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Growth Response and Yield of Several Industrial Potato (Solanum tuberosum L.) Varieties in Highland and Medium-Altitude Environments

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Abstract

The potato processing industry in Indonesia continues to face high market demand, while domestic production remains insufficient (reaching only 1.22 million tons in 2023), resulting in dependence on imported raw materials. The expansion of industrial potato cultivation in medium-altitude regions offers considerable potential due to land availability; however, it is constrained by high-temperature stress, requiring varieties that are both tolerant and high yielding. This study aimed to evaluate the growth response and yield performance of three industrial potato varieties Ventury Agrihorti (local), Atlantik (introduced), and Bliss/Chitra (introduced) under two contrasting altitude conditions: medium altitude (600 masl) and high altitude (1500 masl). The experiment employed a Split Plot Design, with observations covering growth parameters, yield components, and tuber quality indicators, including tuber specific gravity (SG). The results revealed a significant interaction between altitude and variety on several parameters, such as plant height, specific leaf weight, number of tubers, and tuber weight per plant. At medium altitude (600 masl), the Atlantik variety demonstrated the best performance, achieving a productivity of 40.39 t/ha with the highest tuber weight. However, Atlantik produced a high proportion of oversize tubers (41.97%), which does not meet industry grading standards. Conversely, at high altitude (1500 masl), Bliss/Chitra showed superior yield performance with a productivity of 42.96 t/ha, followed by Ventury at 38.46 t/ha. Ventury and Bliss/Chitra also excelled in tuber size distribution, producing the majority of tubers (approximately 94–95%) within the Normal category (Ø 4.5–9 cm), which aligns with industrial processing requirements in both altitude conditions. The specific gravity (SG) values of all three varieties ranged from 1.08 to 1.09, indicating compliance with the minimum quality threshold for potato processing industries (>1.08).

Introduction

Potatoes (Solanum tuberosum L.) are one of the vegetable crops cultivated in Indonesia. Potatoes are expected to thrive in various regions of Indonesia, especially in areas with suitable soil conditions for potato cultivation, particularly since Indonesia is located in the tropics and crossed by two mountain ranges, namely the Mediterranean and Pacific circles. This condition is a blessing for Indonesia because many horticultural crops can be cultivated, including potatoes (Setiyo et al., 2021; Mariyono et al., 2022; Winarsih et al., 2024). Potatoes are a commodity that has high market demand ( ) and are one of the types of vegetable crops cultivated in several regions in Indonesia. In 2023, potato consumption in Indonesia reached 5.3 million tons, both for public consumption and as raw material for the potato processing industry (Kementan RI, 2023).Potato production in Indonesia has only reached 1.22 million

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tons, so potatoes are still imported to meet consumption needs in Indonesia, as was the case in January 2023 when Indonesia imported 7.16 thousand tons of industrial potatoes. In Indonesia, there are several large industries that use potatoes as the main raw material for making potato chips, one of which is PT. Indofood Fortuna Makmur. Indofood uses a partnership system with farmers in several regions in Indonesia to meet the supply needs for potato chips, but the supply from the harvests of partner farmers in Indonesia only meets 40% of the demand, with the remaining 60% still being imported (Central Statistics Agency, 2024). The annual demand for potatoes in the industry is around 100,000-120,000 tons, while domestic production capacity only reaches 40,000-50,000 tons. To meet this demand, imports are carried out, as is the case for industrial potato seeds (Sipayung, 2023; Almekinders et al., 2009; Devi et al., 2024). Currently, the demand for industrial potato seeds is estimated at around 8,000 tons for an area of 4,000 hectares. Of this demand, only about 25% can be met domestically, with the rest being met through imports (Sutiwi & Mukti, 2022). The potato industry requires a specific type of potato as raw material that meets certain quality requirements, and this can only be fulfilled through good potato cultivation practices, not only in terms of planting methods, but also through the use of high-quality seeds and the use of potato varieties that are suitable for industrial needs (Asgar et al., 2016; Andrade-Piedra et al., 2025; Tessema et al., 2025). The standards required by the potato chip industry as raw materials are a specific gravity (SG) of at least 1.067 g ml-1 and a dry matter content of 16.7%, while for French fries, the requirements are elongated tubers weighing 170-284 g, a minimum specific gravity (SG) or specific weight (BJ) of 1.079, and a dry matter content of 20.5% (Budiman, 1999).

The Bliss potato variety is one of the varieties developed using potato seed technology that can be an option, alongside the Atlantic variety as an industrial potato that still relies on imported seeds. Bliss potatoes have a water content of 76.7%, which is lower than Granola potatoes, with a tuber size of 5.8 cm (Hidayat et al., 2018). The industrial potato varieties widely cultivated in Indonesia are the Atlantic and Bliss varieties, which are introduced varieties from various countries, including Scotland, Australia, and Canada, because they have the standard characteristics required by the potato chip industry. Meanwhile, Indonesia itself has several potato varieties for the potato chip processing industry, one of which is the Ventury Agrihorti variety, which is a cross between the Atlantic variety and clone 393284.39. In general, potato plants are cultivated in areas with an altitude of 1,000-3,000 meters above sea level. Potatoes grown at an altitude of less than 1,000 meters above sea level usually produce small tubers, with an average productivity of around 10-15 tons/ha, as the temperature and humidity are not optimal for potato growth (Setiyo et al., 2021). In the 1980s, Magelang Regency, Central Java Province, was known as the " " one of the medium-altitude potato production centers. The varieties planted included local varieties such as Gudril, Marini, and Kapur, with productivity around 4 tons/ha. As potato research and development in medium-altitude areas progressed, farmers began planting other varieties such as Cipanas, Aquilla, DTO 28, and DTO 33, thereby increasing productivity to 11-24 tons/ha (Basuki et al., 2009). In West Sumatra Province, Salimpaung and Batipuh subdistricts are producers of medium-altitude potatoes. The variety planted is the local Batang Hitam variety with a productivity of around 10 tons/ha. Potatoes are planted once a year after rice (Winardi, 2009). Potato cultivation in mediumlands faces the problem of high temperatures, which is a factor that inhibits tuber formation. In addition, high levels of pest attacks can cause crop losses of around 25-90% (Setiawati et al., 2009). Based on the data obtained, potato cultivation in medium-altitude areas in Indonesia is already widespread, but productivity is still lower than in high-altitude areas, and the potato varieties used are not the industrial raw material varieties desired by the potato industry in Indonesia. Therefore, opportunities for the development of industrial potato cultivation in medium-

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altitude areas are still wide open, as they are supported by the availability of vast medium-altitude land in Indonesia. However, this must also be supported by the availability of potato varieties that are tolerant to high temperatures and capable of high production with the support of technical culture technology and pest control technology that enable potato plants to grow optimally. Based on the background description of the existing problems, the author conducted research titled "Growth Response and Yield of Several Industrial Potato Varieties (Solanum tuberosum L.) in High and Medium Elevation Areas."

Methods

Time and Place of the Study

This was undertaken during the months of January to May 2025 which is also the main potato growing period in West Sumatra. The experiment aimed at comparing the growth and yield reactions of plants in opposite altitude regimes; hence, the two sites with significantly different altitude features were purposefully chosen. The use of two different locations facilitated the recording of environmental variations that usually control potato production in Indonesia with reference to temperature gradient and microclimatic variation with altitude.

The experimental location was a site with medium altitude, some 600 m above the sea level in Nagari Lubuk Selatan, in Sangir District, South Solok Regency, West Sumatra. This site is a symbol of the new potato producing areas where high temperatures tend to limit the growth of tubers. The site is high in altitude (around 1,500 m above sea level, located in Nagari Simpang Tj Nan IV, Danau Kembar District, Solok Regency) and is a typical location of highland potato cultivation, which tend to have a better climatic condition to grow potato. The laboratory analyses were supported at Plants Physiology Laboratory, Faculty of Agriculture, Universitas Andalas, Padang, and tuber specific-gravity analyses were also done at the PT Indofood Fortuna Makmur in Tangerang to make sure that the quality assessment was made in accordance with the industrial standards.

Materials and Equipment

The three varieties of potato used in this study were plant materials that are widely related to the industrial processing. These were Ventury Agrihorti variety, a local cultivar sourced in PT Dieng Agro Mandiri, Atlantik and the Bliss (or Chitra) varieties, an introduced variety with their origin in Scotland and Australia. The choice of these varieties was based on the fact that they are relevant to potato processing industry and differing genetic backgrounds, thus enabling meaningful comparisons of varietal responses to different altitude environment.

The other materials that were added to the experiment and included soil conditioners as liquid lime, humic acid, and biological soil amendments, as well as organic and inorganic fertilizers and pesticides. These inputs were used in tandem with recommended cultivation practices in order to facilitate the best growth of the plant along with maintaining similarity between treatments in the management. The tools that were used during the investigation aided field management as well as data collection. Measurements of altitude and soil acidity, land preparation and crop maintenance tools and equipment used in pest and disease control were used. Rulers, digital weighing scales, platform scales, ovens, and Zeal manual hydrometer were used to measure growth and yield, and specific gravity of tubers respectively. The use of documentation tools was also used in the documentation of the conditions of the field and the performance of the plants during the experiment.

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Experimental Design

A split-plot design was used to set up the experiment, as it would allow treating the treatment factors in a hierarchical way. The factor in the main-plot was the altitude since it could not be randomized in one location whereas the subplot factor was the potato variety. Two altitudes were considered, medium altitude of 600 m above sea level and high altitude of 1,500 m above sea level. Three varieties of potato were put to test within every level of altitude namely: Ventury - Agrihorti, Atlantik and Bliss (or Chitra).

The treatment combination was repeated four times to achieve greater statistical consistency, as well as to correct the occurrence of natural field variation. The main plot was 16.35m x 4.10m and the experimental-unit plot was 5.25m x 0.80m each. Plots were also spaced adequately in order to reduce competition and interference between treatments. Overall, the experiment included twenty-four experimental units.

Crop Management and Sampling

All the experimental units contained fifteen potato plants that were treated in the same way during the growing period. The commonly used standard cultivation procedures such as land preparation, planting, fertilization, irrigation, and pest control were equally used in all treatments. Such a consistent management technique was critical to provide that perceived difference in growth and yield could be related more to the effect of altitude and varietal rather than variation in the management practices.

Based on both plots, plants that were chosen were either to be sampled under destructive or non-destructive. They identified five plants to perform non-destructive observations to determine the growth parameters over time and three plants to undergo a destructive sampling to establish variables that demanded the removal of the plants. The sampling plan enabled a wide scope of data gathering without reducing end yield values.

Observation Parameters

Observations in this study covered a wide range of growth, physiological, and yield related The parameters of observations made during this study were very broad covering a range of growth, physiological and yield-related parameters to give the overall picture of the performance of the plant. Vegetative growth was measured in terms of plant height, leaf area, specific leaf weight and root volume. The selection of these variables presented was aimed at describing plant vigor and physiological adaptation to the condition of varied altitudes.

The evaluation of developmental responses was in terms of harvest age which indicated how the environment affecting crop maturity impacted. The yield components were analyzed in terms of the number of tubers per plant and the weight of tubers per plant and the tuber diameter was measured and categorized as oversize, normal, and undersize by the industrial grade of tubers. The quality of tubers was also evaluated by determining the specific gravity that is highly associated with the dry-matter content and the ability to be utilized in industry.

Data Analysis

All the data gathered were statistically analysed through analysis of variance which was suitable to split-plot design. This was analyzed based on the impact of the altitude, variety, and an interaction between them on all the variables observed. In situations where the analysis showed that there were significant differences between treatments, the mean separation was done with Duncan multiple range test at a level of five per cent.

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This method of analysis presented a strong model on how varietal performance was measured in opposite altitude settings. With the combination of field notes and proper statistical examination, the research could come up with valid conclusions on the flexibility and yield of industrial varieties of potatoes that were used in medium and high altitude.

Results and Discussion

Plant Height

The results of plant height observations after analysis of variance showed that there was an interaction between altitude and variety on potato plant height. The average results of plant height observations can be seen in Table 1.

Table 1. Plant Height at Several Elevations and Potato Varieties

Altitude	Ventury	Atlantik	Bliss/Chitra
Medium Altitude	69.29 bA	85.34 aA	85.48 aA
High Altitude	43.19 aB	44.75 aB	46.05 aB

CV: A = 7.40 B = 7.15

Note: Numbers followed by lowercase letters in the same row and numbers followed by uppercase letters in the same column are not significantly different at the 5% DMRT significance level.

Table 1. shows that altitude has different effects on potato varieties. At medium altitude, the Atlantic and Bliss/Chitra varieties did not differ significantly from each other, but differed significantly from the Ventury variety. This shows that at medium altitude, the Atlantic and Bliss/Chitra varieties have a growth advantage over the Ventury variety. Meanwhile, at high altitudes, all varieties did not show significant differences in plant height, indicating that at higher altitudes, the growth performance of the varieties became uniform and no variety was significantly superior. Conversely, Table 1 also shows that varieties have different effects at different altitudes, with all varieties showing a decrease in plant height from medium to high altitudes. This indicates that plant height decreases significantly at higher altitudes, not only in one variety, but consistently in all three varieties. This indicates a significant main effect of altitude on plant height. From the results of the study on the effect of growing altitude and potato variety on plant height, it can be concluded that environmental factors and plant genetic factors are interrelated. The environmental factor of growing altitude was divided into medium and high altitudes; the potato varieties used were Ventury, Atlantik, and Bliss/Chitra. The results showed that in the medium altitude area, the Atlantik and Bliss/Chitra potato varieties showed the best plant height, followed by the Ventury variety. This may be due to the genetic adaptation of the Atlantik and Bliss/Chitra varieties, which are more suited to the temperature and humidity conditions in medium altitude areas. Conversely, in high altitude areas, the three varieties showed relatively uniform plant height, which may indicate that the environmental conditions in high altitude areas may be more optimal for the growth of all these varieties. Previous studies support this finding, namely that a decrease in altitude will affect the increase in temperature, which can affect the productivity of certain potato varieties (Djuariah et al., 2017; Harahap & Jamil, 2006). The growth and production of Granola and Supejhon potato varieties were better at an altitude of 1200 m above sea level than at 750 m above sea level, with no significant interaction between variety and altitude (Mailangkay et al., 2012). The Bliss/Chitra variety has good growth at various doses of NPK fertilizer in highlands, indicating good adaptation to these environmental conditions. Selecting potato varieties that are suitable for the altitude at which they are grown is very important for optimizing plant growth and yield.

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The Atlantik and Bliss/Chitra varieties are more suitable for planting in medium altitude areas, while all varieties perform well in high altitude areas (Arimbi et al., 2023).

Leaf Area

The results of leaf area observations after analysis of variance showed that there was no interaction between altitude and variety on potato leaf area, but there was a single effect between the two treatments. The average results of potato leaf area observations can be seen in Table 2.

Table 2. Leaf Surface Area of Plants at Several Elevations and Potato Varieties

Altitude	Ventury	Atlantik	Bliss/Chitra	Mean
Medium Altitude	11524.413	14529.725	18974.915	15009.68 a
High Altitude	7712.095	10155.300	13922.680	10596.69 b
Mean	9618.25 B	12342.51 B	16448.80 A	

CV: A = 17.36 B = 26.95

Note: Numbers followed by lowercase letters in the same column and numbers followed by uppercase letters in the same row are not significantly different at the 5% DMRT significance level.

Table 2 shows that potato plants cultivated in medium elevations had an average leaf area of 15,009.68 cm², which was significantly larger than plants in high elevations, which only reached 10,596.69 cm². These results indicate that environmental conditions in medium altitude areas, such as warmer temperatures and relatively stable nutrient availability, tend to be more conducive to potato leaf expansion. The optimal temperature in medium altitude areas promotes increased enzymatic activity and the synthesis of hormones such as cytokinin, which play a role in cell division and enlargement. Higher temperatures within the optimal range significantly support the leaf surface area of potato plants.

Table 3.2 also shows that the Bliss/Chitra variety exhibited the highest performance with an average leaf area of 16,448.80 cm², followed by the Atlantik variety at 12,342.51 cm², and the lowest was the Ventury variety at 9,618.25 cm². This indicates that genetically, the Bliss/Chitra variety has the potential for broader leaf morphology, which is likely correlated with higher photosynthetic capacity and greater yield potential. These differences between varieties reflect genetic expression in plant vegetative growth, particularly in terms of leaf tissue development. Leaf area variation between potato varieties contributes significantly to photosynthetic efficiency and overall tuber yield (Asnake et al., 2023).

Specific Leaf Weight

The results of specific leaf weight (SLW) observations after analysis of variance show that there is an interaction between altitude and variety on the specific leaf weight of potatoes. The average results of observations on the specific leaf weight of potato plants can be seen in Table 3.

Table 3. Specific Leaf Weight (SLW) at Several Elevations and Potato Varieties

Altitude	Ventury	Atlantik	Bliss/Chitra
Medium Altitude	2.2168 aA	2.5082 aA	1.5817 bA
High Altitude	1.4129 aB	1.2917 aB	1.3361 aA

CV: A = 31.48 B = 13.66

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Note: Numbers followed by lowercase letters in the same row and numbers followed by uppercase letters in the same column are not significantly different at the 5% significance level.

Table 3 shows that in the medium altitude, the Atlantic variety had the highest specific leaf weight of 2.5082 g/m², which was significantly different from the Bliss/Chitra variety, which had a value of 1.5817 g/m². The Ventury variety was between the two with a value of 2.2168 g/m², which was not statistically significantly different from Atlantik, but significantly different from Bliss/Chitra. Meanwhile, at high altitudes, the specific leaf weight decreased in all varieties. The Ventury variety had the highest value of 1.4129 g/m², followed by Bliss/Chitra at 1.3361 g/m², and Atlantik with the lowest value of 1.2917 g/m². However, statistically, the three varieties at high altitude did not show any significant differences from each other.

Table 3.3 also shows that the Atlantik variety had the highest SLW value in the medium plains at 2.5082 g/m², which was statistically significantly different from the Bliss/Chitra variety, which had an SLW of 1.5817 g/m². The Ventury variety is between the two with a value of 2.2168 g/m², which is not statistically significantly different from Atlantic, but different from Bliss/Chitra. This shows that the Atlantic variety has better physiological leaf performance at medium altitude.

Based on the analysis of the interaction between planting altitude and potato variety on specific leaf weight (SLW), there is a significant effect of both factors on plant physiological parameters. SLW is an important indicator in plant physiology studies because it reflects plant adaptation to environmental conditions, particularly in terms of photosynthetic efficiency and leaf biomass accumulation (Pearce et al., 1969). In the highlands of Ethiopia, it was found that variety adaptation to the environment greatly affects the final yield. Varieties that are suitable for local agroecological conditions produce significantly higher yields. Although this study did not directly measure SLW, the reported tuber yield data can be considered an indirect indicator of physiological efficiency, including leaf performance (Tsagaye et al., 2025).

In medium highlands, the Atlantik variety showed the highest SLW value of 2.5082 g/m², which was statistically significantly different from the Bliss/Chitra variety, which had a value of 1.5817 g/m². The Ventury variety was between the two with a value of 2.2168 g/m². This shows that the Atlantic variety has better adaptability in utilizing environmental conditions in medium altitudes to increase photosynthetic efficiency and leaf biomass accumulation.

Conversely, in highlands, SLW values decreased in all varieties. The Ventury variety had the highest value of 1.4129 g/m², followed by Bliss/Chitra at 1.3361 g/m², and Atlantik with the lowest value of 1.2917 g/m². However, statistically, the three varieties in the highlands did not show any significant differences from each other. The decrease in SLW in highlands can be attributed to environmental conditions such as lower temperatures and different light intensity, which affect the rate of photosynthesis and leaf biomass accumulation (Mailangkay et al., 2012).

Planting altitude affects potato plant growth and production, with plant and tuber growth rates higher at an altitude of 1200 m above sea level than at an altitude of 750 m above sea level. This is in line with findings that environmental conditions in highlands can affect plant physiological parameters, including SLW (Mailangkay et al., 2012). Changes in temperature and light intensity due to differences in altitude affect plant structural characteristics, including the ability of leaves to absorb and convert light into photosynthetic energy (Hu et al., 2023). The relationship between SLW and net photosynthesis rate in alfalfa plants shows that an increase in SLW can improve photosynthetic efficiency. Although this study was conducted

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on different plants, the basic principles of plant physiology underlying the relationship between SLW and photosynthesis can be applied to potato plants (Pearce et al., 1969).

Root Volume

The results of root volume observations after variance analysis showed that there was no interaction between elevation and variety on potato root volume. The average results of potato root volume observations can be seen in Table 4.

Table 4. Root Volume of Plants at Several Elevations and Potato Varieties

Altitude	Ventury	Atlantik	Bliss/Chitra
Medium Altitude	23.75	27.50	27.00
High Altitude	26.75	31.00	34.00

CV: A = 27.85 B = 23.22

Note: The numbers in the columns and rows indicate the same effect according to the F-test.

Table 4 shows that in the medium elevation, the root volume weight for the Ventury, Atlantik, and Bliss/Chitra varieties is 23.75 ml, 27.50 ml, and 27.00 ml, respectively. After moving to highlands, all three experienced an increase, with Ventury reaching 26.75 ml, Atlantik reaching 31.00 ml, and Bliss/Chitra reaching 34.00 ml. This means that all varieties showed a similar physiological response to increased altitude, namely by increasing root system growth. This pattern indicates that the highland environment, which generally has lower temperatures and may cause mild stress to plants, encourages the root system to develop longer and larger in order to expand its reach for water and nutrients that may be more limited in availability. This is a common adaptation mechanism in plants to the highland environment, which applies uniformly to all varieties.

Environmental conditions at high altitudes, such as lower temperatures and different light intensities, can stimulate plants to develop deeper and more extensive root systems as an adaptive response to potential environmental stress. The depth and density of potato roots are influenced by variety and environmental conditions, including irrigation regime and planting date (Stalham & Allen, 2001).

The development of a more extensive root system at higher altitudes can increase the ability of plants to absorb water and nutrients, which is important for plant growth and yield. This is also supported by research showing that potato root systems can develop to a certain depth depending on environmental conditions and cultivation management. Thus, the increase in root volume weight in all potato varieties at high altitudes indicates the plants' adaptive response to different environmental conditions, which can improve water and nutrient absorption efficiency and contribute to overall crop productivity. At higher elevations, fresh tuber weight per plant decreases only slightly, with maximum vegetative growth occurring at medium elevations (around 2372 m), indicating that elevation affects overall plant growth (Hartz et al., 1977).

Harvest Age

Observations of potato crop harvest age after conducting average tests show that there are differences in harvest age between altitude and variety. The average results of observations on potato crop harvest age can be seen in Table 5.

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Table 5. Harvest Age of Potato Plants at Various Altitudes and Varieties

Altitude	Ventury (days)	Atlantik (days)	Bliss/Chitra (days)	Mean (days)
Medium Altitude	65	65	65	65
High Altitude	100	100	100	100

Note: The numbers in the same row and column are the results of the average test.

Table 5 shows data on the harvest age of potato plants based on two altitude levels and three potato varieties, namely Ventury, Atlantik, and Bliss/Chitra. The observation results show a consistent pattern across all varieties, where the harvest age at medium altitude is 65 HST, while at high altitude it is 100 HST. These results indicate a faster harvest age compared to the description of each variety, with an average harvest age for the three varieties based on the description of 110 HST.

Altitude is a significant environmental factor that influences the growth and development of potato plants. Data shows that potato plants grown at high altitudes have a longer harvest period than those grown at medium altitudes. This is due to the lower ambient temperature at high altitudes, which slows down the plant's metabolic rate, thereby prolonging the vegetative and generative phases. Low temperatures in highlands support optimal potato plant growth, but prolong the harvest period (Pantouw et al., 2022).

Conversely, in medium altitudes with higher temperatures, plant physiological processes occur more quickly, including tuber maturation, resulting in a shorter harvest period. However, high temperatures can also cause heat stress in plants, which can reduce crop quality and yield. High temperature stress during the seedling phase can inhibit potato tuber growth and yield. Interestingly, all varieties showed the same harvest period pattern at each altitude, namely 65 HST in medium altitude areas and 100 HST in high altitude areas (Ningsih et al., 2021). This indicates that the effect of altitude on harvest period is general and consistent across the varieties used in this study.

Potato varieties showed differences in harvest age, reflecting the genetic potential of each variety to adapt to environmental conditions. Some varieties were designed to have a shorter harvest age, suitable for medium altitudes, while others had a longer harvest age, suitable for high altitudes. The Granola variety has a faster flowering age compared to local varieties, which can affect the harvest age (Patimah et al., 2021).

Number of Tubers

Observations of the number of potato tubers after analysis of variance showed that there was an interaction between altitude and variety on the number of potato tubers. The average results of observations on the number of potato tubers can be seen in Table 6.

Table 6. Number of Potato Tubers at Several Elevations and Potato Varieties

Altitude	Ventury	Atlantik	Bliss/Chitra
Medium Altitude	5.70 bB	7.10 bA	10.55 aB
High Altitude	13.35 aA	7.50 bA	14.00 aA

CV: A = 25.57   B = 10.99

Note: Numbers followed by lowercase letters in the same row and numbers followed by uppercase letters in the same column are not significantly different at the 5% DMRT significance level.

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Based on Table 6 showing the number of potato tubers, it appears that there is a significant effect of elevation and variety on the number of tubers produced. In general, high altitudes show higher yields than medium altitudes. This can be seen from the average number of tubers of the Ventury variety, which increased dramatically from 5.70 tubers at medium altitudes to 13.35 tubers at high altitudes. The same pattern also occurred in the Bliss/Chitra variety, where the number of tubers increased from 10.55 to 14.00 tubers.

In the Atlantik variety, although there was an increase in the number of tubers from 7.10 tubers in medium altitude areas to 7.50 tubers in high altitude areas, this difference was not very significant in terms of numbers. This shows that the response of each variety to altitude can vary, indicating differences in physiological adaptation between varieties to environmental conditions. From this data, it can also be concluded that the Bliss/Chitra variety is the most stable and superior in producing tubers in both medium and high altitudes. Meanwhile, the Ventury variety showed an excellent response at high altitudes but was not optimal at medium altitudes. The Atlantik variety tends to produce a relatively low number of tubers at both altitudes. These findings are important in determining the right variety for specific agroecological conditions in order to maximize potato production.

Altitude affects various environmental parameters such as temperature, humidity, light intensity, and air pressure, all of which impact plant physiology, particularly photosynthesis and tuber formation. At high altitudes, lower temperatures (15–20°C) support optimal vegetative growth and tuber initiation, especially for varieties that are adaptive to cold temperatures. The optimum temperature for potato tuber formation is in the range of 16–20°C. Excessively high temperatures, such as those found in medium altitude areas (>25°C), can inhibit the tuberization process and reduce tuber yield due to increased respiration and inhibition of enzymes that induce stolon formation.

Potato tuber productivity is influenced by a combination of genetic, environmental, and cultivation management factors. Environmental factors such as temperature, humidity, and light intensity, which differ between highlands and medium altitude areas, greatly affect photosynthesis and tuber formation (Hijmans, 2003). Cooler highlands tend to support more efficient tuber formation, as seen in the increased yields of the Ventury and Bliss/Chitra varieties.

Tuber Weight

Observations of potato tuber weight after analysis of variance showed that there was an interaction between altitude and variety on the number of potato tubers. The average results of observations on potato tuber weight can be seen in Table 7.

Table 7 shows that in the medium altitude area, the Atlantik variety produced the highest tuber weight of 1346.35 grams, which was significantly different from the other varieties. This was followed by Bliss/Chitra with 1085.70 grams, while Ventury produced the lowest tuber weight of 482.07 grams. Meanwhile, in highland areas, Bliss/Chitra was the variety with the highest weight (1432.07 grams), followed by Ventury (1282.10 grams), and the lowest weight was shown by Atlantik (755.69 grams).

Table 7. Tuber Weight of Plants in Several Regions and Potato Varieties

Altitude	**Ventury**	**Atlantik**	**Bliss/Chitra**
Medium Altitude	482.07 bB	1346.35 aA	1085.70 aB
High Altitude	1282.10 aA	755.69 bB	1432.07 aA

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Note: Numbers followed by lowercase letters in rows and numbers followed by uppercase letters in the same column are not significantly different at the 5% DMRT level.

The Ventury variety showed a significant increase from 482.07 grams in the medium altitude region to 1282.10 grams in the high altitude region, indicating that Ventury is more suitable for cultivation in high altitude regions. The Atlantik variety experienced a significant decrease in tuber weight from medium elevation (1346.35 grams) to high elevation (755.69 grams), meaning this variety is more optimally suited for cultivation at medium elevation. Meanwhile, the Bliss/Chitra variety also showed an increase from medium altitude (1085.70 grams) to high altitude (1432.07 grams), indicating that this variety also performs better at high altitudes.

The tuber weight results show that the Bliss/Chitra and Ventury varieties show a significant increase in tuber weight when planted in highlands, while the Atlantik variety experiences a decline in performance under similar conditions. These findings indicate a real interaction between variety and altitude, where a variety's response to different environments is not uniform, thus demonstrating the inseparability of genetic and environmental factors.

Productivity/ha

Observations of potato crop productivity after analysis of variance showed that there was an interaction between altitude and variety on the number of potato tubers. The average results of observations on potato crop productivity can be seen in Table 8.

Table 8. Plant Productivity at Several Elevations and Potato Varieties

Altitude	Ventury	Atlantik	Bliss/Chitra
Medium Altitude	14.46 b B	40.39 a A	32.57 a B
High Altitude	38.46 a A	22.67 b B	42.96 a A

CV: A = 13.20 B = 8.70

Note: Numbers followed by lowercase letters in rows and numbers followed by uppercase letters in the same column are not significantly different at the 5% DMRT significance level.

Table 8 shows that of the three varieties at medium altitude, the Atlantic variety had the highest productivity at 40.39 tons/ha and the lowest productivity was shown by the Ventury variety at 14.46 tons/ha, while the Bliss/Chitra variety had a productivity of 32.57 tons/ha. Meanwhile, in the highlands, the Bliss/Chitra variety had the highest productivity at 42.96 tons/ha, followed by the Ventury variety at with a productivity of 38.46 tons/ha, and the Atlantic variety showed the lowest productivity at 22.67 tons/ha.

The productivity of the Ventury variety in medium lowlands was 14.46 tons/ha, which was the lowest of the three varieties cultivated, while in highlands, the Ventury variety produced a much better productivity of 38.46 tons/ha. Referring to the variety description (Appendix 2), the Ventury variety has a potential tuber yield per hectare of 23.24–32.91 tons. The productivity of the Ventury variety on medium terrain is below its potential yield, while on high terrain it produces higher productivity than its potential yield. This indicates that the Ventury variety is not suitable for cultivation on medium-altitude land.

The productivity of the Atlantik variety on medium terrain is higher than on high terrain, and productivity on both terrains is also higher when compared to the description of the Atlantik variety, which is only 8–20 tons/ha. This shows that the Atlantik variety is suitable for cultivation on medium and high terrain, but has greater potential on medium terrain.

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The Bliss/Chitra variety shows no significant difference in productivity between medium and high altitudes (32.57 tons/ha and 42.96 tons/ha). However, based on the description of the Bliss/Chitra variety, the productivity of the Bliss/Chitra variety in medium and high altitudes is much better than the potential yield based on the description of the Bliss/Chitra variety. This shows that the Bliss/Chitra variety is suitable and has great potential for cultivation in both medium and high altitudes.

Physiologically, varieties have different environmental adaptation thresholds, especially to temperature, humidity, and light intensity, which are influenced by elevation. In highlands, the temperature is relatively lower and solar radiation is higher, so varieties that have the ability to adapt to cold temperatures and high photosynthetic efficiency will be more productive. In this case, Bliss/Chitra and Ventury likely have morphological and physiological adaptation mechanisms such as optimal leaf area, light use efficiency, and root systems that are suitable for highland soil conditions. Conversely, the Atlantik variety, which may be more tolerant of moderate to high temperatures, actually experiences a decline in productivity when planted in colder highlands that are less suitable for its genetic expression.

This assumption of interaction is also supported by the concept of genotype × environment interaction (G×E), which states that the performance of a genotype (in this case, a variety) is greatly influenced by its environment, so that a variety that excels in one location may not necessarily show the same superiority in another location (Falconer & Mackay, 1996). North Sulawesi also shows that potato tuber yields differ significantly between lowlands and highlands, as well as between varieties. The Granola variety, for example, shows better yields in highlands than in lowlands (Mailangkay et al., 2012). The Granola variety is more stable in the face of high temperature stress than Atlantik, indicating that genetic differences greatly determine adaptability (Ningsih et al., 2021).

High temperatures during the tuber formation phase can reduce yields due to decreased photosynthesis rates and enzyme activity, which are physiological responses to environmental stress. Therefore, in highland conditions, varieties with low temperature tolerance and adaptive physiological abilities will show higher yields. Therefore, the different responses among varieties at different elevations are not only caused by the environment itself but by the complex interaction between the physiological, morphological, and genetic characteristics of the plant and its growing environment (Pantouw et al., 2022).

Tuber Diameter

The results of observations of tuber diameter in potato plants after conducting an average analysis show that there are variations in tuber diameter values between altitude and variety. The average percentage of observations of potato tuber diameter can be seen in Table 9.

At medium altitude, the Ventury and Bliss/Chita varieties showed average percentage values for tuber diameter according to PT. Indofood's acceptance criteria for oversized tubers of 0.00% and 0.00%, normal tubers of 94.21% and 94.84%, and undersized tubers of 5.79% and 5.16%. This shows that the Ventury and Bliss/Chitra varieties produce the majority of tuber diameters that meet the standard requirements for the potato industry (Normal Category Ø 4.5–9 cm). Meanwhile, the Atlantik variety had average diameter percentages in the Oversize category of 41.97%, Normal 55.71%, and Undersize 2.32%.

These results indicate that in terms of tuber size, Atlantik is significantly larger than the tubers produced by the Ventury and Bliss/Chitra varieties. This is economically disadvantageous, as the industrial market only accepts tuber diameters in the Normal category.

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Table 9. Potato Tuber Diameter in Several Regions and Potato Varieties

Altitude	Variety	Oversize (%)	Normal (%)	Undersize (%)
Medium	Ventury	0.00%	94.21%	5.79%
	Atlantik	41.97%	55.71%	2.32%
	Bliss/Chitra	0.00%	94.84%	5.16%
High	Ventury	0.00%	95.39%	4.61%
	Atlantik	20.13%	76.66%	3.21%
	Bliss/Chitra	1.40%	91.06%	7.53%

Note: The numbers in the rows are the average test results, which are then categorized based on tuber diameter size.

In the highlands, only the Ventury variety consistently did not produce tubers in the Oversize category, at 0.00%. In fact, there was an increase in the Normal category to 95.39% and a decrease in the Undersize category to 4.61%. For the Atlantik variety, there was a positive trend in the highlands compared to the mediumlands, with a decrease in the Oversize category to 20.13%, an increase in the Normal category to 76.66%, and a decrease in the Undersize category to 3.21%. Meanwhile, in the Bliss/Chitra variety, the Oversize category appeared at 1.40%, which was not previously found in the medium highlands. In the Normal category, there was a decrease to 91.06% and an increase in the Underzise category to 7.53% compared to the medium highlands. From these results, it can be stated that the Ventury variety is stable in producing tuber diameters that meet industrial market demand. Although there was a decrease in the Oversize category in the Atlantik variety, the value is still relatively high and economically detrimental. Similarly, in the Bliss/Chitra variety, there was a decrease in the Normal tuber diameter. This pattern indicates that environmental or cultivation management factors still play an important role, including evaluating the appropriate harvest age to achieve stable yields that meet industrial market demand.

The increase in tuber diameter in highlands is the result of environmental conditions that support the extension of the tuber formation phase. The optimal temperature for potato growth is between 15–20°C. Excessively high temperatures in mediumlands can cause physiological stress and accelerate plant aging (Struik & Wiersema, 2012). The variability in diameter data indicates that the Atlantic variety has high genetic potential for producing large tubers. Both locations still produce tubers in the oversize category, but further study is needed to determine whether they meet industrial market demand standards, possibly through improvements in agronomic management such as irrigation, planting distance, fertilization, or harvest age. Meanwhile, in terms of the industrial market, the Ventury and Bliss/Chitra varieties have great potential for development. Breeding approaches or technical modifications to cultivation are urgently needed to improve yield uniformity. Potato yield stability is greatly influenced by genotype × environment interactions, where superior varieties must be able to maintain their performance under various environmental conditions (Firman et al., 2006). Varieties with high tuber size fluctuations are more suitable for use in intensive agricultural systems that apply precise and controlled agronomic management (Lommen & Struik, 1992).

Tuber Specific Gravity (SG)

Observations of potato tuber specific gravity after analysis of variance showed that there was no interaction between altitude and variety on the number of potato tubers. The average results of potato tuber specific gravity observations can be seen in Table 10.

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Based on Table 3.10, which shows the Specific Gravity/SG of several potato varieties at two altitudes, it can be seen that the SG values are relatively uniform in the range of 1.08 to 1.09. At medium altitude, all varieties, namely Ventury, Atlantik, and Bliss/Citra, had the same SG value of 1.08. Meanwhile, at high altitude, the Atlantik and Bliss/Citra varieties showed a slight increase in SG value to 1.09, while Ventury remained at 1.08.

Table 10. Specific Gravity of Potato Tubers in Several Regions and Potato Varieties

Altitude	Ventury	Atlantik	Bliss/Chitra
Medium Altitude	1.08	1.08	1.08
High Altitude	1.08	1.09	1.09

CV: A = 0.3756 B = 0.2972

Note: Numbers in the same row and column indicate the same effect in the 5% F test.

Specific gravity values are directly related to the dry matter content of potato tubers, where higher SG values usually reflect higher starch content and better quality for processed products such as French fries and chips. An SG value above 1.08 is generally considered sufficient for industrial potato processing. The uniformity of SG in the medium plains, where environmental conditions are relatively stable, provides an opportunity for the three varieties to express their genetic potential optimally and uniformly (Lisinska & Leszczynski, 1989). This environmental stability minimizes external variations that can affect growth and starch accumulation, so that the differences that arise are more influenced by genetic factors than the environment (Li et al., 2018).

Therefore, although the difference is small, the increase in SG values in the Atlantic and Bliss/Citra varieties in highlands can be considered an indicator of slightly better quality compared to the results in mediumlands. The stability of the SG value of the Ventury variety indicates its consistency in forming tuber quality in two different environments, but the Atlantic and Bliss/Citra varieties appear to be more responsive to highland conditions, which may be influenced by lower temperatures and higher solar radiation.

Conclusion

Based on the results of the experiments conducted, the following conclusions can be drawn: There is an interaction between altitude and variety on potato plant growth and yield in terms of the following variables: plant height, specific leaf weight, number of tubers, and tuber weight per plant. The Atlantic variety shows the best effect on growth and yield at medium altitudes, while the Bliss/Chitra and Ventury varieties show the best effect on growth and yield at high altitudes. The Atlantic and Bliss/Chitra varieties show the best effect on potato plant growth and yield at medium and high altitudes.

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