		CEC	BS (%)	CEC	BS (%)	CEC	BS (%)
0	0	13.70^{b}	38	12.78^{ns}	47	14.83^{ns}	56
	50	13.65^{b}	41	12.85	46	14.50	55
	100	13.65^{b}	38	12.84	53	14.59	54
	150	13.32^{b}	42	12.87	52	14.86	59
0.5	0	14.32^{ab}	35	13.15	51	14.16	60
	50	13.32^{b}	42	12.54	51	14.38	61
	100	13.29^{b}	50	13.47	48	15.04	63
	150	13.84^{b}	42	13.54	55	15.36	64
1.0	0	13.76^{b}	44	13.05	63	14.64	80
	50	14.44^{ab}	40	12.47	51	14.59	71
	100	14.09^{ab}	46	13.85	56	15.36	60
	150	15.95^{a}	44	13.90	59	15.29	86
P-value		0.02	0.26	0.56	0.24	0.77	
CV (%)			16.2		11.2		
0L		13.62^{b}	40	12.84^{ns}	49^{b}	14.69^{ns}	56^{b}
0.5L		13.69^{b}	42	1318	51^{b}	14.73	62^{b}
1.0L		14.45^{a}	44	13.32	60^{a}	14.97	74^{a}
P-value			0.27		<0.01		
0P		13.93^{ab}	39	12.99^{ab}	53	14.54^{ab}	65^{ab}
50P		13.80^{ab}	41	12.62^{b}	49	14.49^{b}	63^{ab}
100P		13.58^{b}	42	13.39^{a}	52	14.50^{ab}	65^{b}
150P		14.37^{a}	44	13.44^{a}	55	15.17^{a}	70^{a}
P-value			0.32		0.16		

Tukey's method for means comparison; means presenting the same letters in the same column are not significantly different at $p < 0.05$, ns=not significance.

Table 6. The interactions of lime and P fertiliser effects on soil available P (Bray1-P, mg P kg^{-1}).

Treatments		Field 1	Field 2	Field 3
Lime (t ha^{-1})	P-Fertiliser (kg ha^{-1})			
0	0	21.2^{ns}	29.2^{ns}	11.7^{ns}
	50	30.8	29.6	23.6
	100	22.2	31.9	21.9
	150	26.6	34.4	47.2
0.5	0	24.9	29.2	12.8
	50	24.0	34.1	24.8
	100	28.6	43.7	30.5
	150	36.0	30.7	30.2
1.0	0	18.7	26.5	11.2
	50	25.0	30.2	24.0
	100	25.3	32.1	30.1
	150	42.4	30.1	46.5
P-value		0.30	0.82	0.52

Tukey's method for means comparison; means presenting the same letters in the same column are not significantly different at $p < 0.05$, ns=not significance.

Appendix 4.3. Effect of lime and P fertiliser levels on plant growth in all sites

Table 1. Effect of lime and P fertiliser levels on shoot length, number of leaves and number of tillers at Field site 1.

Lime (t ha^{-1})	P-fertiliser (kg ha^{-1})	Field site 1					
		SL		NL		NT	
		21 DAP	42 DAP	21 DAP	42 DAP	21 DAP	42 DAP
0	0	16.1^{ns}	27.1^{ns}	21.0^{ns}	31.0^{ns}	7.5^{ns}	7.6^{ns}
	50	15.5	26.1	22.5	29.1	6.4	7.8
	100	16.3	26.2	22.7	29.5	7.4	8.4
	150	15.5	26.8	22.4	29.9	7.5	8.0
0.5	0	15.8	26.0	21.9	27.9	7.2	8.1
	50	16.7	27.0	21.8	29.5	6.7	7.7
	100	16.3	27.7	22.7	26.6	6.6	6.1
	150	15.6	28.0	20.2	29.9	6.2	7.7
1.0	0	16.3	27.3	23.7	29.6	6.9	8.0
	50	17.2	27.1	23.3	28.7	7.7	7.7
	100	16.7	27.8	24.9	31.2	8.1	7.9
	150	17.6	27.6	20.3	30.7	8.0	8.1
	CV (%)	5.4	8.4	9.7	9.3	27.0	9.3
	p-value	0.19	0.70	0.44	0.47	0.66	0.64
	0L	15.5^{b}	26.5^{ns}	22.1^{ns}	29.8^{ns}	7.8^{ns}	8.0^{ns}
	0.5L	16.1^{b}	27.2	21.6	28.5	6.6	7.4
	1.0L	16.8^{a}	27.4	23.0	30.0	7.7	7.9
	p-value	<0.01	0.22	0.20	0.22	0.21	0.22
	0P	16.1^{ns}	26.8^{ns}	22.2^{ab*}	29.5^{ns}	8.0^{ns}	8.0^{ns}
	50P	16.5	26.8	22.5^{ab}	29.1	6.9	7.7
	100P	16.4	27.2	23.4^{a}	29.1	7.4	7.5
	150P	16.2	27.5	20.9^{b}	30.1	7.2	7.9
	p-value	0.67	0.76	0.06	0.76	0.60	0.76

Tukey's method for means comparison; means presenting the same letters are not significantly different at α=5%, * α=10%, ns=not significance. SL=shoot length, NL=number of leaves, NY=number of tillers, DAP=days of planting.

Table 2. Effect of lime and P fertiliser levels on shoot length, number of leaves and number of tillers at Field site 2.

Lime (t ha^{-1})	P-fertiliser (kg ha^{-1})	Field site 2					
		SL		NL		NT	
		21 DAP	42 DAP	21 DAP	42 DAP	21 DAP	42 DAP
0	0	17.2^{ns}	25.3^{ns}	23.9^{ns}	35.6^{ns}	5.5^{ns}	7.6^{ns}
	50	17.3	24.0	23.4	39.0	6.5	8.0
	100	17.8	25.1	22.8	35.1	5.7	7.0
	150	17.4	23.7	20.8	35.8	6.7	7.5
0.5	0	19.0	28.2	23.4	39.9	6.5	7.8
	50	18.1	24.4	22.7	36.9	5.7	7.3
	100	17.6	26.4	24.4	39.5	6.3	7.6
	150	19.1	27.5	21.7	39.7	6.5	7.3
1.0	0	18.8	29.9	22.0	38.5	6.2	7.0
	50	17.8	26.3	22.6	37.6	6.1	7.3
	100	18.9	28.8	23.5	41.3	6.5	8.0
	150	18.9	28.0	24.8	38.4	5.8	7.7
	CV (%)	5.4	9.3	8.7	12.5	14.1	12.3
	p-value	0.38	0.77	0.11	0.68	0.29	0.44

0L	17.4^{b}	24.5^{b}	22.7^{ns}	36.3^{ns}	6.1^{ns}	7.5^{ns}
0.5L	18.4^{a}	26.4^{b}	23.0	39.0	6.2	7.5
1.0L	18.6^{a}	27.9^{a}	23.2	38.9	6.1	7.5
p-value	<0.01	<0.01	0.78	0.22	0.89	0.99
0P	18.3^{ns}	27.0^{a*}	23.0^{ns}	38.0^{ns}	6.0^{ns}	7.4^{ns}
50P	17.6	25.3^{b}	22.9	37.8	6.1	7.5
100P	18.1	26.8^{ab}	23.5	38.6	6.1	7.5
150P	18.4	26.4^{ab}	22.4	37.9	6.3	7.5
p-value	0.22	0.06	0.61	0.98	0.87	0.99

Tukey's method for means comparison; means presenting the same letters are not significantly different at α=5%, * α=10%, ns=not significance. SL=shoot length, NL=number of leaves, NY=number of tillers, DAP=days of planting.

Table 3. Effect of lime and P fertiliser levels on shoot length, number of leaves and number of tillers at Field site 3.

Lime (t ha^{-1})	P-fertiliser (kg ha^{-1})	Field site 3					
		SL		NL		NT	
		21 DAP	42 DAP	21 DAP	42 DAP	21 DAP	42 DAP
0	0	19.2^{ns}	26.2^{ns}	24.6^{ab}*	40.8^{ns}	7.0^{ns}	8.3^{ns}
	50	19.8	28.1	24.5^{ab}	41.7	6.2	9.2
	100	20.5	30.3	23.6^{ab}	43.3	5.9	8.2
	150	19.4	26.8	21.6^{b}	38.5	5.8	8.2
0.5	0	18.7	27.0	24.5^{ab}	39.4	6.5	8.9
	50	20.0	28.3	23.3^{ab}	41.6	6.1	8.6
	100	20.2	30.7	23.5^{ab}	44.9	6.4	8.6
	150	19.6	28.7	22.1^{ab}	39.9	6.1	8.1
1.0	0	19.0	28.5	21.5^{b}	37.5	6.0	7.6
	50	20.4	30.4	22.6^{ab}	42.0	6.0	8.3
	100	21.1	29.8	22.5^{ab}	39.1	6.0	7.9
	150	20.0	30.5	25.2^{a}	40.7	7.0	7.7
CV (%)		4.6	7.8	9.1	12.4	14.0	11.5
p-value		0.90	0.65	0.06	0.78	0.31	0.87
0L		19.7^{ns}	27.8^{b*}	23.6^{ns}	41.0^{ns}	6.2^{ns}	8.5^{ns}
0.5L		19.6	28.7^{ab}	23.3	41.4	6.2	8.5
1.0L		19.9	29.8^{a}	22.9	39.8	6.2	7.9
p-value		0.72	0.07	0.71	0.65	1.00	0.12
0P		19.0^{b}	27.2^{b}	23.5^{ns}	39.2^{ns}	6.5^{ns}	8.3^{ns}
50P		20.1^{a}	28.9^{ab}	23.4	41.8	6.1	8.7
100P		20.2^{a}	30.3^{a}	23.2	42.4	6.1	8.2
150P		19.7^{ab}	28.7^{ab}	23.0	39.7	6.3	8.0
p-value		<0.01	0.02	0.91	0.35	0.63	0.33

Tukey's method for means comparison; means presenting the same letters are not significantly different at α=5%, * α=10%, ns=not significance. SL=shoot length, NL=number of leaves, NY=number of tillers, DAP=days of planting.

Table 4. The interaction of lime and fertiliser rates on shoot dry weight (above ground, g/plant) in all sites at 56 DAP.

Treatments		Field site 1	Field site 2	Field site 3
Lime (t ha^{-1})	P-Fertiliser (kg ha^{-1})			
0	0	0.82	2.04^{ns}	2.22^{ns}
	50	1.10	3.07	2.42
	100	1.08	2.72	2.65
	150	1.00	2.36	2.11
0.5	0	1.01	2.49	1.71
	50	1.19	2.20	2.55
	100	1.09	2.95	2.64
	150	1.47	3.24	3.31
1.0	0	0.92	4.53	2.20
	50	0.99	3.42	3.63
	100	1.32	4.18	2.82
	150	1.30	4.18	3.03
CV (%)		23.8	24.9	33.3
p-value		0.39	0.14	0.42
0L		1.00^{ns}	2.55^{b}	2.35^{ns}
0.5L		1.19	2.72^{b}	2.56
1.0L		1.13	4.01^{a}	2.92
p-value		0.13	<0.01	0.19
0P		0.92^{b}	3.02^{ns}	2.04^{b*}
50P		1.09^{ab}	2.89	2.87^{a}
100P		1.16^{ab}	3.28	2.70^{a}
150P		1.26^{a}	3.26	2.82^{a}
p-value		0.02	0.25	0.09

Tukey's method for means comparison; means presenting the same letters are not significantly different at α=5%and * α=10%, ns=not significance.

Table 5. The interaction of lime and fertiliser rates on root dry weight (g/plant) in all sites at 56 DAP.

Treatments		Field site 1	Field site 2	Field site 3
Lime (t ha^{-1})	P-Fertiliser (kg ha^{-1})			
0	0	0.14^{ab*}	0.25^{b}	032^{ns}
	50	0.11^{ab}	0.29^{ab}	0.39
	100	0.12^{ab}	0.35^{ab}	0.42
	150	0.16^{ab}	0.31^{ab}	0.44
0.5	0	0.10^{b}	0.35^{ab}	0.30
	50	0.13^{ab}	0.28^{ab}	0.37
	100	0.12^{ab}	0.27^{b}	0.40
	150	0.22^{a}	0.27^{b}	0.38
1.0	0	0.17^{ab}	0.27^{b}	0.34
	50	0.13^{ab}	0.30^{ab}	0.47
	100	0.19^{ab}	0.35^{ab}	0.37
	150	0.13^{ab}	0.39^{a}	0.41
CV (%)		36.5	16.8	24.9
p-value		0.07	< 0.01	0.82

0L	0.13^{ns}	0.30^{ns}	0.39^{ns}
0.5L	0.14	0.29	0.36
1.0L	0.16	0.33	0.40
p-value	0.41	0.18	0.58
0P	0.13^{ns}	0.29^{ns}	0.32^{b*}
50P	0.12	0.29	0.41^{a}
100P	0.14	0.32	0.40^{a}
150P	0.17	0.32	0.41^{a}
p-value	0.16	0.22	0.07

Tukey's method for means comparison; means presenting the same letters are not significantly different at α=5%and * α=10%, ns=not significance.

Table 6. The interaction of lime and fertiliser rates on bulb dry weight (g/plant) in all sites at 56 DAP.

Treatments		Field site 1	Field site 2	Field site 3
Lime (t ha^{-1})	P-Fertiliser (kg ha^{-1})			
0	0	2.46^{ns}	3.86^{ns}	5.52^{ns}
	50	2.48	4.35	6.28
	100	3.38	4.53	7.35
	150	3.08	5.14	7.06
0.5	0	3.49	4.64	5.05
	50	3.71	4.60	6.55
	100	3.27	4.08	6.21
	150	3.17	4.43	6.78
1.0	0	3.00	4.46	6.17
	50	3.66	4.20	7.21
	100	3.63	5.35	8.18
	150	3.24	5.32	7.33
CV (%)		20.4	17.6	20.5
p-value		0.32	0.27	0.93
0L		2.85^{b}	4.47^{ns}	6.55^{ab*}
0.5L		3.41^{a}	4.44	6.20^{b}
1.0L		3.39^{a}	4.83	7.22^{a}
p-value		0.03	0.32	0.09
0P		2.99^{ns}	4.32^{ns}	5.58^{b}
50P		3.28	4.39	6.68^{ab}
100P		3.43	4.65	7.25^{a}
150P		3.17	4.96	7.06^{ab}
p-value		0.42	0.21	0.02

Tukey's method for means comparison; means presenting the same letters are not significantly different at α=5%and * α=10%, ns=not significance.

Table 7. The interaction of lime and fertiliser rates on total plant biomass (g DM/plant) in all sites at 56 DAP.

Treatments		Field site 1	Field site 2	Field site 3
Lime (t ha^{-1})	P-Fertiliser (kg ha^{-1})			
0	0	3.42^{ns}	6.15	8.06^{ns}
	50	3.69	7.71	9.09
	100	4.58	7.61	10.42

	150	4.24	7.81	9.61
0.5	0	4.60	7.48	7.06
	50	5.02	7.08	9.47
	100	4.49	7.30	9.25
	150	4.85	9.21	10.47
1.0	0	4.11	9.32	8.71
	50	4.78	7.27	11.30
	100	5.14	9.87	11.37
	150	4.68	9.88	10.77
CV (%)		16.7	14.6	21.3
p-value		0.51	0.09	0.78
0L		3.98[b]	7.32[b]	9.29[ns]
0.5L		4.74[a]	7.45[b]	9.06
1.0L		4.67[a]	9.23[a]	10.54
p-value		0.01	<0.01	0.11
0P		4.04[ns]	7.63[ns]	7.94[b]
50P		4.50	7.57	9.95[ab]
100P		4.73	8.26	10.35[a]
150P		4.59	8.55	10.28[a]
p-value		0.14	0.13	0.02

Tukey's method for means comparison; means presenting the same letters are not significantly different at * α=10%, ns=not significance.

Appendix 4.4. Effect of lime and P fertiliser on NPK uptake and removal in all sites

Table 1. Interaction between lime and P fertiliser on NPK concentration in above-ground section (% dry matter).

Lime ($t\ ha^{-1}$)	P-fertiliser ($kg\ ha^{-1}$)	Field site 1			Field site 2			Field site 3		
		N	P	K	N	P	K	N	P	K
0	0	3.42^{ns}	0.26^{ns}	5.12^{ns}	3.44^{ns}	0.27^{ns}	5.14^{ns}	3.22^{ns}	0.30^{ns}	5.17
	50	3.60	0.27	5.09	3.45	0.26	5.07	3.28	0.28	4.65
	100	3.53	0.26	5.51	3.28	0.27	5.29	3.01	0.25	4.88
	150	3.44	0.26	4.91	3.35	0.26	5.08	3.07	0.27	4.40
0.5	0	3.23	0.26	5.46	3.39	0.26	5.08	3.11	0.26	4.95
	50	3.44	0.28	5.52	3.48	0.26	4.87	3.16	0.26	4.59
	100	3.64	0.26	4.96	3.32	0.28	4.82	3.37	0.27	4.74
	150	3.87	0.28	4.64	3.26	0.26	4.93	3.19	0.27	4.56
1.0	0	3.65	0.27	5.08	3.50	0.29	4.79	3.30	0.27	4.89
	50	3.68	0.28	5.07	3.34	0.25	4.82	3.16	0.32	5.22
	100	3.41	0.26	5.20	3.60	0.27	4.58	3.27	0.27	4.64
	150	3.54	0.26	4.35	3.40	0.28	4.66	3.26	0.28	4.60
p-value		0.13	0.59	0.55	0.72	0.51	0.92	0.08	0.30	0.63
0L		3.49^{ns}	0.26^{ns}	5.16^{ns}	3.41^{ns}	0.26^{ns}	5.15^{a}	3.17^{ns}	0.27^{ns}	4.77^{ns}
0.5L		3.54	0.27	5.14	3.36	0.27	4.93^{ab}	3.21	0.26	4.71
1.0L		3.57	0.27	4.92	3.46	0.27	4.71^{b}	3.25	0.29	4.84
p-value		0.77	0.43	0.42	0.53	0.50	0.02	0.58	0.18	0.80
0P		3.43^{ns}	0.26^{ns}	5.22^{a}	3.44^{ns}	0.27^{ns}	5.00^{ns}	3.21^{ns}	0.28^{ns}	5.00^{ns}
50P		3.57	0.27	5.22^{a}	3.43	0.26	4.92	3.23	0.29	4.82
100P		3.52	0.26	5.22^{a}	3.43	0.27	4.90	3.22	0.26	4.75
150P		3.61	0.27	4.63^{b}	3.34	0.26	4.90	3.18	0.28	4.52
p-value		0.48	0.42	0.03	0.68	0.19	0.90	0.92	0.32	0.20
CV (%)		8.4	6.8	11.0	7.0	8.4	8.5	6.2	11.9	11.2

Table 2. Interaction between lime and P fertiliser on NPK concentration in below-ground section (% dry matter).

Lime ($t\ ha^{-1}$)	P-fertiliser ($kg\ ha^{-1}$)	Field 1			Field 2			Field 3		
		N	P	K	N	P	K	N	P	K
0	0	1.83	0.25	1.11^{cd}	1.78^{ns}	0.27^{ns}	1.19^{ns}	1.95^{ns}	0.23^{ab}	1.02^{ns}
	50	1.95	0.28	1.22^{a-d}	1.76	0.26	1.21	1.94	0.21^{ab}	1.08
	100	1.94	0.28	1.41^{a}	1.90	0.30	1.43	1.95	0.21^{ab}	1.09
	150	1.94	0.28	1.28^{abc}	1.47	0.24	1.21	1.87	0.19^{b}	1.00
0.5	0	1.69	0.23	1.14^{bcd}	1.76	0.29	1.49	1.91	0.21^{ab}	1.00
	50	1.93	0.24	1.26^{a-d}	1.74	0.25	1.32	1.90	0.22^{ab}	0.91
	100	1.93	0.24	1.19^{bcd}	1.77	0.26	1.32	1.95	0.26^{a}	1.09
	150	2.00	0.28	1.18^{bcd}	1.73	0.27	1.39	1.94	0.24^{ab}	1.08
1.0	0	2.05	0.26	1.33^{ab}	1.90	0.31	1.50	2.10	0.23^{ab}	1.03
	50	1.89	0.27	1.21^{bcd}	2.04	0.29	1.52	2.03	0.25^{ab}	1.18
	100	1.67	0.26	1.23^{a-d}	1.89	0.30	1.43	1.95	0.24^{ab}	0.96
	150	1.90	0.25	1.08^{d}	1.70	0.27	1.35	2.07	0.24^{ab}	1.02
p-value		0.08	0.16	<0.05	0.37	0..65	0.37	0.62	0.02	0.15
0L		1.91^{ns}	0.27^{ns}	1.25^{ns}	1.73^{ns}	0.27^{ns}	1.26^{b}	1.93^{b}	0.21^{b}	1.05^{ns}

0.5L	1.89	0.25	1.19	1.75	0.27	1.38^{ab}	1.93^{b}	0.23^{ab}	1.02
1.0L	1.88	0.26	1.21	1.89	0.29	1.45^{a}	2.04^{a}	0.24^{a}	1.05
p-value	0.85	0.08	0.44	0.06	0.14	0.03	0.02	<0.01	0.79
0P	1.86^{ns}	0.25^{ns}	1.19^{ns}	1.81^{ab}	0.29^{ns}	1.39^{ns}	1.99^{ns}	0.22^{ns}	1.02^{ns}
50P	1.92	0.26	1.23	1.85^{a}	0.27	1.35	1.96	0.23	1.06
100P	1.85	0.26	1.28	1.85^{a}	0.28	1.39	1.95	0.24	1.05
150P	1.95	0.27	1.18	1.64^{b}	0.26	1.32	1.96	0.22	1.03
p-value	0.51	0.14	0.34	0.03	0.35	0.75	0.89	0.54	0.93
CV (%)	10.1	9.6	11.8	10.9	15.1	14.4	6.2	10.1	13.6

Table 3. Interaction between lime and P fertiliser on nutrient removal (kg/ha).

Lime (t ha^{-1})	P-fertiliser (kg ha^{-1})	Field 1			Field 2			Field 3		
		N	P	K	N	P	K	N	P	K
0	0	22.4^{ns}	2.6^{ns}	21.9^{ns}	43.1^{ns}	5.0^{ns}	46.7^{ns}	56.0^{ns}	6.1^{ns}	52.4^{ns}
	50	27.1	3.0	26.2	56.3	6.2	63.4	62.6	6.5	56.8
	100	31.8	3.7	32.5	55.6	6.6	64.1	69.2	6.8	64.8
	150	29.1	3.4	27.1	47.8	5.8	55.7	61.4	6.0	50.3
0.5	0	27.9	3.2	28.8	51.6	6.2	59.9	46.4	4.6	42.5
	50	34.5	3.7	34.4	48.4	5.4	51.4	63.5	6.5	53.6
	100	31.7	3.3	27.9	52.2	5.8	59.5	65.4	7.4	59.3
	150	37.3	4.1	32.3	56.3	6.4	67.5	73.3	7.8	68.4
1.0	0	29.8	3.3	26.8	73.9	8.5	85.0	62.8	6.4	52.4
	50	32.3	3.9	29.0	61.6	6.5	69.6	81.1	9.3	84.6
	100	32.3	4.0	34.5	76.7	8.4	82.5	77.4	8.3	63.6
	150	33.5	3.6	28.0	70.7	8.1	81.1	77.9	8.2	64.2
p-value		0.69	035	0.31	0.16	0.27	0.26	0.82	0.57	0.39

Appendix 5.1. The effect of treatments and incubation time on soil properties

Table 1. Exchangeable Al^{3+} (cmol (+) kg^{-1})

Treatments	Incubation time (days)			*p*-value
	3	30	60	
Control	1.43 b	1.56 b	1.51 a	0.86
10 t ha^{-1} Local lime (10LL)	1.00 c	0.00 b	0.00 b	-
20 t ha^{-1} Local lime (20LL)	1.00 c	0.00 b	0.00 b	-
30 t ha^{-1} Local lime (30LL)	1.00 c	0.00 b	0.00 b	-
20 t ha^{-1} Agricultural lime (20AL)	1.00 c	0.00 b	0.00 b	-
20 t ha^{-1} Hydrated lime (20HL)	0.00 c	0.00 b	0.00 b	-
6 t ha^{-1} Calcium Super (5CaSup)	0.00 c	0.00 b	0.00 b	-
10 ha^{-1} Calcium Super (10CaSup)	0.00 c	0.00 b	0.00 b	-
5 t ha^{-1} Rice husk biochar (5B)	1.74 ab	1.56 a	1.34 a	0.02
	A	B	B	
10 t ha^{-1} Rice husk biochar (10B)	1.81 ab	1.62 a	1.53 a	0.08
	A	AB	B	
20 t ha^{-1} Rice husk biochar (20B)	1.69 ab	1.40 a	1.56 a	0.32
5 t ha^{-1} Zeolite (5Z)	1.75 ab	1.51 a	1.46 a	0.29
10 t ha^{-1} Zeolite (10Z)	1.86 a	1.52 a	1.46 a	0.00
20 t ha^{-1} Zeolite (20Z)	A	B	B	
	1.83 ab	1.50 a	1.51 a	0.02
	A	B	B	
10 t ha^{-1} Local lime + 10 t ha^{-1} Biochar (10LL+10B)	0.00 c	0.00 b	0.00 b	-
10 t ha^{-1} Local lime + 10 t ha^{-1} zeolite (10LL+10Z)	0.00 c	0.00 b	0.00 b	-
10 t ha^{-1} Local lime + 5 t ha^{-1} iochar + 5 t ha^{-1} zeolite (10LL+5B+5Z)	0.00 c	0.00 b	0.00 b	-
p-value	<0.01	<0.01	<0.01	
CV (%)	19.5	16.7	15.8	

Tukey's method for means comparison; means presenting the same small letters in the same column and same capital letters in the same row are not significantly different at $p \leq 0.05$

Table 2. KCl-Titratable acidity (sum of Al^{3+}+H^{+}) (cmol (+) kg^{-1}).

Treatments	Incubation times (days)			*p*-value
	3	30	60	
Control	2.34 a	2.46 a	2.23 a	0.84
10 t ha^{-1} Local lime (10LL)	0.05 b	0.11 b	0.11 b	<0.01
	B	A	A	
20 t ha^{-1} Local lime (20LL)	0.09 b	0.11 b	0.11 b	0.73
30 t ha^{-1} Local lime (30LL)	0.09 b	0.11 b	0.11 b	0.73
20 t ha^{-1} Agriculture limestone (20AL)	0.09 b	0.11 b	0.11 b	0.74
20 t ha^{-1} Hydrated lime (20HL)	0.09 b	0.11 b	0.11 b	0.74
5 t ha^{-1} Rice husk biochar (5B)	2.70 a	2.42 a	2.04 a	<0.01
	A	A	B	
10 t ha^{-1} Rice husk biochar (10B)	2.76 a	2.36 a	2.11 a	<0.01
	A	B	B	
20 t ha^{-1} Rice husk biochar (20B)	2.66 a	2.25 a	2.17 a	0.13
5 t ha^{-1} Zeolite (5Z)	2.70 a	2.25 a	2.16 a	0.15
10 t ha^{-1} Zeolite (10Z)	2.64 a	2.26 a	2.12 a	0.03

	A	AB	B	
20 t ha^{-1} Zeolite (20Z)	2.70 a A	2.41 a AB	2.17 a B	0.04
10 t ha^{-1} Local lime + 10 t ha^{-1} Biochar (10LL+10B)	0.05 b B	0.11 b A	0.11 b A	<0.01
10 t ha^{-1} Local lime + 10 t ha^{-1} Zeolite (10LL+10Z)	0.05 b B	0.11 b A	0.11 b A	<0.01
10 t ha^{-1} Local lime + 5 t ha^{-1} Biochar + 5 t ha^{-1} Zeolite (10LL+5B+5Z)	0.05 b B	0.11 b A	0.11 b A	<0.01
5 t ha^{-1} Calcium Super (5CaSup)	0.05 b B	0.11 b A	0.11 b A	<0.01
10 t ha^{-1} Calcium Super (10CaSup)	0.05 b B	0.11 b A	0.11 b A	<0.01
p-value	<0.01	<0.01	<0.01	
CV (%)	20.3	13.3	13.8	

Tukey's method for means comparison; means presenting the same small letters in the same column and same capital letters in the same row are not significantly different at $p \leq 0.05$. L=Local Lime, AL=Agriculture Limestone, HL=Hydrated Lime, B=Rice Husk Biochar, Z=Zeolite, CaSup=Calcium Super.

Table 3. The Al:Ca ratio.

Treatments	Incubation time (days)			*p*-value
	3	30	60	
Control	0.66 a	0.44 a	0.42 a	0.31
10 t ha^{-1} Local lime (10LL)	0.0 b	0.0 b	0.0 b	-
20 t ha^{-1} Local lime (20LL)	0.0 b	0.0 b	0.0 b	-
30 t ha^{-1} Local lime (30LL)	0.0 b	0.0 b	0.0 b	-
20 t ha^{-1} Agriculture limestone (20AL)	0.0 b	0.0 b	0.0 b	-
20 t ha^{-1} Hydrated lime (20HL)	0.0 b	0.0 b	0.0 b	-
5 t ha^{-1} Rice husk biochar (5B)	0.79 a A	0.40 a B	0.36 a B	<0.01
10 t ha^{-1} Rice husk biochar (10B)	0.87 a A	0.44 a B	0.42 a B	<0.01
20 t ha^{-1} Rice husk biochar (20B)	0.78 a A	0.38 a B	0.45 a B	<0.01
5 t ha^{-1} Zeolite (5Z)	0.82 a A	0.40 a B	0.40 a B	0.03
10 t ha^{-1} Zeolite (10Z)	0.81 a A	0.42 a B	0.40 a B	<0.01
20 t ha^{-1} Zeolite (20Z)	0.78 a A	0.43 a B	0.38 a B	<0.01
10 t ha^{-1} Local lime + 10 t ha^{-1} Biochar (10LL+10B)	0.0 b	0.0 b	0.0 b	-
10 t ha^{-1} Local lime + 10 t ha^{-1} Zeolite (10LL+10Z)	0.0 b	0.0 b	0.0 b	-
10 t ha^{-1} Local lime + 5 t ha^{-1} Biochar + 5 t ha^{-1} Zeolite (10LL+5B+5Z)	0.0 b	0.0 b	0.0 b	-
5 t ha^{-1} Calcium Super (5CaSup)	0.0 b	0.0 b	0.0 b	-
10 t ha^{-1} Calcium Super (10CaSup)	0.0 b	0.00 b	0.0 b	-
p-value	<0.01	<0.01	<0.01	
CV (%)	40.1	19.4	11.6	

Tukey's method for means comparison; means presenting the same small letters in the same column and same capital letters in the same row are not significantly different at $p \leq 0.05$. LL=Local Lime, AL=Agriculture Limestone, HL=Hydrated Lime, B=Rice Husk Biochar, Z=Zeolite, CaSup=Calcium Super.

Table 4. Exchangeable Mg^{2+} (cmol (+) kg^{-1}).

Treatments	Incubation time (days)			*p*-value
	3	30	60	
Control	0.54 c	0.59 cd	0.57 c	0.12
10 t ha^{-1} Local lime (10LL)	0.56 c	0.55 cd	0.53 c	0.36
20 t ha^{-1} Local lime (20LL)	0.57 c	0.56 cd	0.54 c	0.51
30 t ha^{-1} Local lime (30LL)	0.57 c	0.56 cd	0.53 c	0.12
20 t ha^{-1} Agriculture limestone (20AL)	0.52 c	0.51 d	0.51 c	0.90
20 t ha^{-1} Hydrated lime (20HL)	0.57 c	0.53 cd	0.51 c	0.06*
	A	AB	B	
5 t ha^{-1} Rice husk biochar (5B)	0.55 c	0.57 cd	0.56 c	0.13
10 t ha^{-1} Rice husk biochar (10B)	0.57 c	0.59 cd	0.59 c	0.47
20 t ha^{-1} Rice husk biochar (20B)	0.58 c	0.61 cd	0.59 c	0.29
5 t ha^{-1} Zeolite (5Z)	0.55 c	0.58 cd	0.56 c	0.61
10 t ha^{-1} Zeolite (10Z)	0.55 c	0.57 cd	0.55 c	0.35
20 t ha^{-1} Zeolite (20Z)	0.56 c	0.55 cd	0.59 c	0.24
10 t ha^{-1} Local lime + 10 t ha^{-1} Biochar (10LL+10B)	0.58 c A	0.56 cd A	0.53 c B	0.09
10 t ha^{-1} Local lime + 10 t ha^{-1} Zeolite (10LL+10Z)	0.57 c A	0.56 cd A	0.52 c B	< 0.01
10 t ha^{-1} Local lime + 5 t ha^{-1} Biochar + 5 t ha^{-1} Zeolite (10LL+5B+5Z)	0.58 c A	0.56 cd AB	0.51 c B	0.04
5 t ha^{-1} Calcium Super (5CaSup)	1.75 b B	1.91 b A	1.77 b B	<0.01
10 t ha^{-1} Calcium Super (10CaSup)	2.27 a B	2.75 a A	2.67 a A	0.01
p-value	<0.01	<0.01	<0.01	
CV (%)	5.5	3.5	7.0	

Tukey's method for means comparison; means presenting the same small letters in the same column and same capital letters in the same row are not significantly different at α=5%. L=Local Lime, AL=Agriculture Limestone, HL=Hydrated Lime, B=Rice Husk Biochar, Z=Zeolite, CaSup=Calcium Super.

Table 5. Exchangeable K^{+} (cmol (+) kg^{-1}).

Treatments	Incubation times (days)			*p*-value
	3	30	60	
Control	0.68 ef AB	0.74 a-d A	0.67 a B	0.09*
10 t ha^{-1} Local lime (10LL)	0.67 f AB	0.71 b-e A	0.62 ab B	0.03
20 t ha^{-1} Local lime (20LL)	0.67 f	0.71 b-e	0.64 ab	0.53
30 t ha^{-1} Local lime (30LL)	0.66 f AB	0.71 b-e A	0.59 ab B	0.02
20 t ha^{-1} Agriculture limestone (20AL)	0.68 ef	0.73 b-e	0.56 ab	<0.01
20 t ha^{-1} Hydrated lime (20HL)	A	A	B	
	0.69 def AB	0.73 a-e A	0.60 ab B	0.02
5 t ha^{-1} Rice husk biochar (5B)	0.75 a-d AB	0.79 a-c A	0.72 a B	0.01

10 t ha^{-1} Rice husk biochar (10B)	0.78 ab A	0.79 ab A	0.71 a B	0.06^{*}
20 t ha^{-1} Rice husk biochar (20B)	0.80 a AB	0.84 a A	0.75 a B	<0.01
5 t ha^{-1} Zeolite (5Z)	0.67 f	0.69 c-e	0.60 ab	0.20
10 t ha^{-1} Zeolite (10Z)	0.71 c-f A	0.66 de AB	0.62 ab B	0.10^{*}
20 t ha^{-1} Zeolite (20Z)	0.69 c-f A	0.64 e B	0.63 ab B	<0.01
10 t ha^{-1} Local lime + 10 t ha^{-1} Biochar (10LL+10B)	0.75 abc A	0.76 a-d A	0.65 ab B	0.01
10 t ha^{-1} Local lime + 10 t ha^{-1} Zeolite (10LL+10Z)	0.68 ef A	0.66 de A	0.59 ab A	0.06^{*}
10 t ha^{-1} Local lime + 5 t ha^{-1} Biochar + 5 t ha^{-1} Zeolite (10LL+5B+5Z)	0.73 b-e A	0.73 abc A	0.62 ab B	0.03
5 t ha^{-1} Calcium Super (5CaSup)	0.68 ef A	0.73 b-e A	0.58 ab B	<0.01
10 t ha^{-1} Calcium Super (10CaSup)	0.67 f A	0.70 b-e A	0.46 b B	0.05
p-value	<0.01	<0.01	<0.01	
CV (%)	2.6	4.8	9.6	

Tukey's method for means comparison; means presenting the same small letters in the same column and same capital letters in the same row are not significantly different at α=5%. L=Local Lime, AL=Agriculture Limestone, HL=Hydrated Lime, B=Rice Husk Biochar, Z=Zeolite, CaSup=Calcium Super.

Table 6. Exchangeable Na^{+} (cmol (+) kg^{-1}).

Treatments	Incubation times (days)			*p*-value
	3	30	60	
Control	0.06^{cd}	0.05^{c}	0.06^{c}	
10 t ha^{-1} Local lime (10LL)	0.05^{d}	0.05^{c}	0.07^{c}	
20 t ha^{-1} Local lime (20LL)	0.05^{d}	0.05^{c}	0.04^{c}	
30 t ha^{-1} Local lime (30LL)	0.05^{d}	0.04^{c}	0.07^{c}	
20 t ha^{-1} Agriculture limestone (20AL)	0.09^{cd}	0.05^{c}	0.05^{c}	
20 t ha^{-1} Hydrated lime (20HL)	0.06^{cd}	0.06^{bc}	0.06^{c}	
5 t ha^{-1} Rice husk biochar (5B)	0.06^{cd}	0.06^{bc}	0.07^{c}	
10 t ha^{-1} Rice husk biochar (10B)	0.07^{cd}	0.06^{bc}	0.06^{c}	
20 t ha^{-1} Rice husk biochar (20B)	0.07^{cd}	0.05^{c}	0.06^{c}	
5 t ha^{-1} Zeolite (5Z)	0.12^{cd}	0.09^{bc}	0.13^{bc}	
10 t ha^{-1} Zeolite (10Z)	0.11^{cd}	0.14^{bc}	0.18^{b}	
20 t ha^{-1} Zeolite (20Z)	0.30^{a}	0.22^{a}	0.31^{a}	
10 t ha^{-1} Local lime + 10 t ha^{-1} Biochar (10LL+10B)	0.07^{cd}	0.07^{bc}	0.05^{c}	
10 t ha^{-1} Local lime + 10 t ha^{-1} Zeolite (10LL+10Z)	0.21^{b}	0.11^{bc}	0.18^{b}	
10 t ha^{-1} Local lime + 5 t ha^{-1} Biochar + 5 t ha^{-1} Zeolite (10LL+5B+5Z)	0.13^{c}	0.09^{bc}	0.14^{b}	
5 t ha^{-1} Calcium Super (5CaSup)	0.06^{cd}	0.05^{c}	0.05^{c}	
10 t ha^{-1} Calcium Super (10CaSup)	0.06^{cd}	0.04^{c}	0.04^{c}	
p-value	<0.01	< 0.01	< 0.01	
CV (%)	24.2	34.4	36.0	

Tukey's method for means comparison; means presenting the same letters in the same column are not significantly different at α=5%. L=Local Lime, AL=Agriculture Limestone, HL=Hydrated Lime, B=Rice Husk Biochar, Z=Zeolite, CaSup=Calcium Super.

Appendix 6.1. Insecticide and fungicides sprayers

Plant age (DAP)	Insecticides			Fungicides		
	Brands	Active Ingredients	Rate (ml l^{-1})	Brands	Active Ingredients	Rate (g l^{-1})
20	Sidamethrin 50EC	Sipermetrin	2.0-4.0	Antracol 70WP Folicur 250EC	Propineb Tebuconazole	2.0 0.24
27	Sidamethrin 50EC	Sipermetrin		Antracol 70WP Folicur 250EC	Propineb Tebuconazole	2.0 0.24
35	Prevathon Sidamethrin 50 EC	Chlorantraniliprole 5% Sipermetrin	2.0 2.0-4.0	Antracol 70WP Folicur 250EC	Propineb Tebuconazole	2.0 0.24
42	Endure 120SC	Spinoteram	0.5-1.0	Antracol 70WP Folicur 250EC	Propineb Tebuconazole	2.0 0.24
50	Prevathon Sidamethrin 50EC	Chlorantraniliprole 5% Sipermetrin	2.0 2.0-4.0	Antracol 70WP Folicur 250EC	Propineb Tebuconazole	2.0 0.24
57	Prevathon Sidamethrin 50EC	Chlorantraniliprole 5% Sipermetrin	2.0 2.0-4.0	Antracol 70WP Folicur 250EC	Propineb Tebuconazole	2.0 0.24
63	Prevathon Sidamethrin 50EC	Chlorantraniliprole 5% Sipermetrin	2.0 2.0-4.0	Antracol 70WP Folicur 250EC	Propineb Tebuconazole	2.0 0.24
70	Prevathon Sidamethrin 50EC	Chlorantraniliprole 5% Sipermetrin	2.0 2.0-4.0	Antracol 70WP Folicur 250EC	Propineb Tebuconazole	2.0 0.24
77	Prevathon Sidamethrin 50EC	Chlorantraniliprole 5% Sipermetrin	2.0 2.0-4.0	Antracol 70WP Folicur 250EC	Propineb Tebuconazole	2.0 0.24

Appendix 6.2. Effect of treatments on soil properties

Table 1. The effect of liming materials and fertilisers on soil pH, exchangeable Al and KCl-titratable acidity (0-20 cm soil depth).

Treatments	pH	Al^{3+*}	H^{+*}	KCl-Titratable acidity
			(cmol (+) kg^{-1})	
T1=0L+0P+200N (Control)	4.12^{c}	1.93^{a}	0.97^{ns}	2.90^{a}
T2=0L+60P+200N	4.11^{c}	1.94^{a}	0.89	2.83^{a}
T3=0L+120P+200N	4.20^{c}	1.37^{ab}	0.78	2.15^{ab}
T4=1L+120P+200N	4.36^{c}	1.36^{ab}	0.45	1.81^{b}
T5=2L+120P+200N	4.55^{bc}	1.03^{a-d}	0.34	1.37^{a-e}
T6=4L+120P+200N	4.74^{abc}	0.44^{bcd}	0.43	0.87^{b-e}
T7=8L+0P+200N	5.24^{ab}	0.32^{cd}	0.13	0.44^{e}
T8=8L+60P+200N	5.38^{a}	0.31^{cd}	0.22	0.44^{e}
T9=8L+120P+200N	5.53^{a}	0.20^{d}	0.21	0.41^{e}
T10=0.25CaSup+120P+200N	4.38^{c}	1.87^{a}	0.92	2.79^{a}
T11=0.5CaSup+120P+200N	4.41^{c}	1.35^{abc}	0.34	1.69^{a-d}
T12=1.0CaSup+0P+200N	4.48^{bc}	1.02^{a-d}	0.28	1.30^{b-e}
T13=1.0CaSup+60P+200N	4.49^{bc}	1.17^{a-d}	0.43	1.60^{a-d}
T14=1.0CaSup+120P+200N	4.50^{bc}	1.30^{abc}	0.43	1.73^{a-d}
T15=0L+0P+0N (Nil-N Control)	4.33^{c}	1.43^{ab}	0.51	1.94^{abc}
T16=1.0CaSup+120P+0N	4.47^{bc}	1.00^{a-d}	0.37	1.37^{a-e}
T17=1.0CaSup+120P+150N	4.49^{bc}	1.30^{abc}	0.58	1.88^{abc}
T18=1.0CaSup+120P+250N	4.40^{c}	1.16^{abc}	0.44	1.60^{a-d}
p-value				
CV (%)	6.3	13.5	16.5	14.0

CV=Coefficient of Variance; ns=not significance; Tukey's method for means comparison; means presenting the same letters in the same column are not significantly different at α=5%. * for statistical analysis purpose, the data was transformed with $\sqrt{\alpha+0.5}$.

Table 2. The effect of liming materials and fertilisers on Ca^{2+}, Mg^{2+}, total base cations (TBC), cation exchange capacity (CEC), base saturation (BS) and Al:Ca ratio.

Treatments	Ca^{2+}	Mg^{2+*}	TBC*	CEC	BS	Al:Ca
		(cmol (+) kg^{-1})			(%)	
T1=0L+0P+200N (Control)	2.59^{c}	0.562^{c}	4.10^{d}	14.21^{b-e}	29^{d}	0.80^{a}
T2=0L+60P+200N	2.49^{c}	0.642^{bc}	4.05^{d}	15.09^{abc}	27^{d}	0.80^{a}
T3=0L+120P+200N	3.23^{c}	0.783^{abc}	4.93^{cd}	13.66^{de}	36^{d}	0.38^{a-e}
T4=1L+120P+200N	4.25^{bc}	0.780^{abc}	5.91^{bcd}	14.73^{a-e}	40^{cd}	0.32^{c-f}
T5=2L+120P+200N	4.47^{bc}	0.680^{abc}	5.93^{bcd}	14.12^{b-e}	42^{bcd}	0.25^{c-f}
T6=4L+120P+200N	5.97^{abc}	0.716^{abc}	7.88^{abc}	14.45^{a-e}	55^{a-d}	0.07^{def}
T7=8L+0P+200N	8.36^{ab}	0.647^{bc}	9.78^{ab}	14.37^{a-e}	68^{abc}	0.11^{ef}
T8=8L+60P+200N	9.40^{a}	0.676^{bc}	10.92^{a}	14.95^{a-d}	73^{ab}	0.04^{ef}
T9=8L+120P+200N	10.12^{a}	0.697^{abc}	11.58^{a}	15.40^{ab}	76^{a}	0.01^{f}
T10=0.25CaSup+120P+200N	2.63^{c}	0.660^{bc}	4.08^{d}	15.69^{a}	26^{d}	0.75^{ab}
T11=0.5CaSup+120P+200N	3.47^{c}	0.903^{abc}	5.12^{cd}	13.90^{c-e}	37^{cd}	0.40^{a-d}
T12=1CaSup+0P+200N	3.95^{c}	1.021^{ab}	6.01^{bcd}	13.51^{e}	45^{a-d}	0.27^{c-f}
T13=1CaSup+60P+200N	3.46^{c}	1.098^{a}	5.77^{bcd}	14.09^{b-e}	41^{cd}	0.35^{b-f}
T14=1CaSup+120P+200N	3.53^{c}	1.007^{abc}	5.43^{bcd}	13.43^{e}	40^{cd}	0.39^{a-d}
T15=0L+0P+0N (Nil-N Control)	2.85^{c}	0.782^{abc}	4.71^{cd}	14.02^{c-e}	34^{d}	0.50^{ab}

T16=1CaSup+120P+0N	3.64^{c}	1.050^{ab}	5.84^{bcd}	14.16$^{b\text{-}e}$	41^{cd}	0.32$^{c\text{-}f}$
T17=1CaSup+120P+150N	3.81^{c}	1.020^{ab}	5.74^{bcd}	14.08$^{a\text{-}e}$	41^{cd}	0.36$^{b\text{-}e}$
T18=1CaSup+120P+250N	3.23^{c}	1.017^{ab}	5.52^{bcd}	14.90$^{a\text{-}d}$	37^{cd}	0.36$^{b\text{-}e}$
CV (%)	13.3	21.4	10.42	3.60	28.0	8.6

Total base cations (TBC) = Ca^{2+}+Mg^{2+}+K^{+}+Na^{+}, base saturation (BS)=TBC/CEC x 100%, CV=Coefficient of Variance; ns=not significance; Tukey's method for means comparison; means presenting the same letters in the same column are not significantly different at α=5%;*=α=10%.

Table 3. The effect of liming materials and fertiliser on soil available -P (Bray1-P).

Treatments	Bray 1-P (mg P kg^{-1})
T1=0L+0P+200N (Control)	9.8 bc
T2=0L+60P+200N	16.7 abc
T3=0L+120P+200N	21.0 ab
T4=1L+120P+200N	27.0 a
T5=2L+120P+200N	23.7 a
T6=4L+120P+200N	24.8 a
T7=8L+0P+200N	8.5 bc
T8=8L+60P+200N	18.8 abc
T9=8L+120P+200N	22.2 ab
T10=0.25CaSup+120P+200N	28.33 a
T11=0.5CaSup+120P+200N	25.70 a
T12=1.0CaSup+0P+200N	10.0 bc
T13=1.0CaSup+60P+200N	16.2 abc
T14=1.0CaSup+120P+200N	21.2 abc
T15=0L+0P+0N (Nil-N Control)	6.68 c
T16=1.0CaSup+120P+0N	29.00 a
T17=1.0CaSup+120P+150N	24.12 a
T18=1.0CaSup+120P+250N	25.07 a
CV (%)	26.5

CV=Coefficient of Variance; ns=not significance; Tukey's method for means comparison; means presenting the same letters in the same column are not significantly different at α=5%.

Appendix 6.3. The effect of liming materials and fertilisers on shoot length (cm).

Treatment	21 DAP	42 DAP	63 DAP
T1=0L+0P+200N (control)	14.8 b	18.4 e	16.4 e
T2=0L+60P+200N	15.3 ab	19.1 de	17.7 de
T3=0L+120P+200N	16.2 ab	21.4 a-e	21.2 a-e
T4=1L+120P+200N	17.0 ab	22.4 a-d	22.7 a-d
T5=2L+120P+200N	16.6 ab	22.6 a-d	21.8 a-e
T6=4L+120P+200N	16.8 ab	24.1 ab	24.0 ab
T7=8L+0P+200N	17.2 ab	23.1 a-d	21.8 a-d
T8=8L+60P+200N	16.9 ab	24.1 ab	24.8 ab
T9=8L+120P+200N	17.3 a	25.1 a	25.9 a
T10=0.25CaSup+120P+200N	15.9 ab	21.1 b-e	21.0 a-e
T11=0.5CaSup+120P+200N	15.6 ab	21.4 a-e	19.8 b-e
T12=1.0CaSup+0P+200N	16.1 ab	21.8 a-e	20.5 b-e
T13=1.0CaSup+60P+200N	16.5 ab	23.0 a-d	24.2 ab
T14=1.0CaSup+120P+200N	16.3 ab	21.6 a-e	21.3 a-e
T15=0L+0P+0N (Nil-N Control)	16.3 ab	19.9 c-e	17.4 de
T16=1.0CaSup+120P+0N	16.2 ab	21.7 a-e	19.7 b-e
T17=1.0CaSup+120P+150N	16.2 ab	22.9 a-d	23.7 abc
T18=1.0CaSup+120P+250N	15.8 ab	23.3 abc	24.1 ab
CV (%)	5.7	6.7	10.6

DAP=days after planting; CV=Coefficient Variance; ns=not significance; Tukey's method for means comparison; means presenting the same letters in the same column are not significantly different at α=5%.

Appendix 6.4. The effect of liming materials and fertilisers on shallot dry weight at 56 DAP.

Treatment	Roots*	Bulbs	Above ground (Stems+Leaves)	Total
T1=0L+0P+200N (Control)	0.15ab	2.03 d	0.45 e	2.63 e
T2=0L+60P+200N	0.17 ab	2.66 bcd	0.54 de	3.37 cde
T3=0L+120P+200N	0.18 ab	3.07 a-d	0.87 b-e	4.12 a-e
T4=1L+120P+200N	0.23 ab	3.98 a	1.27 abc	5.49 a-d
T5=2L+120P+200N	0.22 ab	3.95 ab	1.26 abc	5.42 ab
T6=4L+120P+200N	0.25 ab	3.44 abc	1.28 abc	4.97 abc
T7=8L+0P+200N	0.24 ab	3.67 abc	1.28 abc	5.19 ab
T8=8L+60P+200N	0.27 a	3.98 a	1.35 ab	5.60a
T9=8L+120P+200N	0.27 a	3.77 abc	1.46 a	5.50 ab
T10=0.25CaSup+120P+200N	0.19 ab	3.43 abc	1.01 a-e	4.62 a-d
T11=0.5CaSup+120P+200N	0.18 ab	3.35 abc	0.95 a-e	4.49 a-d
T12=1.0CaSup+0P+200N	0.19 ab	3.32 a-d	0.95 a-e	4.46 a-d
T13=1.0CaSup+60P+200N	0.28 a	3.50 abc	1.05 a-d	4.83 a-e
T14=1.0CaSup+120P+200N	0.25 ab	3.32 a-d	1.07 a-d	4.64 a-d
T15=0L+0P+0N (Nil-N Control)	0.12 b	2.57 cd	0.52 de	3.21 de
T16=1.0CaSup+120P+0N	0.26 ab	2.81 a-d	0.74 cde	3.81 b-e
T17=1.0CaSup+120P+150N	0.25 ab	3.71 abc	1.02 a-e	4.97 abc
T18=1.0CaSup+120P+250N	0.26 ab	3.75 abc	1.08 a-d	5.10 ab
CV (%)	0.7	5.9	2.6	7.8

CV=Coefficient Variance; ns=not significance; Tukey's method for means comparison; means presenting the same letters are not significantly different at α=5%. * α=10%.

Appendix 6.5. The effect of liming materials and fertilisers on nutrient uptake at 56 DAP.

Treatment	Below ground (mg/plant)					Above ground (mg/plant)				
	N	P	K	Ca	Al	N	P	K	Ca	Al
T1=0L+0P+200N (control)	3.20 bcd	0.34 fg	2.18 c	0.61 g	7.59 ab*	1.10 f	0.09 e	1.57 f	0.46 h	6.67 d-g
T2=0L+60P+200N	2.42 d	0.18 g	2.32 c	0.65 g	7.77 ab	1.38 def	0.10 e	1.93 ef	0.65 gh	4.65 g
T3=0L+120P+200N	2.63 cd	0.20 g	2.63 bc	0.91 efg	6.67 ab	2.55 a-e	0.17 cde	3.16 c-f	1.03 e-h	5.94 efg
T4=1L+120P+200N	4.33 abc	0.39 ef	3.84 ab	1.53 a-d	9.10 ab	3.66 ab	0.27 abc	5.74 ab	2.16 bcd	12.18 abc
T5=2L+120P+200N	4.37 abc	0.41 c-f	4.20 a	1.65 ab	6.90 ab	3.41 ab	0.24 a-d	5.03 a-d	2.25 bcd	10.97 a-e
T6=4L+120P+200N	4.26 abc	0.40 def	3.78 ab	1.50 a-d	8.98 ab	3.63 ab	0.29 abc	5.52 abc	2.39 a-d	13.15 ab
T7=8L+0P+200N	4.30 abc	0.35 efg	3.86 ab	1.64 abc	6.93 ab	3.25 ab	0.26 abc	5.42 a-d	2.70 abc	12.14 abc
T8=8L+60P+200N	4.89 ab	0.41 c-f	4.13 a	1.76 a	6.23 ab	3.61 ab	0.31 ab	5.64 ab	2.99 ab	10.67 a-e
T9=8L+120P+200N	5.50 a	0.66 a	3.89 ab	1.51 a-d	6.14 ab	3.72 a	0.34 a	6.47 a	3.39 a	14.64 a
T10=0.25CaSup+120P+200N	5.32 a	0.58 abc	3.33 abc	0.99 e-g	6.62 ab	2.24 b-f	0.21 b-e	4.39 a-d	2.00 b-e	9.54 a-g
T11=0.5CaSup+120P+200N	4.92 ab	0.51 a-e	3.03 abc	0.94 e-g	9.84 ab	2.56 a-e	0.19 b-e	3.75 b-f	1.73 c-f	11.35 a-d
T12=1.0CaSup+0P+200N	5.16 a	0.50 a-f	2.97 abc	1.04 d-g	6.87 ab	2.49 a-f	0.18 c-e	4.1 a-e	1.63 d-g	7.86 c-g
T13=1.0CaSup+60P+200N	5.96 a	0.58 abc	3.92 ab	1.20 b-e	6.29 ab	2.93 abc	0.20 b-e	5.24 a-d	1.83 cde	10.07 a-f
T14=1.0CaSup+120P+200N	4.64 ab	0.48 b-f	3.33 abc	1.15 c-f	8.09 ab	2.78 a-d	0.20 b-e	4.72 a-d	2.00 b-e	6.48 d-g
T15=0L+0P+0N (zero treatment)	3.33 bcd	0.38 ef	2.28 c	0.68 fg	5.80 b	1.14 ef	0.12 de	1.90 ef	0.68 fgh	5.01 fg
T16=1.0CaSup+120P+0N	4.67 ab	0.46 c-f	2.91 abc	1.07 d-g	10.26 a	1.62 c-f	0.19 b-e	3.04 def	1.02 e-h	5.47 fg
T17=1.0CaSup+120P+150N	5.83 a	0.56 a-d	3.92 ab	1.18 b-e	8.48 ab	2.69 a-d	0.20 b-e	4.34 a-e	1.61 d-g	9.19 b-g
T18=1.0CaSup+120P+250N	5.90 a	0.65 ab	4.401 a	1.18 b-e	9.92 ab	2.64 a-d	0.23 a-d	4.77 a-d	1.81 cde	9.95 a-f
CV (%)	8.05	0.8	6.1	2.3	21.0	2.6	0.6	11.1	4.8	23.3

CV=Coefficient Variance; ns=not significance; Tukey's method for means comparison; means presenting the same letters in the same column are not significantly different at α=5%.

Appendix 6.6. The effect of liming materials and fertilisers on fresh bulb yield (g m^{-2} and t ha^{1}).

Treatments	Fresh bulb yield (g m^{-2})	Fresh bulb yield (t ha^{-1})*
T1=0L+0P+200N (control)	443.5 f	3.10 g
T2=0L+60P+200N	575.3 def	4.03 efg
T3=0L+120P+200N	698.8 a-e	4.89 a-f
T4=1L+120P+200N	788.0 a-d	5.51 a-d
T5=2L+120P+200N	741.0 a-e	5.79 abc
T6=4L+120P+200N	888.8 a	6.22 a
T7=8L+0P+200N	798.0 abc	5.54 a-d
T8=8L+60P+200N	791.8 a-d	5.79 a-d
T9=8L+120P+200N	911.25 a	6.39 a
T10=0.25CaSup+120P+200N	591.8 cde	4.14 cde
T11=0.5CaSup+120P+200N	663.5 b-e	4.64 b-e
T12=1CaSup+0P+200N	655.0 b-f	4.59 b-f
T13=1CaSup+60P+200N	833.3 ab	3.08 ab
T14=1CaSup+120P+200N	741.8 a-e	5.19 a-f
T15=0L+0P+0N (zero treatment)	540.3 ef	3.78 fg
T16=1CaSup+120P+0N	636.8 b-f	4.46 b-f
T17=1CaSup+120P+150N	756.25 a-e	5.29 a-e
T18=1CaSup+120P+250N	766.3 a-d	5.13 a-d
CV (%)	11.8	11.8

CV=Coefficient Variance; ns=not significance; Tukey's method for means comparison; means presenting the same letters in the same column are not significantly different at α=5%.*70% land use efficiency.

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