GROWTH AND YIELD RESPONSE OF POTATO (*Solanum tuberosum* L.) VARIETIES TO DIFFERENT LIME APPLICATION RATES AT EZHA DISTRICT, GURAGE ZONE, CENTRAL ETHIOPIA

MSc THESIS

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MAY, 2024

WOLKITE, ETHIOPIA

Wolkite University

School of Graduate Studies

Growth and Yield Response of Potato (*Solanum tuberosum* L.) Varieties to Different Lime Application Rates at Ezha District, Gurage Zone, Central Ethiopia

A Thesis Submitted to School of Graduate Studies, in Partial Fulfillment of the Requirements for the Degree of Master of Science in Horticulture

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As Thesis research advisor, we hereby certify that we have read and evaluated this thesis prepared under our guidance by Melis Mare Gebremariam **"Growth and Yield Response of Potato (*Solanum tuberosum* L.) Varieties to Different Lime Application Rates at Ezha District, Gurage Zone, Central Ethiopia"** and we recommend that it shall be submitted as fulfilling the MSc thesis requirement in Horticulture.

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DEDICATION

Kindly, I dedicate this work to my family for all their contributions and untold- enormous effort in my life journey and academic success.

STATEMENT OF THE AUTHOR

By my signature below, I declare and affirm that this thesis work is my work. I have followed all ethical principles in the preparation, data collection, data analysis, and completion of the entire thesis work. All scholarly matter that is included in the thesis has been given recognition through citation. I strongly confirm that I have cited in the body and referenced all sources used in this document. Every serious effort has been made to avoid any plagiarism in the preparation of this thesis.

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BIOGRAPHICAL SKETCH

The author, Melis Mare Gebremariam, was born at Gedeb Kebele in 1994 in Ezha District, Gurage Zone, Central Ethiopia, from his father, Mr. Mare Gebremariam, and his mother, Miss Atsede Wabi. He attended elementary school at Fessa Adventist primary school, secondary school at Kotter Gedra general secondary school, and preparatory school at Agena town secondary preparatory school. The author joined Wolaita Sodo University from 2013–2015 and graduated with a BSc. degree in plant science in 2015. He was employed in the office of the Ezha district Agricultural office worked there from the year 2015 to 2019 as rural entrepreneurship expert and from 2019 to 2020 as Agricultural extension then after in 2021, he joined the postgraduate program at Wolkite University, department of horticulture, to pursue his studies for the degree of Master of Science in Horticulture.

ACKNOWLEDGEMENT

Firstly, I feel great pleasure to place on record my deep sense of appreciation and heartfelt thanks to my major advisor Dereje Dejene (Asst. Prof.), and co-advisor Berhanu Tsegaye (Asst. Prof.) for their keen interest and enthusiasm, tireless supervision, encouragement, constructive comments, suggestions, and support from the initial stage of the proposal development to the final thesis report write-up, without which the successful completions of this thesis work would have been unimaginable. Secondly, I sincerely thank the contribution received from all academic staff at Wolkite University College of Agricultural and Natural Resources, particularly the Department of Horticulture, during my academic journey.

Thirdly, I shall also express my sincere thanks to the Ezha District Administration and Agriculture offices for their financial support, and I shall also express my special thanks to the Ezha District Science and Technology Office for its access to free broadband internet service. I also need to realize my beloved family and parents: Mr. Mare Gebremariam, Mrs. Atsede Wabi, Mrs. Zenbech Siba (for the gift of the experimental site), and my sisters and brothers.

Lastly, I need to say thank you to my friends (Desalegn Kebede, Alemu Wegu, Mihret Degif, Dino Nasir and others), staff members, teachers, and colleagues for their support and encouragement.

ABBREVIATIONS AND ACRONYMS

ANOVA	Analysis of Variance
ATA	Agricultural transformation agency
CEC	Cation Exchange Capacity
CIP	International Potato Center
CSA	Central Statistics Agency
EDAO	Ezha District Agricultural Office
EDTA	Ethylene Diaminetetraacetic Acid
EIAR	Ethiopian Institute of Agricultural Research
FAO	Food and Agricultural Organization
FAOSTAT	Food and Agricultural Organization of the United Nation Statistics
FMANR	Federal Ministry of Agriculture and Natural Resources
LR	Lime Requirement
LSD	Least Significant Difference
Masl	Meters Above Sea Level
MoA	Ministry of Agriculture
NB	Net Benefit
pH	Soil Reaction
RCBD	Randomized, Complete Block Design
SAS	Statistical Analysis System
TN	Total Nitrogen
TVC	Total Variable Cost
USDANRCS	United States Department of Agriculture, Natural Resources Conservation Services

TABLE OF CONTENT

LIST OF TABLES

LIST OF FIGURES

LIST OF TABLES IN THE APPENDIX

LIST OF FIGURES IN THE APPENDIX

Growth and Yield Response of Potato (*Solanum tuberosum* L.) Varieties to Different Lime Application Rates at Ezha District, Gurage Zone, Central Ethiopia

ABSTRACT

Potato is the most important tuber crop for attaining the food security and providing an economic return to growers and the country. However, production and productivity are far below the global average. This is mainly due to poor soil acidity management and a lack of high-yielding adaptable varieties to acid soil. Thus, a field experiment was conducted to evaluate the effect of lime rates on the growth and yield of potato varieties and to determine economically feasible rates of lime for better tuber yield. The experiment was conducted in Ezha district during the 2022 main cropping season. The treatments consisted of factorial combinations of three improved potato varieties (Gudene, Belete, and Dagim) and five lime rates (0.0, 1.5, 3.0, 4.5, and 6.0 t ha^{-1}) laid out in a Randomized Complete Block Design with three replications. Data were collected on phenological, growth and yield parameters and analyzed using SAS (software version 9.3). Liming raises soil pH (5.10 to 6.5), CEC (36.0 to 47.0 Cmol (+) kg^{-1}), Av. P (2.08 to 4.6 mg kg^{-1}), base saturation (28.33 to 77.39%), Ca (7 to 29 Cmol (+) kg^{-1}), and Mg (2 to7Cmol (+) kg^{-1}) contents, but reduces aluminum (1.27 to 0.0 ppm and hydrogen ion (1.53 to 0.4 ppm) concentrations in acidic soils. The results of this experiment showed that the interaction between lime rates and varieties significantly influenced most growth and yield parameters of potatoes. As a result, the highest percentage (13.19%) of small-sized tubers was recorded from Gudene with 0.0 t ha^{-1} lime application rate. Similarly, the highest stem number (7.36), percentage of medium-sized potato tubers (44.88%), and the highest plant height (70.96 cm) were obtained from the Gudene variety with lime rates of 6, 1.5, and 6 t ha^{-1}, respectively. The combined effects of the 4.5 t ha^{-1} lime rate and Belete variety resulted in the potato's relatively high average tuber weight (93.29g). The highest leaf area index (1.53), the highest number of marketable tubers (12.57), and the largest number of total tubers (14.66) were obtained from a variety Belete interacted with 6 t ha^{-1} lime treatment combinations. The maximum unmarketable tuber yield (3.5 t ha^{-1}) was obtained from the Dagim variety with 0.0 t ha^{-1} lime rate. The highest percentage of large-size tubers (81.32%) resulted from the Dagim variety with a lime rate of 6 t ha^{-1}. Statistically the highest marketable tuber yield (46.42 t ha^{-1} and 47.38 t ha^{-1}) and total tuber yield (47.82 t ha^{-1} and 49.12 t ha^{-1}) were obtained from the interaction of variety Belete with 4.5 t ha^{-1} and 6 t ha^{-1}, respectively. The partial budget analysis revealed that the combined application of variety Belete with 4.5 t ha^{-1}lime application rate resulted in the highest net benefit (465,259 Eth Birr ha^{-1}) with an acceptable marginal rate of return (3063.41%) which can be provisionally recommended for small-scale potato producers (farmers) at the study area. However, further research would have to be repeated to get the best conclusive result and a sound full recommendation for a specific area.

Keywords/phrases: *lime rates, potato varieties, soil acidity, tuber yield*

1. INTRODUCTION

Potato (*Solanum tuberosum* L.) belongs to the Solanaceae family and the genus *Solanum (Reddy et al, 2018)*. It originated in the Andes of South America and was initially cultivated near the border of Peru and Bolivia (Mitiku *et al*., 2019). It was introduced to Ethiopia 163 years ago, in 1858, by the German botanist Schimper (Birtukan Belachew, 2016). Its Production has gradually increased from high-land garden lands to field crop status in high-land and mid-land under both irrigated and rain-fed production systems (Egata Shunka, 2021).

Global potato production is estimated at 370.4 million tons from approximately 17.34 million hectares and in Africa producing 26.53 million tons from approximately 1.76 million hectares of land (Jovovic *et al*., 2021). Simultaneously, on a global scale, there was a production volume of 368 million metric tons annually from an estimated area of 17.58 million hectares (Egata Shunka, 2021). Over a century and two decades, potatoes in Ethiopia grew from a garden crop in a few regions to a staple crop produced in many regions and under different agro-ecological conditions (Egata Shunka *et al*., 2019). The area coverage under potatoes increased from 62,000 to 296,000 hectares, and production increased from 0.5 to 3.6 million tons from 2006 to 2016 (Gebremedhin W/Giorgis *et al*., 2015; CSA, 2016).

The Central, Southern, Southeastern, Southwestern, and Northwestern parts of the country have the highest potential for potato production, with altitudes ranging from 1500 to 3000 m and rainfall ranging from 600 to 1200 mm (Damtew Abewoy *et al.*, 2022). Although Ethiopia has suitable environmental, climatic, and edaphic conditions and several improved potato varieties with a huge potential to produce high potato yields (Habtamu Gebreselassie *et al*., 2016), however, currently productivity of potatoes is very low (13.28 t ha^{-1}) as compared to world average 21.77 t ha^{-1} (Damtew Girma, 2023). Many factors that have been identified as causes of low yield, among which are the lack of proper nutrient management, low potential yielding of pre-existing potato varieties, soils that are highly depleted of essential inherent nutrients, and soil acidity problems (Egata Shunka *et al*., 2019). About 70% of Ethiopian cultivated agricultural land is suitable for potato production (Gebremedhin W/Giorgis, 2008). Since potatoes are grown from mid-altitudes to very high mountain tops and from humid to dry areas in the country, productivity improvements will require the development of varieties best adapted to a wide range of environments (Kolech *et al*., 2015).

Potato is one of the most vital vegetable crops and the world's fourth most important crop, following rice, wheat, and maize, and has historically contributed to global food and nutrition security (Damtew Abewoy *et al*., 2022); and the first among root and tuber crops in volume produced and consumed followed by Cassava, Sweet potato and Yam (FAOSTAT, 2019). It is a really important food item crop in Ethiopia, especially within the highland and mid-mid altitude areas (Afewok Solomon *et al*., 2023). It also produces more food per time, area, and other resources than most major crops (Egata Shunka *et al*., 2019). In the last few years, potatoes have continued to grow rapidly in importance for food security and income generation (CSA, 2016).

Soil acidity is a severe threat to crop production in much of Ethiopia's highlands in general and in central Ethiopia in particular. Soil acidity is a major issue in the central Ethiopia highlands of Hadya, and Guragie (Sosena Amsalu and Sheleme Beyene, 2020). Soil acidity is a complex of numerous factors involving nutrient deficiencies and toxicities, low activities of beneficial microorganisms, and reduced plant root growth, which limits the absorption of nutrients and water (Tolossa Ameyu, 2019) and (Sultana *et al*., 2019). The maintenance of soil reaction (pH) at a value optimal for optimizing potato production is a critical step in soil management because soil pH impacts soil characteristics, nutrient availability, and plant nutrition (Egata Shunka *et al*., 2019).

Liming is the application of calcium and magnesium-rich minerals to the soil in various forms, such as chalk, limestone, or hydrated lime. It is a favorable approach when the soil is severely acidic and multi-cropping with acid-sensitive crops is used. In its purest form, lime is primarily composed of calcium (Ca). Because calcium carbonate is a basic and can neutralize acids. Whenever lime is applied to the soil, Calcium and Magnesium ions (Ca^{2+} and Mg^{2+}) displace H^+, Fe^{2+}, Al^{3+}, Mn^{4+}, and Cu^{2+} ions from soil adsorption (bound) sites, raising the soil's pH level. Lime, in addition to improving soil pH, provides large amounts of Ca and Mg, depending on the type of liming materials used. The application of lime in addition to fertilizer, particularly phosphorus, is required for the most efficient crop production on acid soils (Tolossa Ameyu, 2019). Lalljee and Sunita, (2001) also reported that, lime raises soil pH (soil reaction), base saturation, Calcium, and Magnesium contents, but reduces aluminum (Al) concentration in acidic soils.

About 40% of the arable land in Ethiopia is currently covered by acidic soils ($pH < 5.5$), and the problem of soil acidity has been increasing in the country (ATA, 2014). Therefore, soil acidity is a serious concern calling for urgent consideration in most Ethiopian highlands because of its impact on crop yields and soil fertility (Aliyu Nesru *et al.*, 2023). On acidic soils, potatoes have been proven to respond to lime addition. Liming is recommended for soils with a pH of 5.5 or lowers (Sultana *et al.*, 2019). Generally, several practices have been recommended to reclaim soil acidity and enhance the productivity of strongly acidic soils. These include the cultivation of acid-tolerant plants, the use of organic fertilizers, and liming. Of these practices, liming is considered the best measure because its effect is more persistent (Mijangos, 2010). Application of lime at an appropriate rate brings several chemical and biological changes to the soils that are beneficial in improving crop yields on acid soils. But too much application of lime can decrease the availability of phosphorus (P), Iron (Fe), Manganese (Mn), Zinc (Zn), Copper (Cu), and Boron (B) sufficiently to cause deficiencies of those plant nutrients and structure deterioration. Thus, the proportional application of lime to acidic soil brings soil pH to an expected value is essential for maintaining soil health and improving crop productivity (Sultana *et al.*, 2019). However, in the study area, no study has been done on the growth and yield response of potato (*Solanum tuberosum* L.) varieties to different lime application rates.

Therefore, this study was conducted to meet the following objectives:

General objective

To evaluate the interaction effect of lime rates and varieties on the growth and yield response of potatoes in Ezha district, Central Ethiopia.

Specific objectives

1. To determine the effect of lime rates on the growth and yield of potato
2. To determine economically feasible rates of lime for better tuber yield

2. LITERATURE REVIEW

2.1. Origin and Distribution of Potato

Potato plants originated in tropical areas of high altitude in the Andes Mountains in South America, where potato tubers were utilized as early as 8000 years ago (Mitiku *et al*., 2019). As cited by (Camire *et al*., 2009), around 1570 or the late sixteenth century, potatoes were introduced and expanded into Europe by Spanish explorers, initially as a decorative plant and later also for consumption. The crop is grown throughout the world but is of particular importance in temperate climates. Potatoes are cultivated in about 160 countries around the world and consumed every day by over a billion people (Bishwoyog and Swarnima, 2016).In world production, it is an important agricultural plant, not only on account of its consumer importance but also for its industrial and fodder significance (Bishwoyog and Swarnima, 2016).

2.2. Environmental and Cultural Requirements of Potato Crop

Potatoes prefer a cool climate for growth and development. The best-suited altitudes ranged between 1500 and 2800 m.a.s.l. However, for healthy tuber production, particularly for planting purposes, it should be strictly cultivated in high-altitude areas. For high yields, the total crop water requirements are about 500 to 700 mm (MoA, 2011).

A temperature ranging from 15 to 25℃ is ideal for potato tuber development. At higher temperatures, the plant fails to initiate tuber formation and at low temperatures, vegetative growth is restricted by frost (FAO, 2010). The number of tubers produced per plant is higher at lower than at higher temperature. The seed tubers produced at higher temperatures 34℃ are low yielding compared to seed tubers produced at cooler temperatures 7.7℃ (Yean *et al*., *2017*).

Deficiency of rainfall or its uneven distribution is the cause of inhibition of plant development, which affects the yield and its structure, and mainly the lower share of marketable tubers. The potato plant has different water needs during the growing season especially most water needs during tuber formation (Zarzyńska *et al*., 2023)

Liming can ameliorate undesirable, low pH values although care must be taken to ensure that the lime is applied 6 months before the potatoes are to be planted (EARO, 2004).

Potatoes are more prone to common scab when grown in high pH soils. In Ethiopia, the ideal soil type is deep and well drained with a silt loam or sandy loam texture. It should be slightly acidic, with loose and friable structure (EARO, 2004). Lack of nutrients results in retarded growth processes and reduced yield. A potato crop removes nutrients from the soil and replacement is necessary to maintain soil fertility. Among limiting factors for potato production, such as high temperatures, short day length, low light intensity and poor physical and chemical soil conditions, to a great proportion different levels of fertilizer application are responsible for these yield variations. In many cases, application of nutrients, increases yield (Vander, 1981).

Very shallow planting of seed tubers may result in scarcity of soil moisture around the seed piece and in the production of tubers so close to the soil surface that greening caused by exposure to light is a problem. On the other hand, planting too deep will slow tubers to emerge and may be more susceptible to attack by various diseases. As a result, appropriate planting depth should be deeper on lighter soils than on heavy soils (Alexander *et al*., 2001).

2.3. Importance and Production of Potato in Ethiopia

Potato is produced twice a year. The bulk production is during *Belg* (a short rain season, March–June) season, whereas small production takes place during the *Meher* season (a long rain season, July–October) in southern Ethiopia. (Abite Seyifu, 2014) The total area under potato cultivation in 2016/2017 (2009) in Ethiopia is about 66,923.33 ha with an average productivity of 13.768 ton/ha (CSA, 2017)

It is a member of the *nightshade family (Solanaceae)* and is a world-popular food crop and the most important vegetable crop in relation to amounts produced and consumed worldwide (FAO, 2010). Potato takes the fourth rank next to wheat, rice and maize in world production for human consumption. Potatoes provide nutritious food and widely adopted crops and can grow in a diversity of environments; as a result they take advantage of food for the increasing world population, and have the potential for increased vitamin C and protein content. Potato tubers give a very high yield per hectare and are used in a wide variety of table, processed, livestock feed, and industrial uses (Afework Legese and Ewnetu Teshale, 2020).

Potato is the major food and cash crop in Ethiopia especially in the high and mid altitude areas. It is among the leading vegetable crops in Ethiopia (Chanie Yazie *et al.*, 2017). Annual potato production in Ethiopia has increased steadily but too many different reports are reports different figures. According to FAOSTAT, (2019) 349,000 tons in 1993 to around 743, 153 tons in 2018, and also in 2017 potato production in Ethiopia 67,591 hectare of land and 932,701 tons; and 19,302,600 hectares and 388,191,000.00 tons in the world respectively. According to the authors, the area allocated to potato in Ethiopia increased from 50,000 hectares by the mid of 1980 to 160,000 hectares in the early 2001's. Currently, the annual production of potatoes in the 'Meher' season is around 1,141,871.73 tons from 85,988.43 hectares of land with a productivity of 13.28 t ha^{-1} which is very low (13.28 t ha^{-1}) as compared to the world average 21.77 t ha^{-1} (Damtew Abewoy *et al.*, 2022).

In Ethiopia potentially about 70% of arable land can grow potato crops (Gebremedhin W/Giorgis, 2008). Average yields of potato in Africa are 6 to 12 tons ha^{-1} compared to 35–45 t ha^{-1} in Europe and North America (CIP, 2017), and specifically, in Ethiopia, it is 7.97 t ha^{-1} (CSA, 2016) and 8 t ha^{-1} to 12 t ha^{-1}, with average yields of progressive farmers well above 30 t ha^{-1} (Gebremedhin, 2015), which is far below the potential of the crop (CIP, 2017). Inappropriate agronomic practices, shortage of seed tubers of improved potato varieties, soil nutrient depletion, moisture stresses, diseases, and insect pests are the major constraints of potato production in Ethiopia (Workat Sebenie, 2019).

2.4. Opportunities and constraints of potato production in Ethiopia

Ethiopia has possibly the highest potential for potato production of any country in Africa. Among African countries, Ethiopia has the most potential for potato production because about 70% of the available agricultural lands are suitable for potato production, which is located at an altitude range of 1,500 to 3,000 m.a.s.l. with an annual rainfall range 600 and 1,200 mm, which are comfortable agro ecological conditions for potato production (Desta Bekele, 2024).

Currently, potato is produced mainly in the North western, Central and Eastern highlands of Ethiopia (Berhanu *et al.*, 2011). Its production is constrained by a wide range of factors that resulting in low yields. These factors include lack of high yielding varieties tolerant to late blight, poor soil fertility, climatic limitation, inadequate seeds, lack of appropriate cultural practices, poor post-harvest management and storage problems, high cost of farm inputs, diseases and insect pests (Gebremedhin W/Giorgis, 2013).

2.5. Effects of lime application on selected soil chemical properties

Lime application noticeably increased the soil pH and decreased exchangeable aluminum. According to Workneh Ejjigu *et al.* (2023) revealed that treatments that received the highest dose of lime (12 t ha^{-1}) resulted in the highest values of soil pH (6.27), and the lowest exchangeable acidity and exchangeable Al (0.15 and 0.06 Cmol (+) kg-1, respectively). On the other hand, the lowest soil pH (4.89), the highest exchangeable acidity and exchangeable Al (2.11 and 1.30 Cmol (+) kg^{-1}, respectively) were recorded from the control plots (Workneh Ejjigu *et al* 2023). Soil pH is defined as the negative logarithm of the hydrogen ion concentration in the soil solution, so pH 6 is 10 times more acidic than pH 7. However, the salt concentration in the soil solution and the ratio of soil to water volume affect the measurement of pH. The most commonly employed methods to determine a soil's lime requirement involve soil-lime incubations or soil-base titrations; however, because of the time required to reach equilibrium, these methods are very time-consuming. The fact that buffer-pH methods provide a rapid and convenient means of estimating soil lime requirement values, compared with incubation and titration procedures, has meant that several such methods have been proposed over the years (Preston *et al*., 2019).

Measurement of soil pH is the easiest and most commonly performed of all soil analyses and is one of the most indicative measurements of the likely chemical and microbiological properties of a soil (Breitenbreck and Bremner, 1984). However, measurements can be highly ambiguous. Two factors appreciably influencing soil pH measurements are the soil solution ratio and the equilibrium salt concentration. Increasing either factor normally decreases the measured soil pH (Bohn *et al*., 1979).

2.6. Soil pH requirement of potato

Nutrient availability in soil depends on the pH value of soils. Most of the essential plant nutrients are available in the pH range of 5.5 to 6.8; however, soil acidity is a major growth-proscribing issue for plants in many parts of the world (Dereje Dejene *et al*., 2023). At lower pH values potatoes can suffer from aluminum and other heavy metal ion toxicity, as well as restricted Phosphorus (P) or Morbdium (Mo) availability. Potatoes prefer soils with a pH of 5.5 to 7.0 and low salinity, and better tuber yields have been obtained from potatoes grown at soil reactions ranging from pH 5.5 to 7.0. Similarly, the ideal soil reaction for potatoes ranges from 5.2 to 6.5 (Athanase, 2013)

Extreme soil pH should be adjusted where it is practical to do so. At pH values above 7.5, nutrient availability, in particular of phosphorus and the micronutrients, can be reduced, even though high total amounts of these elements may be present in the soil (EIAR, 2004).

2.7. Soil acidity problem in Ethiopia

Ethiopia has a lot of acidic soil (ATA, 2014). The main soil classifications dominated by soil acidity are Nitosol and Oxisol soils. Despite this, Nitisols offer excellent agricultural potential due to their solid structure and great water storage capacity. Soil acidity has formed as a result of the gradual depletion of soil bases in acidic soil conditions (Aboytu Sisay, 2019). Soil acidity, particularly pH <5.5, has a negative impact on crop growth due to high concentrations of aluminum and manganese and a lack of phosphorous, nitrogen, sulfur, and other essential nutrients (Fekadu Mosissa, 2018).

Soil acidity resulted from a rise in the concentration of hydrogen ions (Seble Getaneh and Wubayehu Kidanemariam, 2021). It should occur because of natural and human-induced processes. Acid parent materials, leaching of basic cations calcium, magnesium, and potassium, hydrolysis reactions within the soil exchange sites, rainfall containing sulphuric and nitric acids, cations uptake by the crop over the long run cultivation, crop residue removal, and addition of soluble salts and fertilizers into the soil (mineral and organic) would possibly cause soil acidification (Bikila Takala, 2019).

In Ethiopia, though the amount of inorganic fertilizers applied was small, repeated use of urea (46N-0-0) and diammonium phosphate (DAP) (18N-46P_2O_5-0) over many years was reported as a favorable factor for soil acidification in the Northwestern and Southwestern highlands of Ethiopia. In general, soil acidity elevates the aluminum concentration within the soil solution to a level of toxicity that limits the availability of essential plant nutrients and restricts crop performance (Fanuel Laekemariam and Kibebew Kibret, 2021).

2.8. Potato crop and soil acidity

Liming is an important practice to achieve optimum yields for all crops grown on acid soils. Application of lime at an appropriate rate brings several chemical and biological changes to the soils, which are beneficial in improving crop yields on acid. Potato yields at lower lime rates differed from those at higher rates by about 30%, again substantiating a much longer residual effect with the use of higher rates (Athanase, 2013).

The Ethiopian potato research system has released 31 new potato varieties to address some of these production problems (MoA, 2013). All of these varieties originated outside of Ethiopia, mainly from the International Potato Center (CIP). Although these new varieties are grown in some parts of the country (Woldegiorgis Gebremariam *et al*., 2013), their adoption by farmers in most potato production areas is low (Abebe Kifle *et al*., 2013), so only a limited number of them are grown (Woldegiorgis Gebremariam, 2013). Hence, the majority of smallholder farmers still grow old varieties (Gildemacher *et al*., 2009; Hirpa *et al*., 2010). Improved varieties have better yields (Chakraborty *et al*., 2000) and are more resistant to late blight (Song *et al*., 2003), viruses, and bacterial wilt (Thiele, 1999). Potatoes can play a significant role in ensuring access to food at the household level and can also generate income for smallholders, thereby contributing to the economic sustainability of agricultural systems in developing countries (Thompson and Scoones, 2009). In Ethiopia, potatoes have increasingly become a source of cash income for farmers and retain their importance for household consumption (Gildemacher *et al*., 2009a, 2009b).

2.9. Potato crop response to liming

Liming with calcium carbonate (calcite) or magnesium carbonate (dolomite) has been used to improve acidic soils for centuries. In modern applications, the major goal is to neutralize exchangeable aluminum and enhance the availability of numerous nutrients, primarily calcium, magnesium, and phosphorus. This can often be achieved by increasing the pH to 5.5–6.0 with calcium carbonate (calcite) or magnesium carbonate (dolomite), which has been used to improve acidic soils for centuries (Abruna *et al*., 1964). Plant nutrients are most readily available when the soil pH is near 6.5. Potatoes grown in soils with a pH of 6.5 or higher produce higher yields with less fertilizer. The ideal pH for potatoes ranges from 5.2 to 6.5. The beneficial effects of liming on crop growth are often related to the neutralization of Aluminium and not directly to the change in soil pH (Athanase, 2013).

The combined application of liming, rotted farmyard manure and mineral fertilizers on acidic soils can achieve satisfactory potato yields. The combined application of mineral fertilizers, rotted farmyard manure and liming significantly affected the increase in average tuber weight (Jovovic *et al*., 2021). Liming acid soils is one of best available intervention options to mitigate the negative effects of soil acidity and increase crop production and productivity (Geremew Taye *et al*., 2020).

2.10. Effects of soil acidity on yield and yield attributes of potato

Acidic soil repair is performed trough liming or other acid-neutral materials. Potatoes tolerate well the low pH of the soil, which is why it is often grown in very acidic soils, even when the pH is below 5.5. Regardless of the fact that liming has a beneficial effect on increasing the yield of potatoes, many growers are avoiding it due to fear that increased pH of the soil, could cause intensive development of common scab (Jovovic *et al*., 2021). Profitable potato production, based on high tuber yields, is impossible without the application of high doses of mineral or organic fertilizers and lime (Heitkamp *et al*., 2011).

2.11. Effects of soil acidity on physicochemical properties

Soil acidity has negative impact on nutrient availability and causes Al, and Mn toxicity (Osundwa *et al*., 2013). Furthermore, soil acidity can cause rapid deteriorations in soil physicochemical properties such as soil organic carbon (OC), cation exchange capacity (CEC), soil structure, porosity, and texture. Acidification has effect on complexation of metals with organic matter, dispersion of colloids and eventual bioavailability and trace elements (Bolan *et al*., 2003). Decrease in pH leads to increase in net charge (low in CEC) which leads to lose of soil fertility and ultimately reduces land productivity (Geremew Taye *et al*., 2020). Acidic and very acidic soils are characteristic of the mountainous area, by active acidity forms (H^+, Al^{3+} and Mn^{2+}) block the activity of soil microorganisms involved in the processes of mineralization of organic matter, which makes these soils less suitable for potato growth. The systematic fertilization with organic fertilizers on these soils neutralizes their acidity, increases the nutrient content and improves the adsorptive properties. All of this together affects the improvement of the physical and chemical properties of these soils (Jovovic *et al*., 2021)

2.12. Lime requirement determination methods in Ethiopia

Lime rate determination requires total acidity estimation of the soil, including the capacity (fraction of reserve, exchangeable, and soluble acidity) and intensity (soil solution acidity) factor. Buffer solutions resist abrupt change in pH and have been used to determine the amount of liming materials needed to raise soil pH to a desired target value and are expected to measure both the capacity and the intensity factors of soil acidity (Gobena, 2005). Titration is a method to determine lime rate, direct titrations that give an estimate of exchangeable acidity (Geremew Taye *et al*., 2020).

The selection of an appropriate method to determine LR should consider the nature and variability of soil acidity found in a given geographic area. A test that only measures dissociated H^+ (active acidity) would greatly underestimate the amount of lime needed because it ignores the contribution from the exchangeable H^+ and all forms of soil Al and Fe. That is why soil pH alone cannot be used to determine LR. Any method that is used to estimate LR, therefore, must be able to predict the amount of acidity originating from all sources that will react when lime is added to the soil (Sims, 2018). Therefore, LR should be determined based on soil buffering capacity, which is also influenced by soil organic matter (OM), clay content, effective cation exchange capacity and exchangeable Al or exchangeable acidity of the soil (Fagaria and Baligar 2008; Aitken *et al*. 1990).

Several methods have been developed to determine the potential acidity and consequently, the LR of soils, of which buffer pH methods are widely used because of their simplicity and rapidity. A buffer solution (combination of a weak acid and its conjugate base) resists a marked change in pH of the solution but it starts to decrease in pH when the potential acidity of the soil reacts with the buffer (Sims, 2018). For the determination of the lime requirement estimates by exchangeable acidity method, first, the EA of the soil samples were extracted by neutral, unbuffered salt solution (1 MKCl) and titrated with standard 0.1 MNaOH. Then, the exchangeable Al was obtained by titrate the KCl extract with 0.1 MHCl (Sims, 2018). According to (Gurmu Gebreyes *et al*. (2024), the recommended LR ranged from 1.54 to 11.3 t CaCO3 ha^{-1}which was divergent from the blanket recommended rate of 3 t ha^{-1} (Gurmu Gebreyes *et al*., 2024).

3. MATERIALS AND METHODS

3.1. Description of the Study Area

The field experiment was conducted at Gedeb Kebele, Ezha district, Gurage zone, central Ethiopia, during the main rainy season '*meher*' of the year 2022. The experimental area is located 210 km away from Addis Ababa, the capital city of Ethiopia, and about 52 km from the capital of Gurage Zone, Wolkite, and 10 km from the town of Ezha District, Agena. The experimental area is located between 8°03'30" to 8°16'30" N latitude and 37°50'00" to 38°13'00" E longitude. The elevation of the study site is 2747 m.a.s.l, and the agro ecological condition is '*Dega*'. It receives a mean annual rainfall of 1200 mm, and the minimum and maximum air temperatures are 13.9°C and 23.26°C, respectively. According to Ezha District Agricultural Office (EDAO) (2019) on annual socio economic technical report, the dominant crops cultivated in the study area are Enset (*Ensete ventricosum* L.), barley (*Hordeum vulgare* L.), wheat (*Triticum aestivum* L.), and potatoes (*Solanum tuberosum* L.). According to the Wolkite sample Testing and soil Fertility improvement Center, the soil textural class of the study site was 20.67% clay, 30% silt, and 49.33% sand, which is a texture under the category of sandy clay loam (Bouyoucos, 1962).

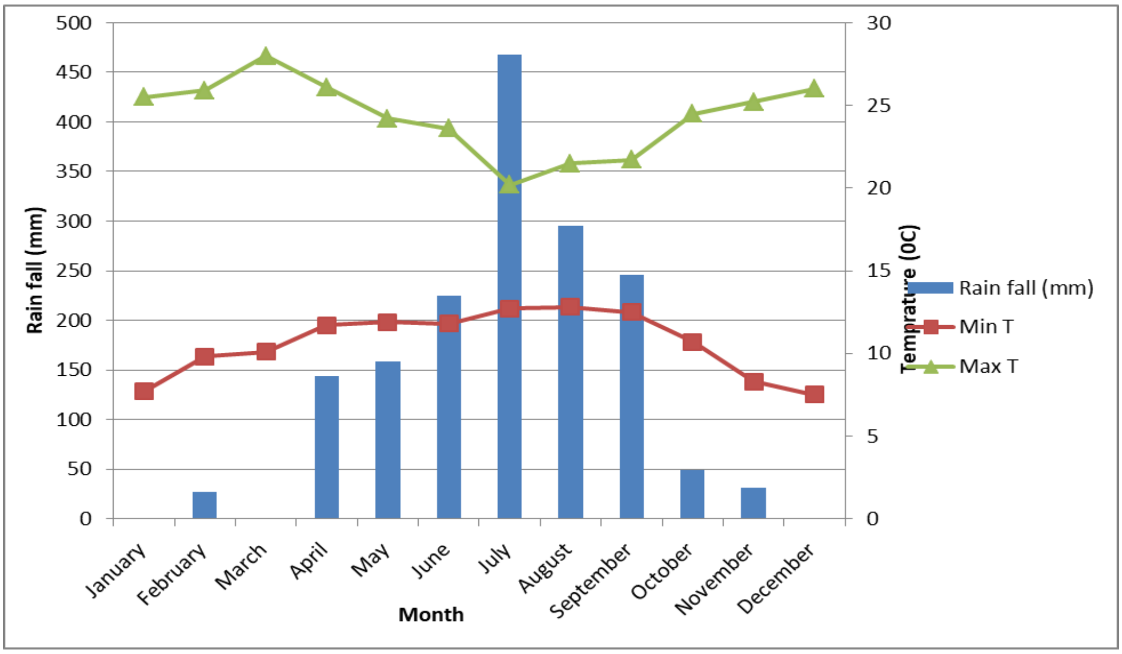

Figure 1. Temperature (°C) and rainfall (mm) condition of the experimental site

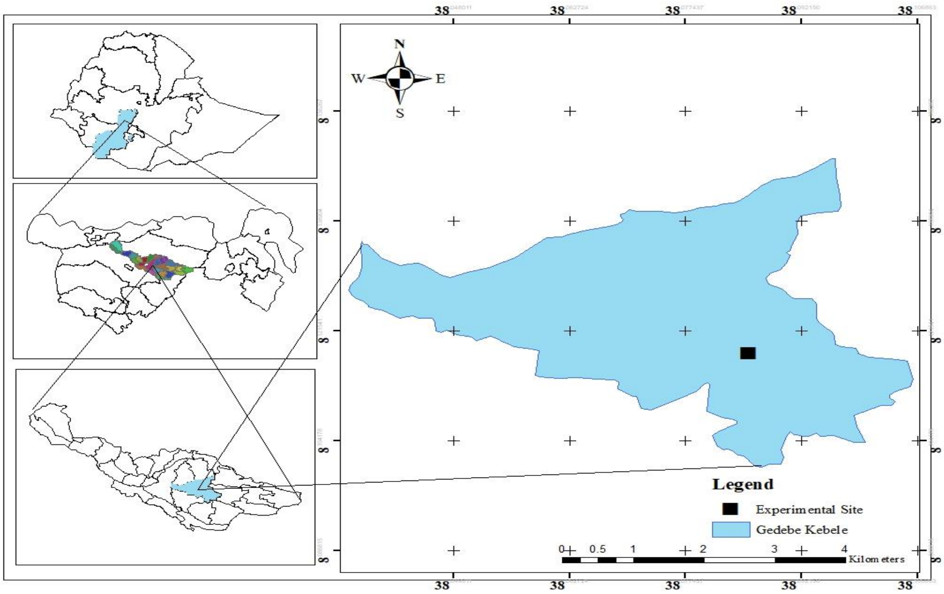

Figure 2. Maps of the Study Area

3.2. Experimental Materials

Three improved potato varieties, namely Gudene, Belete, and Dagim were used as experimental material. The varieties were selected basis on wide-area adaptability, disease resistance, insect and pest tolerance, and comparative tuber yield potential.

Table 1. General description of potato varieties

Description	Name of varieties		
	Belete	Gudene	Dagim
Year of release	2016 G.C	2012 G.C	2020 G.C
Altitude(m)	1600-2800 m.a.s.l	1600-2800 m.a.s.l	1600-2800 m.a.s.l
Rainfall(mm)	750-1000	750-1000	750-1000
Soil type	Fertile and Silt loam or sandy loam texture	Fertile and Silt loam or sandy loam texture	Fertile and Silt loam or sandy loam texture
Breeder	Holleta Agricultural Research Center	Holleta Agricultural Research Center	Adet Agricultural Research Center
Spacing	0.75m between row and 0.30m between plant	0.75m between row and 0.30m between plant	0.75m between row and 0.30m between plant
Days to maturity	110	120	110 to 115
Average Tuber Yield(t ha^{-1}) in the research field	47.19	29.17	33.8 to 47.2

Source: MoA, (2014)

3.3. Treatments and Experimental Design

The treatments consisted of five rates of lime (0.0 t ha^{-1}, 1.5 t ha^{-1}, 3.0 t ha^{-1}, 4.5 t ha^{-1}, and 6.0 t ha^{-1}) and three released potato varieties (Gudene, Belete, and Dagim) which were laid out in 5*3 factorial arrangements, 15 treatment combinations in Randomized Complete Block Design (RCBD) with three replications. The space between blocks and plots was 1m and 0.5 m, respectively and the space between rows and plants was 0.75m and 0.3 m, respectively. The gross plot size was 3.75 * 2.7 meters (10.125 m^2), which could accommodate 5 rows with 9 plants per row in each plot. The data were collected from the central three rows after the border rows and plants were removed. Therefore, the net plot size was 2.25 * 2.1 meters (4.725 m^2). The total area of the experimental field was 63.75 * 11.1 meters (707.625 m^2). The agricultural lime ($CaCO_3$) was broadcasted by hand and incorporated into the soil three months before planting according to the treatments. According to Ketema and Tefera (2022) lime was incorporated in to the soil 15, 30, 45, 60, 75 and 90 days (three months) before sowing.

Table 2. List of treatments in the experiment

Treatment combination	Factors	
	Variety (v)	Lime rate (L) (tons ha^{-1})
V_1L_0	Gudene (V_1)	0.0
V_1L_1	V_1	1.5
V_1L_2	V_1	3.0
V_1L_3	V_1	4.5
$V1L_4$	V_1	6.0
V_2L_0	Belete (V_2)	0.0
V_2L_1	V_2	1.5
V_2L_2	V_2	3.0
V_2L_3	V_2	4.5
$V2L_4$	V_2	6.0
V_3L_0	Dagim(V_3)	0.0
V_3L_1	V_3	1.5
V_3L_2	V_3	3.0
V_3L_3	V_3	4.5
V_3L_4	V_3	6.0

Where, V1L0=Gudene with 0.0 t ha^{-1} lime rate; V1L1= Gudene with 1.5 t ha^{-1} lime rate, V1L2= Gudene with 3.0 t ha^{-1} lime rate, V1L3= Gudene with 4.5 t ha^{-1} lime rate, V1L4= Gudene with 6.0 t ha^{-1} lime rate, V2L0=Belete with 0.0 t ha^{-1} lime rate, V2L1= Belete with 1.5 t ha^{-1} lime rate, V2L2= Belete with 3.0 t ha^{-1} lime rate; V2L3= Belete with 4.5 t ha^{-1} lime rate, V2L4= Belete with 6.0 t ha^{-1} lime rate; V3L0=Dagim with 0.0 t ha^{-1} lime rate, V3L1= Dagim with 1.5 t ha^{-1}, V3L2= Dagim with 3.0 t ha^{-1} lime rate, V3L3= Dagim with 4.5 t ha^{-1} lime rate, and V3L4= Dagim with 6.0 t ha^{-1} lime rate.

3.4. Experimental field management

The experimental site was plowed to a depth of 0.25–0.30 m after the soil was cleared of unwanted materials like rocks and plant residues. Then, the soil was crushed, loosened, and manually leveled by hand. The field was laid out and divided into three blocks, with fifteen plots in each block (Appendix Figure 1). Then, the treatments were assigned to each plot randomly, and the lime was applied in the broadcast method and slightly mixed with the soil by hand before three months of planting (Appendix Figure 2). Medium-sized tubers (39–75 g) with a sufficient number of sprouts (4–5) of each potato variety were selected, and one tuber seed per hill with 0.75 m x 0.30 m spacing was planted at a depth of 0.15m in the soil. NPSB and urea fertilizers with a specified rate of 200 kg ha^{-1} and 165 kg ha^{-1}, respectively, were applied uniformly to all experimental plots except control. However, NPSB fertilizer was applied at the time of planting, and urea fertilizer was applied in a slit form, in which half was applied at the time of planting and the remaining half was applied during the first round of earthing up.

Weeding, cultivation, earthing-up (3 times) (Appendix Figure 3), and late blight control measures taken on July 22, 2022 were done to facilitate root, stolon, and tuber growths. The late blight (*Phythophtora infestants*) disease was controlled by using 2.5 kg ha^{-1} of redomil gold fungicide mixed with 400 to 1000 L ha^{-1} of water and applied two times at a seven-day interval in the foliar application method by using a knapsack sprayer immediately after the sign of late blight has been forecasted (Appendix Figure 4). Weeding was controlled by hoeing, and earthing-up was done with the recommendation to prevent exposure of tubers to direct sunlight, promote tuber bulking, and ease of harvesting. When the plants reached physiological maturity (Appendix Figure 5), i.e., when yellowing or senescence was observed on the lower leaves, the stalks were cut two weeks before harvesting to thicken the tuber periderm and avoid bruising during harvesting and postharvest handling.

3.5. Data collection

3.5.1. Soil sampling and analysis

A composite soil sample was collected from nine spots on the experimental site in a diagonal pattern before planting, and 15 representative samples were collected from each treatment after harvest at a depth of 0–30 cm across the experimental field using a soil auger. Then, the samples were air-dried at room temperature in soil laboratory conditions, crushed with a mortar and pestle, and sieved to pass through a 2 mm mesh for selected soil properties except Organic carbon and total nitrogen which where pass through 0.5 mm mesh. Soil pH, Cation Exchange Capacity (CEC) (Cmol (+) kg^{-1}), available phosphorus (mg kg^{-1}), exchangeable acidity, exchangeable bases (Ca, Mg, K, and Na), total nitrogen, organic carbon, soil texture, and bulk density were analyzed at the Wolkite sample testing and soil fertility improvement center.

The soil pH was determined by a 1:2.5 soil-to-water ratio using a glass electrode attached to a digital pH meter (FAO, 2021). Soil bulk density was determined by the procedure outlined by (Black, 1965). Soil textural class was determined by using the Bouyoucos hydrometer method (Bouyoucos, 1962). Available phosphorus (mg kg^{-1}) was determined by Olsen's method (Olsen *et al*., 1954), and Cation exchangeable capacity was determined titrimetrically by distillation of ammonia that was displaced by Sodium. Total nitrogen was determined according to the modified Kjeldahl method with sulfuric acid by Dewis and Freitas (1984) Organic carbon was determined by the wet digestion method through the chromic acid digestion method, as described by (Walkley and Black, 1934). Exchangeable bases were extracted with 1M NH4OAc at pH 7, and then Calcium and Magnesium were determined by EDTA (Ethylene diamine tetraacetic acid) titration, while Potassium and Sodium were determined using flame photometry (USDANRCS, 1995).

3.5.2. Phenological Parameters

Days to 50% emergence: Days to 50% emergence was recorded with the number of days from planting until when 50% of the plants in each plot emerged from the soil.

Days to 50% flowering: days to 50% flowering was recorded as the number of days from planting to when 50% of the plants in each plot produce flowers.

Days to 90% maturity: was counted and recorded as the number of days from planting to when 90% of the plants in each plot were reached at senescence of vegetative parts or nearly ready for harvesting.

3.5.3. Growth components

Plant height (cm) was recorded by selecting and pre-tagging ten (10) randomly taken plants from the central three rows of each plot and measuring them using measuring tape from the ground surface to the tip part of the plant after the flowering stage.

Number of stems per hill: was determined by counting and taking the average number of main stems from ten randomly taken plants from each plot just before flowering.

The leaf area index was estimated from individual leaf length using the following formula developed by (Firman and Allen, 1989).

Log 10 (leaf area in cm^2) = 2.06 x log10 (leaf length in cm) - 0.458.

3.5.4. Yield components

Average tuber weight per plant (g): This was determined by taking the average tuber weight from ten randomly taken plants from each plot.

Tuber size categories (%): According to Lung'aho *et al*. (2007), all tubers from ten randomly selected plants of three central rows were classified as small (<39 g), medium (39-75 g), and large (> 75 g), and each category was expressed as a percentage.

Marketable tuber number per hill: The mean number of tubers produced from ten plants from the three central rows of each plot counted at harvest and those tubers which are healthy, large and greater than or equal to 25g were considered as marketable tubers.

Unmarketable tuber number per hill: The mean numbers of tubers produced from ten plants from the middle rows were counted at harvest and those tubers which are rotten, diseased, insect infested and green tubers and are less than 25g weight regarded as an unmarketable tuber.

Total tuber numbers per plant: was recorded as the sum of marketable and unmarketable tuber numbers per plant.

3.5.5. Yield parameters

Marketable tuber yield (ton ha^{-1}): All marketable tubers from ten randomly selected plants that were free of diseases, insect pests, and other damage and weighed more than or equal to 25g were recorded as marketable and calculated on a hectare basis (Lung'aho *et al*., 2007).

Unmarketable tuber yield (ton ha^{-1}): Unmarketable tubers include diseased and deformed tubers, as well as tubers weighing less than 25g regarded as unmarketable and computed on a hectare basis (Lung'aho *et al*., 2007).

Total tuber yield (ton ha^{-1}): Total tuber yield was recorded as the sum of marketable and unmarketable tuber yields (Lung'aho *et al*., 2007).

3.6. Data Analysis

The collected data were summarized in Microsoft Excel and subjected to the analysis of variance (ANOVA) by using the general linear model of SAS software (version 9.3). All significant pairs of treatment means were compared using the LSD test at a 5% level of significance. Correlation analysis was carried out using Pearson's simple correlation coefficient for the growth and tuber yield parameters of the potato.

3.7. Partial Budget Analysis

To determine the economic feasibility of the treatments, economic analysis in the form of a net benefit analysis and marginal rate of return was done according to the procedures developed by CIMMYT, (1988) given as follows:

Adjusted Tuber yield (ATY) (ton ha^{-1}) is the average yield adjusted downwards by 10% to reflect the difference between the experimental yield and the yield of farmers.

Gross benefit (GB) (ETB ha^{-1}) was computed by multiplying the field/farm gate price that farmers receive when they sell it as adjusted yield. GB = ATY × farm gate price

Total variable cost (TVC) (ETB ha^{-1}) is calculated by adding the variable costs, which include the cost of lime, farm daily labor cost for lime application, and the cost of the seed tuber and its transportation at the time of planting**.** The costs of other inputs and production practices are considered the same for all treatments or plots.

Net benefits (NB) (ETB^{-1}) are calculated by subtracting the total variable costs (TVC) from the gross field benefits (GFB) for each treatment as follows: **NB = GFB – TVC.**

The marginal rate of return (MRR %) is calculated by dividing the change in net benefit by the change in total variable cost. **MRR (%) =$\triangle$NB/ $\triangle$TVC**

Where,$\triangle$TVC = change in total variable cost and$\triangle$NB = change in net benefit

4. RESULT AND DISCUSSION

4.1. Soil physicochemical properties before and after planting

4.1.1. Soil physicochemical properties before planting

The physical and chemical characteristics of the soil in the study area before lime application and potato planting are shown in Table 3. Proportionally, the soil was 20.67% clay, 30% silt, and 49.33% sand, with a textural class of sandy clay loam (Bouyoucos, 1962). This soil is suitable for potato production due to its good ability to retain nutrients and available water. An ideal soil for potato production is well structured, with good drainage to allow proper root aeration, tuber development, and minimal root disease infestation. Potatoes prefer soils with a pH of 5.5 to 7.0. However, according to Horneck *et al.* (2011), the pH value of the soil in the study area before lime application was 5.10, which is strongly acidic (Appendix Table 6).

According to Tekalign (1991) general guidelines on the interpretation of soil nitrogen and carbon test results, the soil organic carbon content of the study area was 1.82 and characterized as medium, and the total nitrogen content of the soil was low (0.08%), in (Appendix Table 7). According to Olsen (1954) the available phosphorus concentration of the soil in the experimental site was low (2.08). Cation Exchangeable Capacity is a measure of a soil's ability to retain and release elements such as potassium, Calcium, Magnesium, and sodium. In general, soils high in Cation Exchangeable Capacity content are considered agriculturally fertile. According to Landon and Manual (1991), the Cation Exchangeable Capacity content of the soil in the study site was high (36 Cmol (+) kg^{-1}).

According to FMANR (1990), the exchangeable Na of soil is classified as < 0.30 Cmol (+) kg^{-1} rated as low, 0.30-0.70 Cmol (+) kg^{-1} rated as medium, and > 0.70 Cmol (+) kg^{-1} rated as high. Thus, the result of the soil at the study site revealed that the exchangeable Sodium level (0.1 Cmol (+) kg^{-1}) was low. Thus, the results of the soil at the study site revealed that the exchangeable potassium level (1.1 Cmol (+) kg^{-1}) was high. The result of the soil at the study site revealed the exchangeable Calcium (7.0 Cmol (+) kg^{-1}) level was high (FMANR, 1990)

Table 3. Selected physicochemical properties of soil at the experimental site before planting

Soil properties	Measured value	Rating	Reference /method
Soil particle size distribution (%)			
Clay	20.67		
Silt	30.00		
Sand	49.33		
Textural class	Sandy clay loam		(Bouyoucos, 1962)
Soil bulk density (g cm^3)	1.05		
Soil pH (1:2.5 soil to H_2O)	5.10	strongly acidic	(Horneck *et al*., 2011)
Organic carbon (%)	1.82	Moderate	(Tekalign *et al.*,1991)
Total Nitrogen (%)	0.08	Low	(Tekalign *et al.*,1991)
Cation Exchangeable Capacity (Cmol (+) kg^{-1})	36	High	(Landon,1991)
Available Phosphorus (mg/kg soil)	2.08	Low	(Olsen *et al*., 1954)
Exchangeable acidity	2.80		
Exchangeable Al(ppm)	1.27	Medium	(Horneck *et al*., 2011)
Exchangeable H(ppm)	1.53	Medium	(Horneck *et al*., 2011)
Exchangeable bases			
Exchangeable Na (Cmol (+) kg^{-1})	0.10	Low	(FMANR, 1990)
Exchangeable K (Cmol (+) kg^{-1})	1.10	High	(FMANR,1990)
Exchangeable Ca (Cmol (+) kg^{-1})	7.00	High	(FMANR,1990)
Exchangeable Mg (Cmol (+) kg^{-1})	2.00	High	(FMANR,1990)
Percent base saturation	28.33		

4.1.2. Soil physicochemical properties after lime application

After the lime was applied to the soil, the pH value of the soil increased as the rate of lime increased in each treatment combination (Table 4). The result showed that when the rate of lime increased from 0.0 to 6.0 t ha^{-1}, the pH value of the soil increased from 4.9 to 6.5, respectively, in plots of Gudene potato. Similarly, when each lime rate was combined with the Dagim variety, the pH values raised from 5.2 to 6.2 as the rates of lime increased from 0.0 to 6.0 t ha^{-1}. Also, when lime rates were combined with the Belete potato variety, the pH value increased from 5.2 to 6.5 as the lime application rates increased from 0.0 to 4.5 t ha^{-1}. This indicated that the lime application rates change the soil pH from strongly acidic soil to moderately and slightly acidic soil (Appendix Table 6). In general, as the lime rates increased, the soil pH would also increase indicates the quantity of lime application had a linear relationship with soil pH in strongly acidic conditions. The raised in soil pH by the application of lime might be due to a reduction in H^+ and

Al^{3+} concentration in the soil solution by the neutralizing and buffering ability of lime (Dereje Dejene *et al*., 2023). The result show that, as the lime rates range from 0.0 to 6.0 t ha^{-1}, the available phosphorous showed increments from 1.9 to 4.2 mg kg^{-1} for Gudene and 2.4 to 4.3 mg kg^{-1} in Dagim varieties. But, in the Belete variety plot, as the lime rate range from 0.0 to 4.5 t ha^{-1}, the availability of phosphorus increased from 2.0 to 4.6 mg kg^{-1} and declaimed further for an increment in the lime rate. So, this finding showed that, as the rate of lime increased, the pH value of the soil increased, and due to this reduction in soil acidity, the concentration and availability of phosphorus increased.

Table 4. Some of soil chemical properties after lime application

Treatments		Soil properties				
Varieties	Lime (t ha^{-1})	Ph	OC (%)	TN (%)	CEC (Cmol(+) kg^{-1})	Av. P (mg kg^{-1})
Gudene	0.0	4.9	0.8	0.1	37	1.9
Gudene	1.5	5.6	1.7	0.1	40	2.7
Gudene	3.0	5.8	2.2	0.2	42	2.8
Gudene	4.5	6.4	2.7	0.3	44	3.6
Gudene	6.0	6.5	2.7	0.2	47	4.2
Belete	0.0	5.2	2.1	0.1	38	2.0
Belete	1.5	5.8	2.0	0.2	40	3.0
Belete	3.0	6.0	2.3	0.2	43	3.4
Belete	4.5	6.5	2.3	0.2	46	4.6
Belete	6.0	6.4	2.0	0.2	44	4.3
Dagim	0.0	5.2	2.5	0.1	39	2.4
Dagim	1.5	5.6	2.3	0.1	39	2.8
Dagim	3.0	5.9	2.1	0.2	41	3.9
Dagim	4.5	6.1	2.3	0.2	42	4.0
Dagim	6.0	6.2	2.0	0.2	45	4.3

pH= soil reaction, OC= Organic carbon, TN= Total nitrogen, CEC=Cation Exchangeable Capacity, Av. P=Available phosphorus

The finding was in agreement with Athanase (2013), who found that the application of lime rate in acid soils reduces aluminium toxicity, improves pH, Calcium, and Magnesium, and increases both available Phosphorus and plant root systems in the soil. Similarly, Achalu Chimdi (2022) found that, the liming of acidic soils could increase soil pH, which enhances the release of phosphate ions fixed by Al^{3+}, H^{+1}, and Fe^{3+}ions into the soil solution and the likely displacement of Al^{3+}, H^{+1}, and Fe^{3+}ions by the Ca^{2+} ions it contains. Additionally, the increment of available phosphorus content of the soils collected from different treatments with increasing application lime rate may be attributed to increasing pH due to liming that could release the unavailable phosphorus which was previously fixed with aluminium and Iron at low soil pH condition. This finding also agree with Dereje Dejene *et al*. (2023), who state that the status of available P increased by 45% over the control due to the application of lime and organic matter. This might be due to the conversion of unavailable P into available form because of the rise in pH and reduction of exchangeable acidity.

Table 5. Exchangeable bases and acidity of the soil after lime application

Treatments		Soil properties						
Varieties	Lime t ha^{-1}	Exchangeable bases (Cmol (+) kg^{-1})				BS (%)	Exchangeable acidity (ppm)	
		Na^+	K^+	Ca^{+2}	Mg^{++}		EX. Al^{+3}	EX. H^+
Gudene	0.0	0.2	0.6	7	2	26.49	1.6	1.8
Gudene	1.5	0.5	1.3	15	3	49.50	0.0	1.2
Gudene	3.0	0.2	1.2	17	4	53.33	0.0	0.8
Gudene	4.5	0.5	1.3	23	5	67.73	0.0	0.4
Gudene	6.0	0.2	1.2	27	7	75.32	0.0	0.4
Belete	0.0	0.1	1	8	2	29.21	1.0	1.2
Belete	1.5	0.2	1.4	18	3	56.50	0.0	0.8
Belete	3.0	0.3	1.2	21	4	61.63	0.0	0.4
Belete	4.5	0.3	1.3	29	5	77.39	0.0	0.4
Belete	6.0	0.2	1.5	22	6	67.50	0.0	0.4
Dagim	0.0	0.2	1.1	8	2	28.97	1.2	1.6
Dagim	1.5	0.2	1.1	16	3	52.05	0.0	0.8
Dagim	3.0	1.3	1.2	19	4	62.20	0.0	0.8
Dagim	4.5	0.1	1.3	21	4	62.86	0.0	0.4
Dagim	6.0	0.2	1.5	24	6	70.44	0.0	0.6

Na^+=Sodium ion, k^+=Potassium ion, Ca^{2+}=Calcium ion, Mg^{2+}=Magnesium ion, Ex.Al^{3+}=Exchangeable Aluminium, Ex.H^+=Exchangeable Hydrogen

The result reveals that, after the lime was applied, the exchangeable acidity (Al^{3+}, H^+) decreased as the lime rates increased. The results of Al^{3+} (1.27 ppm) and H^+ (1.53 ppm) obtained in the study area before liming and non-limed plots were higher than the results obtained from limed plots. In the same way, the maximum result of exchangeable Al^{3+} and H^+ values obtained from the non-limed plots were higher than those obtained from limed plots, indicating the neutralizing effect of lime on Al and H in acid soils (Ubi *et al*., 2016). Also Aboytu Sisay (2019) indicated that soil pH consistently increased from 4.37 to 5.91 as the lime rate increased. Conversely, the exchangeable acidity was significantly reduced from 1.32 to 0.12 Cmol (+) kg^{-1} because of lime application. When the rates of agricultural lime applied to the soil increased the concentration of exchangeable bases like Ca^{2+} in the soil solution increased thereby decreasing the percent of total Phosphorus adsorption patterns and exchangeable acid from the soil exchange complex (Achalu Chimdi, 2022).The result of this finding showed that the highest and the lowest Cation exchange capacity (47 Cmol (+) kg^{-1} and 37 Cmol (+) kg^{-1}) were recorded from lime application rates of 6 t ha^{-1} and control respectively. This finding is par with Dereje Dejene *et al*. (2023), the Cation exchange capacity of the soil has been significantly increased in lime-treated pots; the highest (31.58 Cmol (+) kg^{-1}) value was obtained in treatment 8.44 t·ha^{-1} lime. The results of this finding show that, as the rate of lime increase the pH of the soil also increases; because of this the base saturation also increases. The application of different lime rates changes both base saturation and soil pH simultaneously (parallel) in acidic soil. Base saturation is the percentage of the soil Cation Exchangeable Capacity that is occupied by basic cations (calcium, magnesium, potassium, and sodium) at the current soil pH value (London, 1991).

Table 6. Analysis of the variance (ANOVA) of tested parameter

Parameters	Replication Df (2)	Variety Df (2)	Lime rate Df (4)	Interaction Df (8)	Error Df (28)	CV (%) Df (2)
Days to 50% emergence	18.95	23.75**	1.83^{ns}	1.03^{ns}	1.74	7.24
Days to 50% flowering	35.35	234.75**	136.52**	2.33**	0.68	1.34
Days to 90% maturity	40.46	160.06**	137.11**	25.51**	4.94	2.04
APH	39.2	1011.79**	424.11**	15.91**	3.54	3.32
ASNPH	0.04	5.52**	4.9**	0.44*	0.17	6.8
LAI	0.0119	0.015**	0.075**	0.0018*	0.00069	1.87
ATWPP	248.25	1843.77**	228.96**	80.52*	31.94	7.53
SST	0.63	76.76**	30.90**	18.89**	4.83	28.04
MST	26.69	1895.55**	42.83^{ns}	104.74**	20.76	18.03
LST	33.25	2345.13**	107.94**	143.83**	37.26	9.28
MTN	0.54	58.18**	12.51**	5.34**	0.44	8.67
UMTN	0.65	0.38 ^{ns}	0.52 ^{ns}	0.52 ^{ns}	0.24	0.24
TTN	1.56	60.68**	12.66**	6.98**	1.36	12.53
MTY	23.76	493.46**	381.84**	36.61**	1.5	4.12
UMTY	0.03	1.34**	4.19**	0.26**	0.06	11.32
TTY	24.6	454.92**	307.75**	39.33**	1.43	3.76

4.2. Crop Phenology

4.2.1. Days to 50% Emergence

The analysis of variance showed that days to emergence was highly significantly ($p<0.01$) affected by the main effect of potato variety. However, the main effect of lime rate and the interaction effects did not influence this parameter ($p>0.05$); (Appendix Table 1).

The longest days to emergence (19.6 days) were recorded from Dagim variety, while the shortest days to emergency (17.13 days) were obtained from the Gudene variety, which was statistically in par with the Belete variety (17.93) (Table 7). Thus, variety Dagim emerged lately than Gudene and Belete by 12.6% and 8.5%, respectively. The Variation in emergence between the varieties could be linked to the genetic differences between the varieties. Potato emergence was mostly dependent on the consumption of reserve material and metabolites in the mother tuber, rather than on external factors such as lime treatment.

Table 7. The main effect of variety and lime rate on days to 50% emergence of potato

Treatments	Days to 50% emergence
Varieties	
Gudene	17.13^{b}
Belete	17.93^{b}
Dagim	19.6^{a}
LSD(0.05)	0.98
CV (%)	7.24

LSD = Least significant difference at 5% level; CV (%) =Coefficient of variation. Means in the columns followed by the same letter are not significantly different at 5% level of significance.

In line with this finding, Solomon Fantaw *et al*. (2019) discovered that potato varieties had a substantial difference on the day to 50% emergence. Similarly, Bewketu Haile, (2012) revealed that potato varieties had an impact on the day to 50% emergence. The longest days (19.2) were reported from the Gudene variety.

In agreement with this result, Afework Solomon *et al*. (2023) found that lime application had no effect on potato plant emergence. The minimum and maximum days to 50% emergence were 19.25 and 20.75 days for the application of 15 t ha^{-1} lime rates and the control plot, respectively.

4.2.2. Days to 50% flowering

According to the analysis of variance, the interaction effect as well as the main effects of variety and lime rate had a highly significant ($p<0.01$) influence on the days to 50% flowering of potatoes (Appendix Table 1).

The longest days to flowering (72.33 days) were obtained at the treatment interaction of the Gudene variety with 0 t ha^{-1} lime application rate, which was followed by when the same variety interacted with 1.5 t ha^{-1} (69.33 days). This showed that the days to flowering for variety Gudene at 0 t ha^{-1}exceeded when the same variety interacted at 1.5 t ha^{-1} by 4.15% (Table 8). Similarly, variety Dagim interacted with 0 t ha^{-1}lime treatment and had prolonged days to flowering compared with variety Belete at 4.5 t ha^{-1} and 6 t ha^{-1} exceeded by 14.28% and15.31%, respectively. However, the shortest days to flowering (55.33 days) were obtained at treatment combination of variety Belete and 6 t ha^{-1} lime application rates, which was statistically parity with treatment combination of the same variety with 4.5 t ha^{-1} lime rate. This showed that liming affected shortening of flowering period. So, the more lime added to treat acid soil, the more accelerated growth of the potato to give early flowering than acid-affected soil. This demonstrated that planting potato varieties with no or low lime rates delayed the flowering period, whereas planting potato varieties with the highest lime rate shortened the days for flowering. This might be due to lime application on acidic soils, which reduces toxic Al concentration and increases the availability of P, Ca, and N and therefore enhances plant growth and flowering.

This result is in line with Afework Solomon *et al.* (2023) who reported that days to 50% flowering were highly significantly ($P<0.01$) influenced by the application of lime. The same authors showed that dates to 50% of flowering showed an increasing trend as the amount of lime decreased and the longest days to flowering were found from the application of the full buffer method (15 t ha^{-1}) while the shortest was from the control and micro-dosing of lime (0.06 t ha^{-1}).

4.2.3. Days to 90% Maturity

According to the analysis of variance, the interaction effect as well as the main effects of variety and lime rate were highly significant ($p<0.01$) influence on the days to 90% maturity of potatoes (Appendix Table 1).

Table 8. Interaction effect of variety and lime rate on days to 50% flowering and 90% physiological maturity of potato

Variety	Lime rate (t ha^{-1})	Day to 50% flowering	Days to 90% maturity
Gudene	0	72.33^{a}	114.33^{a}
	1.5	69.33^{b}	112.0b^{c}
	3	65.0^{cd}	113.33^{b}
	4.5	63.67^{d}	106.33^{fgh}
	6	60.33^{ef}	107.67^{cde}
Belete	0	64.0^{cd}	115.67^{a}
	1.5	60.33^{ef}	116.0^{a}
	3	57.67^{g}	108.0^{cd}
	4.5	56.0^{h}	108.0^{cd}
	6	55.33^{h}	101.0^{i}
Dagim	0	65.33^{c}	105.67^{def}
	1.5	61.67^{e}	108.67^{bc}
	3	59.33^{f}	105.33^{efg}
	4.5	57.67^{g}	103.0^{hig}
	6	56.67^{gh}	102.3^{hi}
LSD(0.05)		1.38	3.71
CV (%)		1.34	2.04

Mean followed by same letter are not significantly different; LSD (0.05) = Least significant difference at 5% level; CV (%) =Coefficient of variation. Means in the columns followed by the same letter(s) are not significantly different at 5% level of significance.

The longest days to 90% physiological maturity of potato (116 days) was obtained from a treatment combination of variety Belete and 1.5 t ha^{-1} lime application rate, this is statistically parity with treatment combinations of the same variety interacted with 0 t ha^{-1}; and variety Gudene without lime treatment (0 t ha^{-1}) (Table 8). However, the shortest days to physiological maturity were obtained by the interaction of Belete with a maximum lime application rate of 6 t ha^{-1} (101 days) which was statistically on par with treatment combinations of variety Dagim with 4.5 t ha^{-1} lime application rate and same variety at 6 t ha^{-1} lime application rate. Prolonged days to maturity with lower and without lime rates might be associated with varietal differences in the period to maturity due to the genetic makeup of potato varieties in response to lime treatment. The vegetation period for potatoes varied from 81 to 109 days depending on the varieties used (Tilahun Bekele, 2018).

4.3. Growth parameters

4.3.1. Plant height

According to the analysis of variance, the interaction effect as well as the main effects of variety and lime rate had a highly significant ($p<0.01$) influence on the plant height of potatoes (Appendix Table 2).

The longest (70.96cm) height of potato was obtained from the interaction of variety Gudene at maximum lime application rate (6 t ha^{-1}) which is statistically similar with treatment combinations of the same variety with a lime rate of 4.5 t ha^{-1} (70.76cm) and Belete combined with 4.5 t ha^{-1} (68.83cm) and 6 t ha^{-1} (69.4cm) rates of lime. The shortest height of the potato (42cm) was recorded from the treatment combination of Dagim variety in the acid untreated plot which was statistical on par with the treatment combination of the same variety at 1.5 t ha^{-1} lime rate (43.67cm) (Table 9). The medium height of the potato was recorded from all the other treatment combinations. This showed that increasing application rates of lime also increased the height of potato varieties. This is because the treatment of acid soil increases soil nutrient availability by enhancing mineralization which makes plants grows vigorously. Liming might also reduce the detrimental effect of soil acidity on plant growth due to high concentration of H^+ and Al^{3+} ions in acid soils.

In line with this result, Fikru Tamiru and Nigatu Ebisa (2022) investigated that, the maximum plant height (82.13 cm) was obtained from the highest lime rate (5.0 t ha^{-1}) and the minimum plant height (42.33 cm) was recorded from non-lime application treatment. Similarly, Afework Solomon *et al.* (2023) showed that, the tallest mean plant height (46.08 cm) was recorded in plots treated with 15 t ha^{-1} lime rate whereas the shortest (36.28 cm) was observed in the control plot.

4.3.2. Average stems number per hill of potato

The statistical analysis of the data revealed that there was a significant ($p<0.05$) difference in the average stem number per hill of potatoes among the treatment interactions. In the same way, both the main effects of varieties and lime rates had highly significant ($p<0.01$) influence on the same parameter of potatoes (Appendix Table 2).

Thus, variety Gudene at a maximum lime application rate of 6 t ha^{-1} exhibited the largest number of stems per hill (7.36), which was statistical parity with treatment combinations of Gudene with 3 t ha^{-1} (7.1) and variety Belete with 4.5 t ha^{-1} (7.26) and 6 t ha^{-1}(7.3). However, the lowest number of stems per hill was obtained from the interaction of Belete with the control treatment (5.0) and a lower lime rate of 1.5 t ha^{-1} (5.2) (Table 9). This result coincides with the result of Afework Solomon *et al.* (2023), whose report showed that application of different levels of lime had a significant ($p<0.01$) effect on the number of stems per hill. The same authors investigated that the maximum number of main stems (3.63) was observed in the 15 t ha^{-1} treatment, whereas the minimum number of main stems (2.25) was observed in the non-limed treatment. The results generally showed that the number of stems increased in parallel with an increment in the lime application rate. The increase in stem number while increasing the rate of lime applications may be attributed to the positive role the lime may have played in bringing the soil pH to normal levels for the growth and development of the potato plant (Afework Solomon *et al.,* 2023).

Of the study showed that many main stems arise from each tuber because has several "eyes," which give rise to a stem. Potato stems can be either the main stem, which grows directly from a seed tuber, or the secondary stem, which branches from the main stem. The potato main stem produces the tubers. Each stem from a single eye can be regarded as an independent production unit because tubers are formed from stems. The general crop performance, harvestable yield, and tuber numbers were strongly influenced by stem numbers per hectare. Khandakhar *et al*. (2004) also reported that, stem number per hill increased significantly with increasing the rates of lime application.

4.3.3. leaf area index of potato

The statistical analysis of the data revealed that there was significant ($p<0.05$) difference in the leaf area index of potatoes among the treatment interactions. In the same way, both the main effects of varieties and lime rates had a highly significant ($p<0.01$) influence on the leaf area index of potatoes (Appendix Table 2).

Increasing the application of lime rates to 4.5 t ha^{-1} and 6 t ha^{-1} with Gudene and Belete varieties resulted in significantly higher values of leaf area index (1.51 and 1.53) of potato. The lowest leaf area index value (1.26 and 1.27) was recorded in the non-limed plots with Dagim and Gudene varieties, respectively. The increases in the leaf area index of potato varieties at the highest lime rates might be due to the difference in the genetic potential of varieties to respond positively to lime treatment. Benntt *et al*. (2014), in studies conducted in semi-arid regions, reported that the use of lime up to 5 t ha^{-1} can improve crop vegetative cover, hydraulic conductivity, and soil health. This result is in line with Fikru Tamiru and Nigatu Ebisa (2022), who reported that the highest leaf area (140.07cm^2) was recorded from the application of lime (5 t ha^{-1}) and the minimum (178.13 cm^2) was found from the non- lime (0 t ha^{-1}) application. Similar authors pointed out that, different minerals responsible for the development of chlorophyll like N, Ca, and Mg concentration, increased with increasing lime rates. This may be associated with a higher N_2-fixation rate by N_2-fixing bacteria and higher Ca and Mg uptake with increasing lime rates.

Table 9. Interaction effect of variety and lime rate on growth parameters of potato

Variety	Lime rate (t ha^{-1})	Plant height (cm)	Average stem number per hill	Leaf area index
Gudene	0	53.0^{cd}	6.06^{d}	1.27^{h}
	1.5	55.5^{c}	6.46^{bcd}	1.31^{g}
	3	60.3^{b}	7.1^{ab}	1.44^{cd}
	4.5	70.76^{a}	7.0^{abc}	1.49^{ab}
	6	70.96^{a}	7.36^{a}	1.51^{ab}
Belete	0	54.36^{cd}	5.0^{e}	1.32^{ef}
	1.5	54.8^{cd}	5.2^{e}	1.36^{e}
	3	55.9^{c}	6.26^{d}	1.47^{bc}
	4.5	68.83^{a}	7.26^{a}	1.51^{ab}
	6	69.4^{a}	7.3^{a}	1.53^{a}
Dagim	0	42.0^{f}	4.9^{e}	1.26^{gh}
	1.5	43.67^{ef}	5.16^{e}	1.34^{ef}
	3	46.53^{e}	5.23^{e}	1.41^{d}
	4.5	52.03^{d}	6.36^{cd}	1.42^{d}
	6	51.83^{d}	6.26^{d}	1.43^{cd}
LSD(0.05)		3.15	0.7	0.04
CV (%)		3.32	6.8	1.87

LSD = Least significant difference at 5% level; CV =Coefficient of variation. Means in the columns followed by the same letter are not significantly different at 5% level of significance.

4.4. Yield components

4.4.1. Average tuber weight per plant

The statistical analysis of the data revealed that there was a significant ($p<0.05$) difference in the average tuber weight of potatoes among the treatment interactions. In the same way, both the main effects of varieties and lime rates had a highly significant ($p<0.01$) influence on the tuber weight of potatoes (Appendix Table 3).

The treatment combination of 4.5 t ha^{-1} lime rate and Belete variety resulted in the highest average tuber weight of potato (93.29 g), which was statistically parity with treatment combinations of both Belete and Dagim varieties with an equal rate of 3 t ha^{-1} limes, respectively. However, the significantly lowest (54.28 g and 58.12 g) average tuber weight was recorded from the interaction of variety Gudene with a non-limed plot and by the interaction of the same variety with 1.5 t ha^{-1}, respectively (Table 10). Increasing the rates of lime up to 4.5 t ha^{-1} showed increased weight of tuber for most of the tested potato varieties. However, further increases of lime to 6 t ha^{-1} did not result in increased weight of potato tuber.

This result is in agreement with the result of Jovovic *et al.* (2021), who reported that the application of liming significantly increased the average tuber weight and yield of potatoes. The same authors reported that the largest average tuber weight (82 g in 2015 and 84.5 g in 2016) of potatoes was obtained from limed plots, while the lowest average weight of tubers (79.2 g in 2015 and 81.7 g in 2016) was recorded from non-treated plots.

Table 10. Interaction effect of variety and lime rate on average tuber weight per plant

Average tuber weight (g/plant)					
	Lime rate (t ha^{-1})				
Varieties	0.0	1.5	3.0	4.5	6.0
Gudene	54.28^{h}	58.12^{gh}	59.56^{ef}	75.68^{ef}	75.36^{fg}
Belete	$74.7d^{ef}$	76.16^{cde}	87.69^{ab}	93.29^{a}	75.36^{cdef}
Dagim	78.84^{bcde}	80.67^{bcde}	84.67^{abc}	85.95^{bcd}	79.75^{bcde}
LSD(0.05)	9.45				
CV (%)	7.53				

LSD (0.05) = Least significant difference at 5% level; CV (%) =Coefficient of variation. Means followed by the same letter are not significantly different at 5% level of significance.

4.4.2. Tuber size categories

4.4.2.1. Small size tuber (<39 g) (%)

Based on the analysis of variance, the interaction effect as well as the main effects of varieties and lime rates had a highly significant ($P<0.01$) influence on the small-sized tuber percentage of potatoes (Appendix Table 3).

Gudene variety in the non-limed plots gave the highest proportion of small-sized tubers (13.19%) which was not significantly different with treatment combinations of variety Dagim (12.71%) in the non-limed plot as well as when variety Gudene, Belete and Dagim both interacted with 1.5 t ha^{-1} lime rate (10.19%, 11.84% and 10.81%), respectively (Table 11). This showed that most potato varieties exhibited the highest proportion of small-sized tubers at non-limed or lowest lime treatment rates, even though there is data inconsistency. This is because a non-significant difference was observed when Gudene variety interacted with both the untreated plot and plot treated with maximum lime rate (6 t ha^{-1}). In conclusion, all the tested potato varieties recorded significantly highest proportion of small sized tubers when they interacted with 0 t $ha^{-1}$and 1 .5 t ha^{-1}, except Belete at non-lime rate which resulted in lowest proportion of small sized tubers. This might be due to the difference in the genetic makeup of varieties that respond differently to different lime application rates.

4.4.2.2. Medium size tuber (39-75 g) (%)

The analysis of variance revealed that the main effect of variety and the interaction of variety and lime rates was highly significantly ($p<0.01$) influenced the medium-sized tuber proportion. However, the main effect of lime rate did not influence ($p>0.05$) medium-size tuber proportion (Appendix Table 3).

Proportionally, the highest medium-size tuber (44.88%) was obtained at treatment interaction of Gudene variety and 1.5 t ha^{-1} lime rates which is statistically at par with treatment interaction of the same variety (Gudene) at 3 t ha^{-1} lime rate (40.91%). Thus, variety Gudene at both the lowest and medium lime treatment conditions can provide the highest medium sized potato tubers. The lowest proportion for medium-sized tubers was recorded by the interaction of variety Dagim with 1.5 t ha^{-1} (11.69%) and 3 t ha^{-1} (11.68%) lime treatment rates. The same variety interacted with all lime treatment rates to give significantly the lowest proportion of medium-size tubers except at 4.5 t ha^{-1}. This might be due to the inherent genetic difference among the potato varieties to respond differently to lime application.

In similar a vein, Habtamu Gebreselassie *et al*. (2016) reported that significantly the highest medium-sized tubers in weight expressed in percentage were calculated for Gudene grown at Arberkete (34.42%), followed by the Belete variety (22.49%).

Table 11. Interaction effect of variety and lime rate on tuber size categories

Varieties	Lime rate (t ha^{-1})	Small size tuber (%)	Medium size tuber (%)	Large size tubers (%)
Gudene	0	13.19^{a}	30.25^{cd}	56.55^{cde}
	1.5	10.19^{abcd}	44.88^{a}	44.91^{f}
	3	12.44^{ab}	40.91^{ab}	$46.64d^{ef}$
	4.5	7.26^{cdefg}	32.56^{cd}	60.16^{dc}
	6	12.50^{ab}	35.95^{bc}	51.53^{def}
Belete	0	6.54^{defg}	27.06^{de}	66.38^{bc}
	1.5	11.84^{ab}	29.28^{cd}	58.86^{cd}
	3	3.65^{g}	15.91^{fgh}	80.43^{a}
	4.5	5.14^{g}	20.66^{ef}	74.18^{ab}
	6	5.86^{efg}	29.08^{cd}	65.05^{bc}
Dagim	0	12.71^{a}	15.79^{fgh}	71.48^{a}
	1.5	10.81^{abc}	11.69^{h}	77.48^{a}
	3	8.88^{bcde}	11.68^{h}	79.43^{a}
	4.5	7.70^{cdef}	20.32^{efg}	71.97^{ab}
	6	5.77^{efg}	12.90^{gh}	81.32^{a}
LSD(0.05)		3.67	10.21	10.21
CV (%)		24.51	18.03	9.28

LSD (0.05) = Least significant difference at 5% level; CV (%) =Coefficient of variation. Means in the columns followed by the same letter are not significantly different at 5% level of significance

4.4.2.3. Large size tuber (>75 g) (%)

The analysis of variance showed that the interaction effect as well as the main effects of variety and lime rates were highly significantly ($p<0.01$) influenced large size tuber proportion of potatoes (Appendix Table 3).

Significantly the highest proportion of large-size potato tuber was obtained from variety Dagim interacted with all lime rates which was statistically at par with treatment combination of variety Belete at 3 t ha^{-1} (80.41%) and 4.5 t ha^{-1} (74.18%). The lowest proportion of large-size tuber was obtained from the interaction of variety Gudene with 1.5 t ha^{-1} (44.91%), 3 t ha^{-1} (46.64%) and 6 3 t ha^{-1} (51.53%) (Table11). Statistically variety Dagim responded equally and significantly highest proportion of large-sized tuber with and without all the lime treatment rates. This is because potato varieties vary in their response to lime rates might be due to their genetic makeup to respond differently to different rates of lime application.

Habtamu Gebreselassie *et al.* (2016) reported that significantly, the highest large-sized tubers in weight expressed in percentage were calculated for Belete grown at Haramaya (80.64%), followed by the Gudene variety (60.74%), whereas at Hirna, significantly highest number of large size tubers was calculated for Belete (57.76%) and Gudene (36.26%) varieties.

4.4.3. Marketable tuber number per hill

According to the analysis of variance, the interaction effect as well as the main effects of varieties and lime rates were highly significantly ($p < 0.01$) influenced the marketable tuber number of potato (Appendix Table 3).

The experiment results showed that the maximum number of marketable tuber (12.57) was obtained from the interaction of variety Belete with the maximum rate of lime (6.0 t ha^{-1}), followed by variety Belete with 4.5 t ha^{-1} lime rate (10.3). On the other hand, the minimum number of marketable tubers (4.23) was recorded from the treatment combination of the Dagim variety with a 1.5 t ha^{-1} lime rate (Table 12). Thus, the highest number of marketable tubers at the treatment combinations of variety Belete with 6 t ha^{-1}exceeded the lowest number of marketable tubers at the treatment combinations of variety Dagim with 1.5 t $ha^{-1}$by 66.35%. Dagim variety responded significantly lowest number of marketable tubers when interacted with 0 t ha^{-1} (5.33), 1.5 t ha^{-1}(4.23), 3 t ha^{-1} (5.43) and 4.5 t ha^{-1} (5.83).

This result is in line with the report of Jovovic *et al.* (2021) whose report showed that the application of lime fertilizer had a positive effect on the productivity of potatoes. In agreement with this result, Rahman *et al.* (2014) revealed that different levels of phosphorous and calcium increased the average number of tubers per hill. All the treatments showed significant effects over the control. The maximum number of tubers per hill (10.33) was obtained from a higher lime rate application and the minimum number of tubers per hill (6.93) was obtained from control treatment.

Table 12. Interaction effect of variety and lime rate on marketable and total tuber number per hill

Variety	Lime rate (t ha^{-1})	Marketable tuber number per hill	Total tuber number per hill
Gudene	0	6.76^{efgh}	8.73^{def}
	1.5	9.16^{bc}	11.86^{b}
	3	9.73^{bc}	11.03^{bc}
	4.5	8.53^{cd}	10.13^{bcd}
	6	9.67^{bc}	11.33^{b}
Belete	0	6.96^{ef}	8.33^{def}
	1.5	6.80^{efg}	9.13^{cde}
	3	7.63^{de}	8.6^{def}
	4.5	10.3^{b}	11.06^{bc}
	6	12.57^{a}	14.66^{a}
Dagim	0	5.33^{ij}	6.93^{fg}
	1.5	4.23^{j}	5.93^{g}
	3	5.4^{3ij}	7.26^{efg}
	4.5	5.83^{ghij}	7.26^{efg}
	6	6.1^{ghi}	7.66^{efg}
LSD(0.05)		1.36	1.95
CV (%)		8.67	12.53

LSD (0.05) = Least significant difference at 5% level; CV (%) =Coefficient of variation. Means in the columns followed by the same letter are not significantly different at 5% level of significance.

4.4.4. Total tuber number per hill

According to the analysis of variance, the interaction of varieties and lime rates as well as the main effects had significantly ($p<0.01$) influenced the total tuber number per hill (Appendix Table 3).

The current result indicated that the highest total tuber number of potatoes was recorded from a treatment combination of Belete variety with maximum lime rates of 6 t ha^{-1} (14.66) whereas significantly lowest number of tubers (6.93, 5.93, 7.26, 7.26, 7.66) were obtained from interaction of variety Dagim with all limes rates of 0 t ha^{-1}, 1.5 t ha^{-1}, 3 t ha^{-1}, 4.5 t h^{-1} and 6 t ha^{-1}, respectively (Table 12). All the other treatment interactions resulted in a medium number of tubers per hill. This might be due to the difference in the genetic makeup of varieties in response to lime application rates for the total tuber number of potatoes per hill. This result agreed with result of Jovovic *et al*. (2021), whose report showed that the highest total tuber numbers (6.3 in 2015 and 7.18 in 2016) of potatoes were obtained from limed plots while the lowest number of tubers (5.8 in 2015 and 6.6 in 2016) were resulted from plots without lime treated.

4.5. Yield parameters

4.5.1. Marketable tuber yield of potato varieties (t ha^{-1})

Based on the analysis of variance the interaction effect as well as the main effects of varieties and lime rates were significantly ($p<0.01$) influenced the marketable tuber yield of potatoes (Appendix Table 4).

Statistically the highest marketable tuber yield (47.38 t ha^{-1}) of potatoes was recorded by the interaction of the Belete variety with 6 t ha^{-1} lime rate which was statistically parity with the treatment combination of Belete variety with 4.5 t ha^{-1} lime rate (46.42 t ha^{-1}) (Table 13). However, the lowest marketable tuber yield (19.66 t ha^{-1}) was obtained by the interaction of the Dagim variety at a non-limed rate which was statistically similar to marketable tuber yields (19.90 and 21.49 t ha^{-1}) obtained from varieties Dagim and Gudene with lime rates of 1.5 and 0 t ha^{-1} lime, respectively (Table 13). The above result showed that the increments in lime application rate had a direct relation to the marketable tuber yield of potatoes. This is because lime might enhance the nutrient availability of the soil by increasing soil pH and available phosphorous released nitrogen and also reduced aluminum toxicity. Nutrients enhance the quality of tubers and make them more marketable **(**Afework Solomon, *et al*. 2023). Liming also enhances root development and water and nutrient uptakes necessary for healthy plant growth (The *et al*., 2006; Van, 2007).

In agreement with this result, Fikru Tamiru and Nigatu Ebisa (2022) reported that, a significant difference was found among the combination of different levels of lime and vermicompost application on the marketable tuber yield of potato. Similar authors reported the maximum marketable tuber yield (33 t ha^{-1}) was obtained at the maximum application of lime (4.9 t ha^{-1}) rate while the minimum marketable tuber yield (17.98 t ha^{-1}) resulted from the null application of lime and vermicompost. The result also agreed with Afework Solomon *et al*. (2023), who found that the highest marketable yield was gained from 15 t ha^{-1} lime rate with a tuber yield of 19.71 t ha^{-1}; whereas, the lowest was found in the control plot (15.07 t ha^{-1}). Similarly, a significant difference ($P<0.01$) in the amounts of marketable tuber yields due to the application of different lime rates was reported by Afework and his co-workers **(**Afework Solomon, *et al*. 2023).

Table 13. Interaction effects of variety and lime rate on yields of potato in Ezha district

Varieties	Lime rate (t ha^{-1})	Marketable tuber yield (ton ha^{-1})	Unmarketable tuber yield (ton ha^{-1})	Total tuber yield (ton ha^{-1})
Gudene	0	21.49^{g}	2.76^{b}	24.24^{g}
	1.5	28.24^{e}	2.50^{b}	28.06^{f}
	3	29.15^{de}	2.03^{cd}	31.19^{d}
	4.5	30.57^{cd}	1.40^{e}	31.97^{cd}
	6	31.81^{bc}	1.64^{de}	33.45^{bc}
Belete	0	26.03^{f}	2.73^{b}	28.76^{ef}
	1.5	28.24^{e}	2.40^{bc}	30.65^{ed}
	3	32.92^{b}	1.59^{e}	34.51^{b}
	4.5	46.42^{a}	1.36^{e}	47.82^{a}
	6	47.38^{a}	1.74^{ed}	49.12^{a}
Dagim	0	19.66^{g}	3.50^{a}	23.16^{g}
	1.5	19.90^{g}	3.42^{a}	23.33^{g}
	3	24.66^{f}	2.62^{b}	27.28^{f}
	4.5	31.96^{bc}	1.61^{e}	33.58^{bc}
	6	30.15^{cde}	1.48^{e}	31.62^{cd}
LSD(0.05)		2.04	0.41	2.0
CV (%)		4.12	11.32	3.76

LSD (0.05) = Least significant difference at 5% level; CV (%) =Coefficient of variation. Means in the columns followed by the same letter are not significantly different at 5% level of significance.

4.5.2. Unmarketable tuber yield (t ha^{-1}) of potato varieties

According to the analysis of variance, unmarketable tuber yield of potato was highly significantly ($p<0.01$) influenced by the interaction effect and the main effects of variety, and lime rates (Appendix Table 4).

Statistically the lowest unmarketable tuber yield of potatoes was obtained at treatment combinations of all the three varieties with lime application rates of 4.5 t ha^{-1} and 6 t ha^{-1} which are in statistical parity, whereas the highest unmarketable tuber yield (3.42 tha^{-1} and 3.5 t ha^{-1}) was obtained from treatment combination of variety Dagim with 1.5 t ha^{-1} and at control plot, respectively, which was statistically in par with combination of variety Gudene with moderate lime application rate of 3 t ha^{-1} (2.03 t ha^{-1}) (Table 13). Thus, the lowest unmarketable tuber yield of potato which was recorded by all the three varieties at the highest lime application rates might be due to the positive effect of lime addition towards increasing soil pH and increased availability of soil nutrients resulted in reduced yield of unmarketable tubers. Limiting or reducing crop production primarily by impairing root growth due to the toxicity of high concentrations of soluble aluminum (Al) to roots. However, the lime rate increased to a certain extent, and soil acidity decreased because of the neutralizing ability of lime. The result indicated that the amount of lime applied in the soil and its unmarketable tuber yield were inversely related which means, that as the lime rate decreased, the soil pH, available phosphorous and CEC reduced and aluminum toxicity increased. Thus, as these parameters are reduced the size of the potato tuber also diminishes (Afewok Solomon *et al*., 2023).

In line with this finding, Fikru Tamiru and Nigatu Ebisa (2022) discovered that lime rate and vermicomposting had a significant effect on the unmarketable tuber yield (t ha^{-1}) of potatoes. The highest (3.89 t ha^{-1}) and lowest (1.03 t ha^{-1}) unmarketable tuber yields were recorded with 0 and 4.9 lime rates, respectively. Similar to this, Afewok Solomon *et al* (2023) reported that the highest unmarketable yield (2.10 t ha^{-1}) was gained from the control plot while the lowest (1.10 t ha^{-1}) was with the incorporation of 15 t ha^{-1} lime rate.

4.5.3. Total tuber yield (t ha^{-1}) of potato varieties

According to the analysis of variance, total tuber yield of potato was highly significantly ($p<0.01$) influenced by the interaction effect, and the main effects of variety and lime rates (Appendix Table 4).

Statistically, the highest total tuber yield of potato was obtained from the interaction of variety Belete with the highest application rates of lime at 4.5 t ha^{-1} (47.82 t ha^{-1}) and 6 t ha^{-1} (49.12 t ha^{-1}), which are statistically similar. However, statistically the lowest yields of potato (23.16 t ha^{-1}, 23.33 t ha^{-1}, and 24.24 t ha^{-1}) was obtained from interaction of variety Dagim with 0 t ha^{-1}and1.5 t ha^{-1}, and Gudene varieties interact with no-limed plot, respectively (Table 13). The highest yield obtained in plots that were limed was probably due to the positive effects of liming on soil properties. Liming improved overall soil properties: soil pH increased from 5.10 to 6.5, available P increased from 2.08 to 4.6 mg kg^{-1}, total nitrogen increased from 0.08% to 0.3%, and CEC increased from 36.0 to 47.0 Cmol (+) kg^{-1}. Contrary to this, exchangeable acidity reduced from 2.80 to 0.4 Cmol (+) kg^{-1} and exchangeable Al reduced from 1.27 to 0.00 Cmol (+) kg^{-1}. This implies that soil improvement after liming resulted in an increased yield of potatoes.

The current result coincides with the finding of Fikru Tamiru and Nigatu Ebisa (2022) who obtained that the maximum total tuber yield (34.46 t ha^{-1}) was recorded with the application of the highest lime level (4.9 t ha^{-1}) whereas the lowest (21.87 t ha^{-1}) was recorded from treatment without lime application. Similar to this, Jovovic *et al*. (2021)

reported that the total tuber yield (27.6 t ha^{-1} in 2015 and 33.4 t ha^{-1} in 2016) of potatoes was obtained from limed plots while the lowest total tuber yield (21.9 t ha^{-1} in 2015 and 25.5 t ha^{-1} in 2016) were resulted from plots without lime. Athanase (2013) also reported that the maximum total tuber yield of 24.82 t ha^{-1} was resulted with the highest agricultural lime rate (4.2 t ha^{-1}), but the lowest result (14.30 t ha^{-1}) was recorded with control plot (0 t ha^{-1}). Afewok Solomon *et al* (2023) reported that amounts of lime applied with different rates significantly ($p<0.01$) affected the total tuber yield of potato. Similar authors investigated that application of 15 t ha^{-1} gave the highest fresh total potato tuber yield (20.80 t ha^{-1}) and the lowest was obtained in the control plot (17.17 t ha^{-1})

4.6. Correlation Analysiss among Growth and Yield Parameters

The correlation between growth and yield components of potatoes as influenced by the application of lime was computed and its results are shown in Table 15. The present study indicated that Plant height was highly significantly and positively correlated with days to 50% flowering (r=0.98**), average stem number (r=0.53**), marketable tuber number (r=0.66**) and marketable tuber yield (r=0.40**), and significantly and positively correlated with total tuber yield (r=0.16*). This is in line with Afewok Solomon *et al*, (2023) Plant height had a positive and highly significant correlation (r=0.451**) with total tuber yield and marketable yield (r=0.544**). The positive and significant association of plant height indicates that plant height is an important tuber yield attribute that should be considered in the selection criteria for yield improvement. These results were coinciding with the findings of who reported that applications of lime increased the height of potato plants (Table 14). According to Minwyelet Jembere (2017), the analysis of correlation showed that plant height, days to maturity, leaf area, stem per hill, average tuber weight, and marketable tuber yield was highly positively correlated ($P < 0.001$) with yield of potato.

Average stem number per hill was highly significantly and positively correlated with marketable tuber number (r=0.43**) and significantly and positively correlated with total tuber yield; according to, Khayatnezhad *et al*. (2011) reported stronger positive correlations were found between tuber yield and main stems/plant (r= 0.925), plant tuber weight (r=0.992), plant height (r=0.843), but highly significantly and negatively correlated with leaf area index (r=-0.42**), unmarketable tuber number (r=-0.42**) and total tuber number (r=-0.47**) and also significantly and negatively correlated with medium size tuber (r=-0.37*) and large size tuber (r=-0.34*). In line with (Afework Solomon *et al*, 2023) a positive and highly significant correlation was observed between the number of main stems per hill and marketable tuber yield (r=0.684**) (Table 14).

Average tuber weight per plant was highly significantly and positively correlated with small size tuber (r=0.53**), and also significantly and positively correlated unmarketable tuber number (r=0.29*), but highly significantly and negatively correlated with marketable tuber number (r=-0.65**), marketable tuber yield (r=-0.74**), days to 50% flowering (r=-0.49**) and days to 50% maturity (r=-0.68**). Marketable tuber number was highly significantly and positively correlated with marketable tuber yield (r=0.71), average plant height (r=0.66**) and average stem number per hill (r=0.43**) (Table 14)

In agree with Tsegaye Girma (2017), there were significant and strong correlations among numbers of plants per hill, number of tubers per hill, and marketable tuber yield with high number of plants and tubers per hill..

Table 14. Simple correlation coefficient (r) for growth and yield parameters of potato varieties in Ezha district (2022)

	DTE	DTF	DTM	APH	ASNPH	ATWPP	SST	MST	LST	MTN	UNMT	TTN	MTY	UMTY	TTY	LAI
DTE	**1.00**															
DTF	-0.00^{ns}	**1.00**														
DTM	-0.00^{ns}	-0.00^{ns}	**1.00**													
APH	-0.00^{ns}	0.98**	-0.17^{ns}	**1.00**												
ASNPH	-0.40**	0.55**	-0.07^{ns}	0.53**	**1.00**											
ATWPP	-0.24^{ns}	0.49**	0.68**	0.59**	-0.11^{ns}	**1.00**										
SST	-0.11^{ns}	-0.37*	0.68**	0.48**	-0.07^{ns}	0.53**	**1.00**									
MST	-0.10^{ns}	0.64**	0.61**	0.52**	-0.37*	-0.2 ^{ns}	-0.12^{ns}	**1.00**								
LST	-0.01 ^{ns}	0.52**	0.69**	-0.4**	-0.34*	-0.2 ^{ns}	-0.33*	0.79**	**1.00**							
MTN	-0.05 ^{ns}	0.64**	-0.21^{ns}	0.66**	0.43**	-0.65**	-0.25*	-0.10^{ns}	-0.2^{ns}	**1.00**						
UMTN	-0.06 ^{ns}	-0.25^{ns}	-0.20^{ns}	-0.28^{ns}	-0.05^{ns}	0.29*	0.22^{ns}	-0.05^{ns}	-0.04^{ns}	-0.34*	**1.00**					
TTN	-0.03 ^{ns}	0.72**	0.35*	0.65**	-0.47**	0.03^{ns}	0.03^{ns}	0.78**	0.68**	0.49**	0.32*	**1.00**				
MTY	-0.07 ^{ns}	0.32*	0.52**	0.40**	-0.11^{ns}	-0.74**	0.39**	0.31*	0.30*	0.71**	-0.31*	-0.01^{ns}	**1.00**			
UMTY	-0.01^{ns}	0.61**	0.46**	0.52**	-0.42**	-0.13^{ns}	-0.12^{ns}	0.83**	0.70**	-0.23^{ns}	-0.17^{ns}	0.87**	0.30*	**1.00**		
TTY	-0.24^{ns}	-0.12^{ns}	-0.22^{ns}	0.16*	0.03*	0.23 ^{ns}	-0.17 ^{ns}	-0.09^{ns}	-0.11^{ns}	-0.29^{ns}	0.41**	-0.11^{ns}	-0.34*	-0.06^{ns}	**1.00**	
LAI	-0.05^{ns}	0.60**	0.42**	0.52**	-0.42**	-0.07^{ns}	-0.10^{ns}	0.75**	0.66**	-0.33*	-0.27^{ns}	0.87**	0.18^{ns}	0.93**	0.16*	**1.00**

DTE=Days to emergence, DTF=Days to flowering; DTM=Days to maturity; APH=Average plant height; ASNPH=Average stems number per hill; ATWPP=Average tuber weight per plant; SST=Small size tuber; MST=Medium size tuber; LST=Large size tuber; MTN=Marketable tubers number; UMTN=Unmarketable tubers number; TTN=Total tubers number; MTY=Marketable tuber yield; UMTY=Unmarketable tuber yield; TTY=Total tuber yield; and LAI=Leaf area index

4.7. Partial Budget Analysis

The partial budget analysis of the 15 treatments is shown in (Table 15). The economic analysis was done using the cost-benefit and marginal rate of return analysis as described by CIMMYT (1988). Marketable tuber yields of potatoes were used to calculate the gross benefit of each treatment. Based on this, the highest net benefit of 465,259 Birr ha^{-1} was obtained from the treatment combination of 4.5 t ha^{-1} lime application rate with variety Belete, followed by the treatment combination of the same variety with 6 t ha^{-1} lime rate application (43,0370 Birr ha^{-1}). On the other hand, the lowest net benefits (33,527 Birr ha^{-1}) and 42,562 were obtained from variety Dagim with 1.5 and 0 t ha^{-1} lime application rates, respectively (Table 15). Additionally, the highest marginal rate of return (3,063.41%) was obtained from the treatment combination of the Belete variety and 4.5 t ha^{-1} lime application rates. Therefore, the combined application of variety Belete with 4.5 t ha^{-1} lime application rate resulted in the highest net benefit (465,259 Eth Birr ha^{-1}) and an acceptable marginal rate of return (3,063.41%) for producers or farmers.

Table 15. Summary of partial budget analysis of potato varieties to the application of lime rates

Treatment		AMY(kg ha^{-1})	ADMY(kg ha^{-1})	GFB (ETB ha^{-1})	TVC (ETB ha^{-1})	NB (ETB ha^{-1})	Marginal rate of return (%)
Variety	Lime rates (t ha^{-1})						
Gudene	0	21490	19341	328797	258236	70551	0
	1.5	25560	23004	391068	271045	120023	386.23
	3	29153	26238	446046	278895	167151	600.36
	4.5	30570	27513	467721	286745	180976	176.11
	6	31813	28632	486744	294595	192149	142.33
Belete	0	26030	23427	398259	258236	140023	0
	1.5	28243	25419	432123	271045	161078	164.38
	3.0	32920	29628	503676	278895	224781	811.50
	4.5	46420	41778	752004	286745	465259	3063.41
	6.0	47383	42645	724965	294595	430370	-452.77
Dagim	0	19660	17694	300798	258236	42562	0
	1.5	19907	17916	304572	271045	33527	-70.54
	3.0	24660	22194	377298	278895	98403	826.45
	4.5	31967	28770	489090	286745	202345	1324.10
	6.0	30157	27141	461397	294595	166802	-452.78

Where; AMY =Average marketable Yield, ADMY= Adjusted Marketable Yield, GFB = Gross Field Benefit, NB=Net Benefit, TVC =Total Variable Cost, ETB = Ethiopian Birr, Lime cost = 5 ETB kg^{-1}, NPSB fertilizer cost =40.00ETB kg^{-1}, Farm gate price of potato = 17.00 ETB kg^{-1} and Labor cost = 200.00 ETB day^{-1}.

5. CONCLUSION AND RECOMMENDATION

Liming raises soil pH (5.10 to 6.5), CEC (36.0 to 47.0 Cmol (+) kg^{-1}), Av. P (2.08 to 4.6 mg kg^{-1}), percent base saturation (28.33 to 77.39%), Ca (7 to 29 Cmol (+) kg^{-1}), and Mg (2 to7Cmol (+) kg^{-1}) contents, but reduces aluminum (1.27 to 0.0 ppm and hydrogen ion (1.53 to 0.4 ppm) concentrations in acidic soils.

The analysis of variance showed that the interaction between lime rates and varieties significantly ($p<0.01$) influenced almost all the growth, yield and yield related parameters of potatoes. However, days to emergency and the number of unmarketable tubers were highly significantly influenced by the main effects. As a result, the longest days to emergence (19.6 days) were recorded from a variety of Dagim. The longest days to 50% flowering (72.33) and longest days to 90% maturity (114.33) were obtained from the interaction of variety Gudene without lime application. Significantly, the tallest height of potato (70.76cm, 70.96cm 68.83cm, and 69.4cm) was recorded from the interaction of varieties Gudene with 4.5 t ha^{-1} and 6 t ha^{-1} as well as Belete with 4.5 t ha^{-1} and 6 t ha^{-1}, respectively. Significantly highest average stem number (7.36) and leaf area index (1.53) of potatoes were obtained by the interaction of Gudene and Belete varieties with 4.5 and 6 t ha^{-1}lime application rates respectively.

The combined use of variety Belete with 3 t ha^{-1} and 4.5 t $ha^{-1}$and variety Dagim with 3 t ha^{-1} gave significantly the highest average tuber weight of potato (87.69 g/plant, 93.29 g/plant, and 84.67 g/plant), respectively. The significantly highest proportion of small tubers was recorded from the Gudene and Dagim varieties when combined with the lowest lime rate (1.5 t ha^{-1}) and non-limed plot. Statistically, the highest proportion of medium-size tubers (44.88% and 40.91%) was obtained from the interaction of variety Gudene with 1.5 t ha^{-1} and 3 t ha^{-1} lime rates. Statistically, highest proportion of large-size tuber was recorded from the interaction of variety Belete with all lime treatment rates. The highest marketable tuber number (12.57) and total tuber number per hill (14.66) were recorded from the combined application of variety Belete and 6 t ha^{-1}, respectively. Statistically highest marketable yield (46.42 t ha^{-1} and 47.38 t ha^{-1}) and total tuber yield (47.82 t ha^{-1} and 49.12 t ha^{-1}) of potato were obtained from the combined use of variety Belete and 4.5 t ha^{-1} and 6 t ha^{-1} lime rates, respectively.

In general, higher rates of lime application resulted in greater increases in soil pH, CEC, percent base saturation, available phosphorus and exchangeable bases but decreased exchangeable acidity ($Al^{+3}$and H^{+}). The application of 6.0 t ha^{-1} and 4.5 t ha^{-1} lime rates, which interacted with the Belete variety, produced the statistically highest tuber yield of potato (49.12 t ha^{-1} and 47.82 t ha^{-1}) respectively. However, the lowest tuber yield was obtained from the non-limed plots.

The partial budget analysis results revealed that the highest net benefit (465,259 Eth Birr ha^{-1}) with a marginal rate of return (3,063.41%) was recorded from the combined effect of the Belete variety and 4.5 t ha^{-1} lime application rates. In conclusion, the result of this study shows that different rates of lime and varieties, with their interactions, have a promising impact on the growth and yield of potatoes. Based on the results of the present study, the most economically attractive treatment combinations for small-scale farmers in the area were revealed to be 4.5 t ha^{-1} lime rate and variety Belete. Therefore, the combined use of variety Belete with 4.5 t ha^{-1} lime application rate resulted in the highest net benefit (465,259 Eth Birr ha^{-1}) with an acceptable marginal rate of return (3,063.41%) recommended for small-scale producers (farmers) around the study area. However, further research would have to be repeated to get the best conclusive result and a sound full recommendation for a specific area.

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7. APPENDICES

Appendix Table 1. Means squares of analysis of the variance for phenological parameters

Sources of variation	DF	Means squares		
		DTE	DTF	DTM
Replication	2	18.95	35.35	40.46
Variety	2	23.75**	234.75**	160.06**
Lime rates	4	1.83^{ns}	136.52**	137.11**
Variety x lime rates	8	1.03^{ns}	2.33**	25.51**
Error	28	1.74	0.68	4.94
CV (%)		7.24	1.34	2.04

*CV =Coefficient of variation; DF= degree of freedom; ns= non-significant; *= significant at 5% level of significance; **= significant at 1% level of significance; DTE= Days to 50% emergence; DTF= Days to 50% flowering; DTM= Days to 90% physiological maturity*

Appendix Table 2. Means squares of analysis of variance for growth parameters

Sources of variation	DF	Means squares		
		APH	ASNPH	LAI
Replication	2	39.2	0.04	0.0119
Variety	2	1011.79**	5.52**	0.015**
Lime rates	4	424.11**	4.9**	0.075**
Variety x lime rates	8	15.91**	0.44*	0.0018*
Error	28	3.54	0.17	0.00069
CV (%)		3.32	6.80	1.87

*CV =Coefficient of variation; DF= degree of freedom; ns= non-significant; *= significant at 5% level of significance; **= significant at 1% level of significance; PH= Plant height; ASNPH= Average stem number per hill; LAI= Leaf area index*

Appendix Table 3. Means squares of analysis of variance for yield components

Sources of variation	DF	Means squares						
		ATWPP	Size categories (%)			MTN	UMTN	TTN
			SST	MST	LST			
Replication	2	248.25	0.63	26.69	33.25	0.54	0.65	1.56
Variety	2	1843.77**	76.76**	1895.55**	2345.13**	58.18**	0.38^{ns}	60.68**
Lime rates	4	228.96**	30.90**	42.83^{ns}	107.94**	12.51**	0.52^{ns}	12.66**
Variety x lime rates	8	80.52*	18.89**	104.74**	143.83**	5.34**	0.52^{ns}	6.98**
Error	28	31.94	4.83	20.76	37.26	0.44	0.24	1.36
CV (%)		7.53	28.04	18.03	9.28	8.67	30.39	12.53

*CV =Coefficient of variation; DF= degree of freedom; ns= non-significant; *= significant at 5% level of significance; **= significant at 1% level of significance; ATWPP= Average tuber weight per plant; SST= Small size tuber; MST= medium size tuber; LST= Large size tuber; MTY=Marketable tuber number; UMTN=Unmarketable tuber number; TTN=Total tuber number.*

Appendix Table 4. Means squares of analysis of variance for yield parameters

	Means squares			
Sources of variation	DF	MTY	UMTY	TTY
Replication	2	23.76	0.03	24.60
Variety	2	493.46**	1.34**	454.92**
Lime rates	4	381.84**	4.19**	307.75**
Variety x lime rates	8	36.61**	0.26**	39.33**
Error	28	1.50	0.06	1.43
CV (%)		4.12	11.32	3.76

*CV =Coefficient of variation; DF= degree of freedom; ns= non-significant; *= significant at 5% level of significance; **= significant at 1% level of significance; MTY=Marketable tuber yield; UMTY=Unmarketable tuber yield; TTY=Total tuber yield*

Appendix Table 5. Weather condition of the experimental site (2022)

Months	Weather element		
	Total rain fall (mm)	Average temperature (^{0}C)	
		Minimum	Maximum
January	0.0	7.7	25.5
February	26.8	9.8	25.9
March	0.0	10.1	28.0
April	144.0	11.7	26.1
May	159.0	11.9	24.2
June	224.5	11.8	23.6
July	468.2	12.7	20.2
August	295.5	12.8	21.5
September	245.5	12.5	21.7
October	49.5	10.7	24.5
November	31.0	8.3	25.2
December	1.2	7.5	26.0

Source: Ethiopian metrological agency (2022)

Appendix Table 6. Classification of soil pH ranges

Denomination (name for a category)	pH	Reference
Strongly acidic	<5.1	Horneck *et al*. (2011)
Moderately acidic	5.2–6.0	
Slightly acidic	6.1–6.5	
Neutral	6.6–7.3	
Moderately alkaline	7.4–8.4	
Strongly alkaline	>8.5	

Appendix Table 7. General guidelines on the interpretation of some soil property-tested results

Soil properties	Measured value	Rating	Reference
Organic C (%)	< 0.5	Very low	Tekalign (1991)
	0.5-1.5	Low	
	1.5-3.0	Moderate	
	> 3.0	High	
Total N (%)	< 0.05	Very low	Tekalign (1991)
	0.05-0.12	Low	
	0.12-0.25	Moderate	
	> 0.25	High	
Available phosphorus (mg kg^{-1})	<10	Low	Olson *et al*.(1954)
	10-25	Medium	
	25-50	High	
	>50	Excessive	
Cation Exchangeable Capacity (Cmol (+) kg^{-1})	<5	Very low	Landon and Manual (1991)
	5-15	Low	
	15-25	Medium	
	25-40	High	
	>40	Very high	
Exchangeable Na (Cmol (+) kg^{-1})	<0.03	Low	FMANR (1990)
	0.03-0.70	Medium	
	>0.70	High	

Appendix Figure 1.Site selection, design and layout of experimental site

Appendix Figure 2. Lime applications in the experimental site.

Appendix Figure 3. Earthing up of potato in the study area.

Appendix Figure 4.Late blight control, plant height measuring and study site observation of major and co-advisors

Appendix Figure 5. Physiological maturity and harvesting of potato in the study site

Appendix Figure 6.Tuber weight and size categories of potato after harvesting