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*Full Length Article*

# Influence of Tuber Size and Variety on Agronomic Traits and Yield of Potato (*Solanum tuberosum*) grown in Highlands of Northern Pakistan

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**Abstract**

Optimization of tuber size is crucial for enhancing potato cultivation and production, worldwide. A field research was carried out to evaluate the effects of different tuber size and varieties on growth and yield traits of potato crop during summer irrigation season 2023 under the environmental conditions of Battakundi Northern Pakistan. Experimental materials were consisted of five potato varieties namely Sarpomira, Burna, Coroda, Rocco and Cardinal with different tuber sizes including small (31.5 $\pm$ 2.5 g), medium (57 $\pm$ 2.5 g) and large (77.5 $\pm$ 2.5 g), respectively. Randomized complete block design was employed with three replications. Results exhibited that potato varieties and tuber size had significantly ($P < 0.01$, $0.05$) influenced the studied traits except number of stems plant$^{-1}$ and unmarketable tuber yield. The variety Sarpomira produced highest marketable (34.58, 33.55 and 31.45 t ha$^{-1}$) tuber yield for small, medium and large tubers, respectively. Lowest gross income (436140.00 PKR ha$^{-1}$) and net benefit (366475.60 PKR ha$^{-1}$) were exhibited from the variety Burna coupled with medium tuber size. The highest gross income (622440.00 PKR ha$^{-1}$), net benefit (562039.60 PKR ha$^{-1}$) and acceptable (952.43%) marginal rate of return was produced from the variety Sarpomira in combination with small tuber size. Therefore, it is concluded that this treatment combination has potential to improve farmers' income by increasing productivity and reducing input costs, which makes potato production economically more viable. Further, it can empower smallholder farmers to enhance their production systems, improve livelihoods, and play a key role in contributing to regional food security.

**Keywords:** Potato; Tuber size; Sarpomira; Marginal rate of return; Smallholder farmers

## Introduction

The potato (*Solanum tuberosum* L.) belongs to the Solanaceae family, which is often referred to as the nightshade family. Potatoes are considered as one of the most important cash crops. They can produce a high yield of tubers in a relatively short passage of time, making them efficient for food production (Asnake *et al.* 2023). Additionally, potatoes provide a good source of carbohydrates, vitamins (like vitamin C and several B vitamins), and minerals (Luitel *et al.* 2020). Potato production and consumption occurs on a large scale worldwide (Batool *et al.* 2020; Caliskon *et al.* 2022). According to FAO data, global potato production has seen impressive figures, with around 376 million tons harvested from about 18.1 million ha (FAOSTAT 2023). This highlights the potato's significance as a staple food crop worldwide. The high yield per ha is a testament to the efficiency of potato cultivation, making it a vital resource for food security in many countries.

In Pakistan, potatoes are grown in three main cropping seasons namely spring, autumn, and summer. This diverse cultivation allows farmers to take advantage of various agro-ecological conditions across the country, from plains to highland and hilly areas (Majeed and Muhammad 2018). In Pakistan, potatoes are cultivated on approximately 341,000 ha, yielding an average production of around 8.32 million tons (PBS 2022-23). This level of production highlights the importance of potatoes as a staple food and cash crop in the country. Punjab is the largest (75%) producer of potato whereas highlands/hilly areas of Khyber Pakhtunkhwa, Gilgat-Baltistan and Azad Kashmir are also major shareholder of potato production in Pakistan. Despite the potential for high yields, potato production in Pakistan is

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often lower compared to neighboring countries, primarily due to various biotic (like pests and diseases) and a-biotic (such as drought, soil quality, and temperature extremes) stresses (Majeed *et al.* 2017; Majeed and Muhammad 2018). Drought and salinity are also one of the main reasons to restrict the potato production in Pakistan (Rai *et al.* 2011; Levy *et al.* 2013).

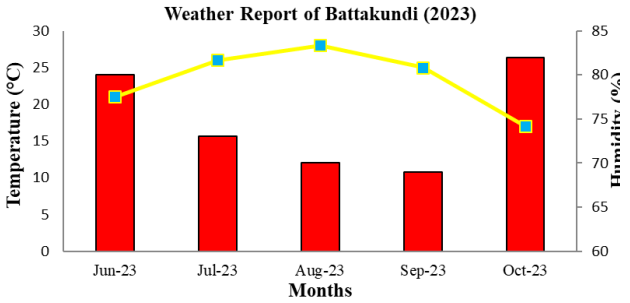
Using disease-free seed potatoes and standard tuber size is crucial for achieving high yields and successful seed potato production (Asnake *et al.* 2023). Generally, using larger tuber size of potato tends to result in better performance, leading to higher tuber yields and improved quality compared to smaller tubers. The production of different sizes of potato tubers is notably effected by choice of potato variety and the agro-ecological conditions in which they are grown (Regasa *et al.* 2022). The shortage of superior seed and tuber size is a key factor limiting crop productivity in Pakistan, alongside the challenges posed by biotic and a-biotic stressors**.** By addressing this issue through improved seed distribution systems**,** financial support for seed purchases, and training programs**,** Pakistan can significantly enhance crop yields and improve food security (Arif *et al.* 2024). In the highlands and hilly areas of Pakistan such as Kaghan, Battakundi and their surrounding areas, where smallholder farmers often use small tuber size (less than 25 g) for potato cultivation, especially for domestic use during the winter season. Additionally, the lower temperature and long shiny days of the environment Battakundi and other mountainous areas have the potential to cultivate and increase potato production, which could improve and enhance income for household of the area (Hassan *et al*. 2023) especially during summer season.

Optimizing tuber size and selecting high yielding variety are crucial factors for enhancing potato cultivation and production, globally. Additionally, both the potato variety and tuber size play crucial roles in determining the quality and quantity of the potato yield (Zeleke *et al.* 2021), ultimately increase overall potato production, economically (Ebrahim *et al.* 2018; Regasa *et al.* 2022). Despite many research studies on various aspects of potato cultivation and production, there is still a dire need for further research to understand the full impact of factors like tuber size and different potato varieties on yield and other related attributes (Masarirambi *et al.* 2012). It is noteworthy that the interaction between potato varieties and tuber sizes (small, medium, large) has not been sufficiently explored in the highlands of northern Pakistan. This lack of focused research could contribute to suboptimal potato production in the region. To address this, more localized studies are needed to assess the specific conditions of the highland areas, where environmental factors such as altitude, temperature, and soil types differ from those in other regions. By addressing these research gaps, researchers can provide tailored recommendations that will help farmers in northern Pakistan to improve their potato production, increase yields, and boost profitability while ensuring sustainability. Therefore, the current investigation was carried out with the aim to select the optimum tuber size that maximizes yield, yield attributing traits and quality for specific high-yielding potato varieties in the highlands of northern Pakistan. Assessing different high-yielding potato varieties for their compatibility with selected tuber sizes will help to identify and select the best combinations for enhancing potato production in the region. The economic analysis of potato production related to tuber size is also an essential component that can provide valuable insights that empower smallholder farmers to enhance their practices and could play a significant role in improving their livelihood, food security and economic growth. Despite many investigations over many years on this important crop, more information is required on interrelationships of plant populations and tuber sizes in relation to its growth and subsequent yield. Despite many investigations over many years on this important crop, more information is required on interrelationships of plant populations and tuber sizes in relation to its growth and subsequent yield. Despite many investigations over many years on this important crop, more information is required on interrelationships of plant populations and tuber sizes in relation to its growth and subsequent yield. Despite many investigations over many years on this important crop, more information is required on interrelationships of plant populations and tuber sizes in relation to its growth and subsequent Despite of many research studies on various aspects of potato cultivation and production, there is still a dire need for further research to understand the full impact of factors like tuber size and different potato varieties on yield and other related attributes (Masarirambi *et al.* 2012). It is noteworthy that the interaction between potato varieties and tuber sizes (small, medium, large) has not been sufficiently explored in the highlands of northern Pakistan. This lack of focused research could contribute to suboptimal potato production in the region. To address this, more localized studies are needed to assess the specific conditions of the highland areas, where environmental factors such as altitude, temperature, and soil types differ from those in other regions. By addressing these research gaps, researchers can provide tailored recommendations that will help farmers in northern Pakistan to improve their potato production, increase yields, and boost profitability, while ensuring sustainability. Therefore, the current investigation was carried out with the aim to select the optimum tuber size that maximizes yield, yield attributing traits and quality for specific high-yielding potato varieties in the highlands of northern Pakistan. Assessing different high-yielding potato varieties for their compatibility with selected tuber sizes will help to identify and select the best combinations for enhancing potato production in the region. The economic analysis of potato production related to tuber size is also an essential component that can provide valuable insights that empower smallholder farmers to enhance their practices and could play a significant role in food security and economic growth.

## Materials and Methods

### Study site overview

The experiment was carried out in seed potato research and multiplication farm Battakundi (34°56'0" N latitude and 37°46'0" E longitude), Mansehra District, Northern Pakistan during the 2023. Average maximum temperature (°C) and humidity (%) observed during the summer season were 23.4°C and 74.8%, respectively, whereas soil of the experimental area was found to be lower in organic matter and was acidic in nature having pH of 5.5. Additionally, monthly average temperature (°C) and relative humidity (%) data are presented in Fig. 1.




*Source: www.climate-data.org*

**Fig. 1:** Weather report of Battakundi 2023. Mean temperature (°C) and humidity (%) for the months (June 2023 to October 2023). Red vertical bars are showing humidity while yellow curved line with blue boxes shows temperature fluctuations during the studied period

### Description of experimental materials

The experimental material was consisted of potato varieties namely Sarpomira, Burna, Coroda, Rocco and check 'Cardinal'. The varieties Sarpomira and Burna originated in Hungry and Germany, while Coroda and Rocco originated in Holland and Austria, respectively. Whereas, check variety 'Cardinal' originated in Holland. Different tubers were collected from Hazara Agriculture Research Station Abbottabad and categorized on the basis of their size (small, medium and large) and weight (31.5 g, 57 g and 77.5 g). The pedigree of potato varieties including information about their parentage, origin, year of release and their codes are presented in Table 1. This information is essential for understanding the genetic composition and yield potential of the potato varieties.

### Treatments and field layout

Five different potato cultivars and three different tuber sizes including small (31.5 ± 2.5 g), medium (57 ± 2.5 g) and large (77.5 ± 2.5 g) were used as treatments, also highlighted by Asnake *et al.* (2023). The weight of tuber sizes was maintained uniform within each category with maximum weight difference of about ± 2.5 g.

The experiment was replicated three times using a randomized complete block design, ensuring the robustness and reliability of the results. Planting density was optimized by setting the row-to-row distance at 75 cm and the tuber-to-tuber distance at 25 cm. A total of 24 tubers were grown per plot, consisting of two rows with a 3 meter row length, covering a plot size of 4.5 m².

### Management of experimental plants

Experimental plots were prepared after proper plough and soil bed raising. Healthy and well sprouted tuber size was sown, manually. Fertilizers applied were diammonium phosphate (220 kg $ha^{-1}$), potassium sulphate (260 kg $ha^{-1}$) and Urea (180 kg $ha^{-1}$), accordingly. Standard agronomic practices including irrigation and fungicide were applied according to the recommended rates. Harvesting was also performed manually, ensuring consistent and accurate data collection. All other necessary pre and post-cultural practices including weeding, spraying and hoeing were applied, uniformly and timely to maintain crop health and vigor throughout the experiment.

### Data Collection

**Phenological parameters:** Days to 50% emergence were counted from the date of tubers plantation onwards up to completion of 50% tubers in each plot. Similarly, days to 50% flowering were also measured. Whereas, days to 90% maturity were recorded from the date of tuber plantation onwards up to completion of 90% tubers maturity particularly when plants started to show senescence haulm and leaves (Asnake *et al.* 2023). The mean values were calculated for further data analysis.

**Growth parameters:** In the present study, data for plant height (cm), stems number per plant and leaf area per plant ($cm^2$) were also recorded. The plant height of seven random potato plants was calculated using meter rod. Similarly, stems number and leaf area per plant were also calculated from seven randomly selected plants upon the completion of 50% flowering (Asnake *et al.* 2023). Leaf area was calculated by using the formula where leaf length (cm) and width (cm) was multiplied to get leaf area in $cm^2$.

**Tuber yield parameters:** The harvested tubers were divided into three different categories including small (< 25 g), medium (25 – 38 g), and large (> 75 g) tuber size (Asnake *et al.* 2023). Different tuber sizes were weighed individually and tuber yield for small, medium and large tubers were converted into tons $ha^{-1}$, respectively. Further, marketable (> 25 g) and unmarketable (< 25 g) tubers were separated from different tuber sizes.

### Statistical analysis

The analysis of variance (ANOVA) for the recorded data on the characters studied different potato varieties was

**Table 1:** Pedigree of potato varieties used for selection of seed tuber size and economic analysis

| Variety | Parentage | Origin | Release year | Code |
|---|---|---|---|---|
| Sarpomira | 76.PO.12.14.268 × D187 | Hungry | 2003 | 87.4.120 |
| Burna | KARDAL × SPOLIA | Germany | 2007 | UP6.434/2 |
| Coroda | *AR 76-199-3 × KONST 80-1407* | Holland | 1998 | KK83-216 |
| Rocco | ALWARA × MA 81-536 | Austria | 1998 | NO 89-2525 |
| Cardinal | *TULNAR/DEVRIES54-30-8×SVP55-89* | Holland | 1972 | BRANDS60-51 |

**Table 2:** Phenological traits of potato plants as effected by varieties and their tuber size

| Variables | Days to 50% emergence | Days to 50% flowering | Days to 90% maturity |
|---|---|---|---|
| (a) Variety | | | |
| Sarpomira | $33^{a}$ | $61^{a}$ | $111.67^{a}$ |
| Burna | $28.33^{b}$ | $56.33^{b}$ | $86.67^{c}$ |
| Coroda | $31^{ab}$ | $49.33^{c}$ | $90.67^{b}$ |
| Rocco | $31.33^{a}$ | $42.67^{d}$ | $82.67^{d}$ |
| Cardinal © | $31^{ab}$ | $49^{c}$ | $90.67^{b}$ |
| Significant sign | ** | *** | *** |
| LSD (0.05) | 2.76 | 2.09 | 3.59 |
| (b) Tuber size category | | | |
| Small (31.5 $\pm$ 2.5 g) | $31.33^{a}$ | $63.33^{b}$ | $114.33^{b}$ |
| Medium (57 $\pm$ 2.5 g) | $30.67^{b}$ | $62.11^{a}$ | $94.67^{a}$ |
| Large (77.5 $\pm$ 2.5 g) | $28.67^{b}$ | $59.67^{b}$ | $88.67^{b}$ |
| LSD (0.05) | ** | ** | ** |
| CV (%) | 4.74 | 2.15 | 2.07 |

*** = Very highly significant, ** = Highly significant, NS = Non-significant, LSD = Least Significant Difference, CV = Coefficient of Variation

conducted using Statistix 8.1 (Analytical Software 2005). Following the ANOVA, the LSD (Least Significant Difference) Fisher test ($P < 0.05$) was used to compare treatment means and to identify their significant effects. By employing these statistical methods, the study aimed to analyze the data, identify significant differences among treatment means, and to explore the relationships between different traits.

### Economic analysis

Marginal rate of return (MRR) and partial budget analysis for potato varieties and their tuber size combinations were determined using the procedure described by CIMMYT (1988). MRR was calculated based on the total variable cost, defined as the seed tuber cost for each treatment, using the specified formula and methodology, as highlighted by CIMMYT (1988). Labor costs were constant across all treatments, while other costs were measured on a quantity basis.

## Results

### Phenological Parameters of Potato

**Days to 50% emergence:** Analysis of variance showed highly significant differences for both variety and tuber size ($P < 0.01$). However, their interaction ($P > 0.05$) did not influence the said trait. Potato variety Burna took the lowest days to emerge and completed 50% emergence (28.33 days) in comparison with other three varieties and a check cultivar (Table 2). Potato variety Sarpomira took the highest number of days to complete 50% emergence (33 days) followed by Rocco, Coroda and check variety 'Cardinal'.

In case of tuber size, tubers with large size took the lowest days to germination (28.67 days) in comparison with medium and small tuber size which took 30.68 and 31.33 days in completing 50% emergence of potato plants (Table 2). Mostly, it was observed that the lower tuber size of potato had taken the highest days to emergence as presented in this study.

**Days to 50% flowering:** Days to flowering showed very highly significant ($P < 0.001$) differences for potato variety and significant ($P < 0.01$) differences for tuber size. Meanwhile, interaction effects of variety and tuber size did not affect the studied trait. Regarding results, potato variety Rocco flowered earliest (42.67 days) followed by check variety 'Cardinal' and Coroda, respectively. Meanwhile, potato variety Sarpomira took the highest (61 days) days (Table 2).

It was noted that flowering took lower days if tubers grown were consisted of larger size. In present study, large tuber size took the lowest days to 50% flowering followed by medium and small tuber size having 59.67, 62.11 and 63.33 days, respectively (Table 2).

**Days to 90% maturity:** Very highly ($P < 0.001$) effects on variety and highly ($P < 0.01$) significant effects on tuber size were observed for maturity while their interaction showed only significant ($P < 0.05$) effects. Mostly, early maturing potato plants are highly desirable in comparison with late maturing potato plants. This study suggested that potato variety Rocco matured earliest (82.67 days) followed by Burna and check variety 'Cardinal' while Sarpomira took the highest time (111.67 days) to attain maturity (Table 2). In case of tuber size, tubers with large size matured

earlier (88.67 days) in comparison with small and medium tubers (Table 2). Current findings exhibited that large tuber size showed early emergence followed by lower days to flower and maturity in comparison with small tuber size.

## Growth Parameters

**Plant height:** ANOVA showed significant ($P < 0.05$) influences on potato variety, tuber size and their interaction. Small tuber size of variety check 'Cardinal' showed tallest (45.62 cm) plants followed by small tuber size of Rocco (44.25 cm) and large tuber size of Sarpomira (43.80 cm) whereas shortest plants (34.49 cm) was recorded for the large tuber size of variety Coroda followed by medium tubers of check 'Cardinal' variety having 36.16 cm plant height (Table 3).

**Number of shoots per plant:** This is a significant trait that contributes towards high potato yield. Non-significant ($P > 0.05$) effects were observed for potato variety, tuber size and their interaction. The varieties Rocco and check 'Cardinal' produced the highest (5.00) and lowest (3.67) shoots number plant$^{-1}$, respectively (Table 4). In the case of tuber size, maximum (4.67) shoots plant$^{-1}$ was produced from tubers having larger size followed by medium and small tuber size which produced least (3.67) shoots per plant. This study clearly demonstrated that increasing tuber size has resulted in enhancing shoot number and vice versa (Table 4).

**Leaf area per plant:** Leaf area plant$^{-1}$ showed significant ($P < 0.05$) influence on potato variety, tubers size and their interaction. Maximum leaf area per plant (43.26 cm) was produced from medium tubers of check variety 'Cardinal' followed by large tubers of check variety 'Cardinal' and medium tubers size of variety Rocco having leaf area of 39.18 and 37.22 cm, respectively. Whereas, minimum leaf area per plant (27.89 cm) was observed for the variety Burna (Table 3).

## Yield and Yield Attributing Traits

**Small sized (25 – 38 g) tuber yield:** The results demonstrated significant ($P < 0.05$) influences on potato varieties and tuber size but their interaction did not influence. The variety Sarpomira produced maximum (14.35 tons ha$^{-1}$) tuber yield whereas Coroda gave minimum (11.91 t ha$^{-1}$) tubers yield (Fig. 2A). Tuber size of potato had also affected ($P < 0.05$) the tubers yield of small size. Regarding size of tuber, maximum (9.46 t ha$^{-1}$) tuber yield was received from tubers having larger size while minimum (5.23 t ha$^{-1}$) yield was noted in small tubers size (Fig. 2B), indicative of high tuber yield by increasing tuber size from small to large.

**Medium-sized (39 – 75 g) tuber yield:** Analysis of variance showed highest ($P < 0.001$) effects on potato variety and significant ($P < 0.05$) effects on tuber size of potato meanwhile medium tubers size interaction was not affected by two factors analysis. Maximum medium tubers (11.47 t ha$^{-1}$) production had observed in Rocco whereas minimum tubers yield (7.33 t ha$^{-1}$) was noted in potato plants of variety Coroda (Fig. 3A). Mostly, medium size of tubers is preferred by potato breeders and growers due to their ideal seed size and marketability. In this study, tubers size of potato plants significantly ($P < 0.05$) influenced the medium tubers. Larger tuber size of potato produced the highest (10.34 t ha$^{-1}$) medium tubers production whereas the lowest medium tubers yield (6.97 t ha$^{-1}$) was produced from tubers consisted of smaller in size (Fig. 3B).

**Large-sized (> 75 g) tuber yield:** ANOVA showed highly ($P < 0.001$) significant effects on variety and significant ($P < 0.05$) effects on tuber size and their interaction ($P < 0.05$). The highest large tuber size (11.33 t ha$^{-1}$) yield was observed in variety Burna in comparison with Sarpomira and local check 'Cardinal' having production of 10.6 and 9.71 t ha$^{-1}$, respectively. However, the lowest (6.15 t ha$^{-1}$) production was recorded in variety Rocco (Fig. 4A). Mostly large tuber size of potato plants is producing highest potato production and are also desirable for their high marketability, eyes number, sprouting and high food potential (Fig. 4B).

**Table 3:** Interaction effects of variety and their tuber size on different growth parameters of potato varieties

| Varieties | Tuber size category (g) | Plant height (cm) | Days to 90% maturity (days) | Leaf area plant$^{-1}$ (cm) |
|---|---|---|---|---|
| Sarpomira | Small | 42.63$^{a}$ | 111.33$^{a}$ | 33.12$^{ab}$ |
| | Medium | 43.50$^{a}$ | 110.67$^{a}$ | 32.06$^{b}$ |
| | Large | 43.80$^{a}$ | 112.00$^{a}$ | 34.77$^{a}$ |
| Burna | Small | 41.12$^{a}$ | 84.67$^{d}$ | 27.89a |
| | Medium | 38.03$^{b}$ | 91.00$^{b}$ | 31.82$^{b}$ |
| | Large | 37.46$^{b}$ | 90.33$^{bc}$ | 35.82$^{b}$ |
| Coroda | Small | 39.40$^{b}$ | 90.00$^{bc}$ | 33.24$^{ab}$ |
| | Medium | 36.45$^{b}$ | 89.33$^{b}$ | 34.42$^{b}$ |
| | Large | 34.49$^{b}$ | 87.67$^{c}$ | 36.62$^{bc}$ |
| Rocco | Small | 44.25$^{a}$ | 86.33$^{cd}$ | 35.89$^{b}$ |
| | Medium | 37.87$^{b}$ | 88.33$^{b}$ | 37.22$^{b}$ |
| | Large | 36.69$^{b}$ | 89.67$^{bc}$ | 36.25$^{a}$ |
| Cardinal © | Small | 45.62$^{c}$ | 90.67$^{b}$ | 35.72$^{b}$ |
| | Medium | 36.16$^{b}$ | 90.67$^{b}$ | 43.26$^{a}$ |
| | Large | 36.56$^{b}$ | 93.00$^{b}$ | 39.18$^{b}$ |
| LSD (0.05) | | * | ** | * |

** = Highly significant, * = Significant, NS = Non-significant, LSD = Least Significant Difference

**Table 4:** Response of shoot number of different potato varieties and their tuber size

| Variables | No. of shoots per plant |
|---|---|
| (a) Variety | |
| Sarpomira | 4.67 |
| Burna | 3.67 |
| Coroda | 4.00 |
| Rocco | 5.00 |
| Cardinal © | 3.67 |
| LSD (0.05) | NS |
| (b) Tuber-size category | |
| Small (31.5 $\pm$ 2.5 g) | 3.67 |
| Medium (57 $\pm$ 2.5 g) | 4.00 |
| Large (77.5 $\pm$ 2.5 g) | 4.67 |
| LSD (0.05) | NS |
| CV (%) | 21.95 |

LSD = Least Significant Differences, CV = Coefficient of Variation

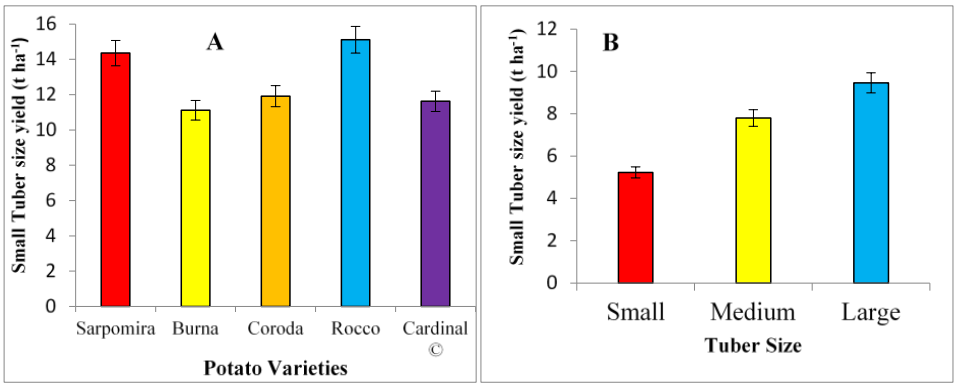



**Fig. 2:** Potato varieties (**A**) and their tuber size (**B**) effects on tuber yield (t ha$^{-1}$) received from tubers of small size. Vertical column shows yield for different potato varieties (**A**) and their tuber size (**B**) and bar shows standard error percentage

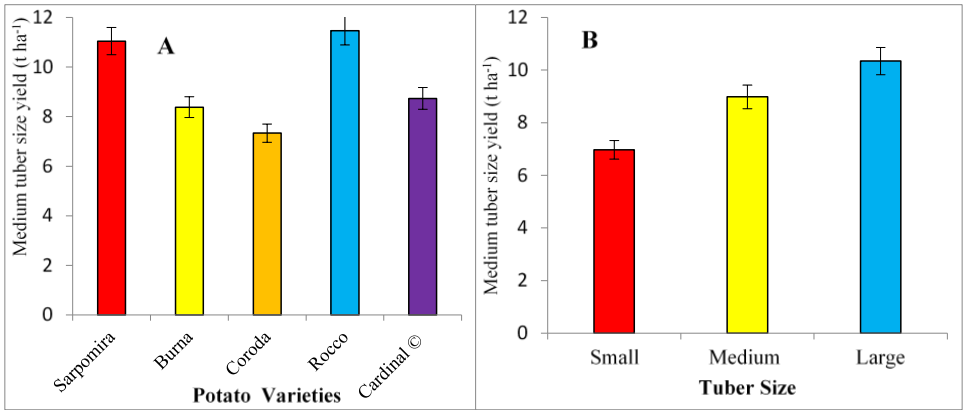



**Fig. 3:** Potato varieties (**A**) and their tuber size (**B**) effects on tuber yield (t ha$^{-1}$) received from tubers of medium size. Vertical column shows yield for different potato varieties (**A**) and their tuber size (**B**) and bar shows standard error percentage

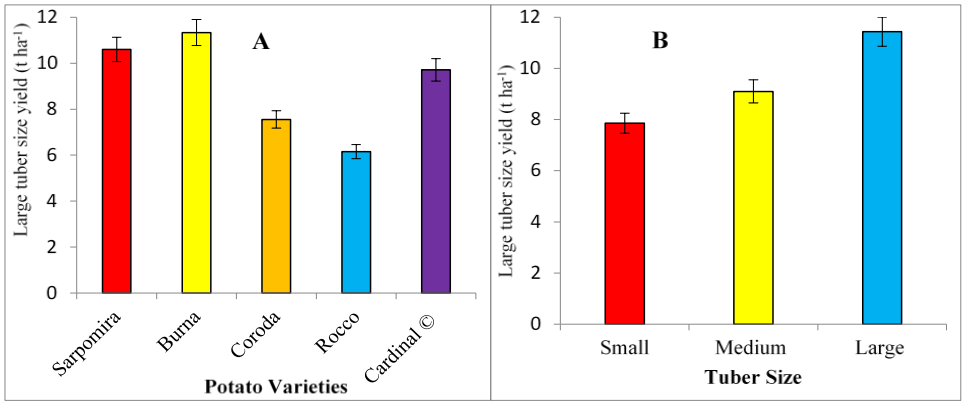



**Fig. 4:** Potato varieties (**A**) and their tuber size (**B**) effects on tuber yield (t ha$^{-1}$) received from tubers of larger size. Vertical column shows yield for different potato varieties (**A**) and their tuber size (**B**) and bar shows standard error percentage

**Total tuber yield:** Total tuber yield demonstrated highly significant ($P < 0.001$) effects on potato variety and tuber size while significant ($P < 0.05$) effects was observed for their interaction. Generally, maximum yield (36.00 t ha$^{-1}$) was recorded from variety Sarpomira followed by Rocco and Burna having yield of 32.74 and 30.82 t ha$^{-1}$, respectively. Meanwhile, variety Coroda produced the lowest (26.82 t ha$^{-1}$) total tuber yield (Fig. 5).

Tuber size showed that the highest total yield (36.81 t ha$^{-1}$) had produced from small tubers of variety Sarpomira followed by medium and large tuber size of same variety Sarpomira having values of 35.78 and 34.39 t ha$^{-1}$, respectively. Small tubers size of variety Coroda gave the lowest (26.42 t ha$^{-1}$) tuber yield as presented in Table 5.

**Marketable tuber yield (MTY):** It was considered one of the most important traits of potato while selecting potato

**Table 5:** Interaction effects of variety and their tuber size on yield attributing traits of potato varieties

| Varieties | Tuber size category (g) | Total tubers yield (t ha$^{-1}$) | Marketable tuber yield (t ha$^{-1}$) | Unmarketable tuber yield (t ha$^{-1}$) |
|---|---|---|---|---|
| Sarpomira | Small | 36.81$^{a}$ | 34.58$^{a}$ | 2.23 |
| | Medium | 35.78$^{a}$ | 33.55$^{a}$ | 2.23 |
| | Large | 34.39$^{a}$ | 31.46$^{a}$ | 2.93 |
| Burna | Small | 30.81$^{b}$ | 28.78$^{b}$ | 2.03 |
| | Medium | 27.66$^{c}$ | 24.23$^{c}$ | 3.43 |
| | Large | 27.51$^{b}$ | 27.11$^{b}$ | 0.4 |
| Coroda | Small | 26.42$^{c}$ | 24.32$^{b}$ | 2.1 |
| | Medium | 27.73$^{c}$ | 25.51$^{c}$ | 2.22 |
| | Large | 29.24$^{b}$ | 28.26$^{b}$ | 0.98 |
| Rocco | Small | 31.83$^{b}$ | 29.34$^{b}$ | 2.49 |
| | Medium | 31.76$^{b}$ | 31.20$^{c}$ | 0.56 |
| | Large | 29.86$^{b}$ | 27.74$^{b}$ | 2.12 |
| Cardinal © | Small | 30.95$^{b}$ | 29.24$^{c}$ | 1.71 |
| | Medium | 31.83$^{b}$ | 31.10$^{b}$ | 0.73 |
| | Large | 29.64$^{b}$ | 28.68$^{c}$ | 0.96 |
| LSD (0.05) | | *** | ** | NS |
| CV (%) | | 4.93 | 3.87 | 2.47 |

*** = Very highly significant, ** = Highly significant, * = Significant, NS = Non-significant, LSD = Least Significant Difference, CV = Coefficient of Variation

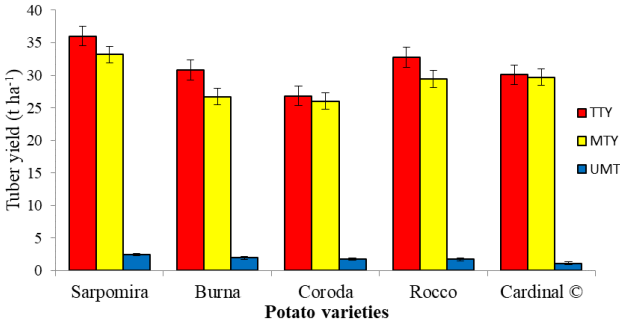



**Fig. 5:** TTY = Total tuber yield (t ha$^{-1}$); MTY = Marketable tuber yield (t ha$^{-1}$); UMTY = Unmarketable tuber yield (t ha$^{-1}$) of potato varieties. Vertical column shows tuber yield of potato varieties and error bar with standard error

varieties with higher potato production and fetching high economics for potato growers. Highly ($P < 0.01$) significant effects on potato variety and tuber size while significant ($P < 0.05$) effects on their interaction by two factor analysis were determined. The potato varieties Sarpomira produced the highest (33.19 t ha$^{-1}$) MTY whereas the lowest (26.03 t ha$^{-1}$) MTY was recorded from variety Coroda. The check variety 'Cardinal' also produced (29.67 t ha$^{-1}$) remarkable MTY (Fig. 5).

Regarding the tuber size of potato plants, the highest MTY (34.58 t ha$^{-1}$) was received from Sarpomira having small tubers while the lowest MTY (24.23 t ha$^{-1}$) was recorded from medium tubers of variety Burna (Table 5).

**Unmarketable tuber yield (UMTY):** Analysis of variance revealed non-significant ($P > 0.05$) effects on potato variety, tuber size and their interaction for UMTY trait. The check variety 'Cardinal' had produced lowest (1.13 t ha$^{-1}$) UMTY of potato whereas the highest (2.46 t ha$^{-1}$) UMTY was observed in variety Sarpomira followed by Burna and Coroda having UMTY of 1.95 and 1.77 t ha$^{-1}$, respectively (Fig. 5).

Tuber size of potato combination showed that medium tubers produced the highest (3.43 t ha$^{-1}$) UMTY while larger tubers of variety Burna gave lowest (0.4 t ha$^{-1}$) UMTY (Table 5).

## Economic analysis

Generally total variable costs and net benefits of each variety were considered as partial budget analysis. During the current findings, MTY was declined up to 10% to meet and compare it with tuber yield conditions of potato growers. Meanwhile, fresh potato was sold at rate of 20.0 PKR per kg in potato field at the time of harvesting. The potato variety Sarpomira in combination with smaller tubers produced the highest (562039.60 PKR ha$^{-1}$) net benefit followed by medium tuber size of variety Sarpomira and check variety 'Cardinal' with net benefit of 531235.40 and 505351.54 PKR ha$^{-1}$, respectively. Meanwhile, the lowest net benefit (366475.60 PKR ha$^{-1}$) was recorded from medium tubers size of potato variety Burna followed by small and medium tuber sizes of variety Coroda, respectively (Table 6).

In term of marginal rate of return, large tuber size of the check variety 'Cardinal' produced the highest (1583.05%) marginal rate of returns although it was coupled with a relatively low net benefit (Table 7). However, some of the combinations were excluded discarded from marginal rate of returns analysis as they were found to be dominated such as large tuber size of Rocco and Burna (Table 7), which were associated with high total seed variable costs. On the other hand, small-sized tubers of the variety Rocco showed the lowest marginal rate of return (2.89%), which is neither acceptable in potato-growing regions like Battakundi, nor in developing countries such as Pakistan. In these areas, potato production strategies are needed to ensure broader adaptation, improve food security, enhance the economy for smallholder farmers and promote sustainable agriculture.

## Discussion

Enhancing potato tuber production and improving the livelihoods of smallholder farmers are critical goals in agricultural development, particularly in regions where potatoes are a staple crop. The focus on identifying and selecting the optimal tuber size in relation to high-yielding potato varieties have several benefits such as improved yield, high marketability, sustainability and improved livelihood. The variation and diversity observed among potato varieties in terms of days to 50% emergence were influenced by their genetic composition (Table 2), as highlighted in the studies by Dash *et al.* (2018) and Fentaw *et al.* (2019). This characteristic is an important phenological trait that can impact both the early growth and overall productivity of the crop. Generally it was noted the size of the tuber plays a significant role in the early growth

**Table 6:** Partial budget analysis of potato varieties and their tuber size

| Variety | Tuber size category | Seed cost (Rs. ha$^{-1}$) | Marketable yield (Rs. ha$^{-1}$) | Adjustable yield (t ha$^{-1}$) | Gross income (Rs. ha$^{-1}$) | Net benefit (Rs. ha$^{-1}$) |
|---|---|---|---|---|---|---|
| Sarpomira | Small | 60400.40 | 34.58 | 31.12 | 622440.00 | 562039.60 |
| | Medium | 72664.60 | 33.55 | 30.19 | 603900.00 | 531235.40 |
| | Large | 80664.20 | 31.46 | 28.33 | 566680.00 | 486015.80 |
| Burna | Small | 51360.90 | 28.78 | 25.90 | 518040.00 | 466679.10 |
| | Medium | 69664.40 | 24.23 | 21.81 | 436140.00 | 366475.60 |
| | Large | 65446.34 | 27.11 | 24.39 | 487980.00 | 422533.66 |
| Coroda | Small | 50180.25 | 24.32 | 21.89 | 437760.00 | 387579.75 |
| | Medium | 67466.34 | 25.51 | 22.95 | 459180.00 | 391713.66 |
| | Large | 75334.46 | 28.26 | 25.43 | 508680.00 | 433345.54 |
| Rocco | Small | 50200.00 | 29.34 | 26.40 | 528120.00 | 477920.00 |
| | Medium | 66668.78 | 31.20 | 28.08 | 561600.00 | 494931.22 |
| | Large | 60446.20 | 27.74 | 24.97 | 499320.00 | 438873.80 |
| Cardinal © | Small | 48346.78 | 29.24 | 26.32 | 526320.00 | 477973.22 |
| | Medium | 54448.46 | 31.10 | 27.99 | 559800.00 | 505351.54 |
| | Large | 61776.20 | 28.68 | 25.81 | 516240.00 | 452463.80 |

Potato sale rate was fixed @ 20.0 PKR kg$^{-1}$ in field

**Table 7:** Marginal rate of return of potato effected by potato variety and their tuber size

| Treatment combinations | TVC (Rs. ha$^{-1}$) | NB (Rs. ha$^{-1}$) | DA | MMR (%) |
|---|---|---|---|---|
| Cardinal © × Small | 48346.78 | 477973.54 | | --- |
| Coroda × Small | 50180.25 | 387579.75 | DO | --- |
| Rocco × Small | 50200.00 | 477920.00 | | 2.89 |
| Burna × Small | 51360.90 | 466679.10 | DO | --- |
| Cardinal © × Medium | 54448.46 | 505351.54 | | 645.68 |
| Sarpomira × Small | 60400.40 | 562039.60 | | 952.43 |
| Rocco × Large | 60446.20 | 438873.80 | DO | --- |
| Cardinal © × Large | 61776.20 | 452463.80 | | 1583.05 |
| Burna × Large | 65446.34 | 422533.66 | DO | --- |
| Rocco × Medium | 66668.78 | 494931.22 | | 867.99 |
| Coroda × Medium | 67466.34 | 391713.66 | DO | --- |
| Burna × Medium | 69664.40 | 366475.60 | DO | --- |
| Sarpomira × Medium | 72664.60 | 531235.40 | | 605.49 |
| Coroda × Large | 75334.46 | 433345.54 | DO | --- |
| Sarpomira × Large | 80664.20 | 486015.80 | | 565.27 |

DO = Dominated, MRR = Marginal Rate of Return, TVC = Total Variable Cost, NB = Net Benefit. DA = Dominance Analysis

dynamics of the potato plant. Smaller tubers**,** due to having fewer eyes, slower sprouting, and limited stored food, generally take longer to emerge**,** flower**,** and mature compared to larger tubers. This delay in growth is an important consideration in potato crop management**,** and it helps in explaining that why larger tubers are often preferred for high-yielding and early-maturing potato production systems. However, both small and large tubers can be viable options depending on the specific growing conditions and objectives of the farmer.

In the present study, larger tubers exhibited earlier emergence, flowering**,** and maturity (Table 2) because of their greater store of reserve materials, particularly carbohydrates**,** which are critical for early growth. This is well-supported by the research of Ebrahim *et al.* (2018)**,** Arif *et al.* (2024) and Naz *et al.* (2024). Meanwhile, Zikhali and Griffiths (2015) reported that both genetic and environmental factors play a crucial role in flowering of potatoes. This aligns with the broader understanding of plant development, where flowering is a complex trait influenced by a range of internal genetic factors and external environmental conditions. It was observed that the check cultivar "Cardinal" had also exhibited earlier emergence**,** flowering, and maturity along with other tested varieties is an interesting finding. This trend is consistent with the results reported in the studies by Alemayehu and Jemberie (2018), Getie *et al.* (2018) and Asnake *et al.* (2023). These studies highlighted that how different cultivars, whether improved or traditional, can exhibit significant variation in their growth patterns due to differences in their genetic makeup, physiological characteristics and environmental effects.

The time to maturity in crops, including potatoes, is certainly influenced by a variety of factors such as varietal characteristics**,** planting date, cultural practices, and particularly the environmental conditions of the region. This observation is well supported by the works of Bekele (2018) and Alemayehu and Jemberie (2018) and both of them have explored how these factors contribute to the timing of maturity and overall growth cycle of crops. Genetic variation plays a key role in shaping various growth parameters of crops, including plant height and shoot number. The study by Getie *et al.* (2018) presented the significance of genetic diversity in influencing these traits in potato plants. Additionally, tuber size can also significantly influence various growth parameters in potatoes, including plant height**,** shoot number, and leaf area. The studies by Masarirambi *et al.* (2012),

Dagne *et al.* (2018), Regasa *et al.* (2022) and Arif *et al.* (2024) and have observed and emphasized that larger tubers often lead to more vigorous growth in terms of plant height**,** shoot development, and leaf area.

Tuber yield and the associated yield-attributing traits are the most important characteristics when selecting high-yielding potato varieties, especially for specific regions. The genetic composition of the variety and agronomic practices play a crucial role in determining tuber size and overall potato production. The study by Bekele and Hale (2019) underlined the critical role of both genetic factors and management practices under different environments in shaping these characteristics, which directly influence the success of potato farming. It is utmost worth mentioning that tuber yield generally increases with the tuber size and it could also be affected by environmental factors. As noted here (Table 5), larger tubers typically produce higher yields compared to smaller ones. This notion is reinforced by different studies (Ozkaynak 2021; Asnake *et al.* 2023; Singh *et al.* 2023; Arif *et al.* 2024)**,** advocating that larger seed tubers can lead to increased tuber production. Small seed tubers often have fewer buds, which means fewer sprouts and less stored food (carbohydrates), leading to reduced vegetative growth and plant development**.** This ultimately results in the production of small tubers and a lower overall yield**.** This idea is well-supported by Dagne *et al.* (2018), who highlighted the key factors that contribute to the poor performance of small tubers and mainly connected with genetic structure of potato and environmental factors influencing the tuber size and yield (Tessema *et al.* 2020).

Marginal analysis is an essential tool in agricultural economics, particularly when evaluating the economic viability and efficiency of different agricultural inputs or practices. When applied to the study of dominance analysis and the marginal rate of return (MRR), it provides a comprehensive way to assess the economic performance of various input-output relationships, such as seed tuber sizes or agronomic practices in potato production (CIMMYT 1988). Dominance analysis involves comparing the costs and returns of various treatments (in this case, seed tuber sizes) to identify which treatment dominates the others. A treatment is considered dominated if it results in a higher cost but a lower or equal net benefit compared to another treatment. This method, as outlined by CIMMYT (1988) and Ahmed *et al.* (2007), is critical in guiding farmers towards economically beneficial practices that optimize their investment in agricultural inputs, such as seed tuber sizes, ensuring maximum profitability. In dominance analysis**,** it is important to identify and exclude dominated treatment combinations before proceeding with further economic analysis, such as the marginal rate of return (MRR) analysis. This step ensures that only the most economically efficient treatments are considered for the MRR calculation**,** thereby avoiding unnecessary complexity and focusing on the best-performing option. By marking dominated treatments as "DO" and excluding them from the MRR analysis, the analysis focuses only on the most economically viable options. Dagne *et al.* (2019) suggested that using larger tuber size can lead to higher economic returns and reduced production costs in potato farming.

The low MRR of 2.89% for the Rocco variety with small tubers indicated economic inefficiency (Table 7), which is not acceptable in developing regions like Pakistan, where farmers face significant socio-economic pressures and food security challenges**.** To address this, it is crucial to adopt farming practices and seed potato varieties that provide higher economic returns and are sustainable**.** By focusing on higher-yielding varieties with larger tubers and improving access to better agricultural practices and inputs, farmers can achieve higher profitability and contribute to long-term food security and socio-economic development. The current findings align with the findings of Bist *et al.* (2023). The current findings clearly demonstrated the importance of selecting the right tuber size for economic viability in potato farming. While large seed tuber size of the 'Cardinal' variety can generate a high MRR (Table 7)**,** their low net benefits highlight the trade-offs between yield and production costs. The 31–40 g tuber size had emerged as the most advantageous choice, offering a balance between yield potential**,** cost efficiency, and economic returns. This is consistent with the findings of Bist *et al.* (2023) and can be particularly valuable for regions facing economic constraints, such as Pakistan, where maximizing yield and minimizing costs are critical for ensuring food security and the sustainability of farming.

## Conclusion

It is concluded that variety Sarpomira produced the highest MTY in combination with small, medium and large tuber sizes, respectively. However, the variety Sarpomira in combination with small tuber size had produced the highest gross income (622440.00 PKR $ha^{-1}$) and net benefit (562039.60 PKR $ha^{-1}$) coupled with acceptable rate (952.43%) of MMR. Therefore, this treatment combination is identified and selected as optimal combination in term of tuber yield, quality and growth rates in the highlands of northern Pakistan. Additionally, this treatment combination could improve farmers income through increased productivity and reduced input costs, making potato production economically, more viable. It is noteworthy that utilizing small tuber size, along with the variety Sarpomira*,* could be implemented on a large scale to enhance potato production. This approach has the potential to empower smallholder farmers by improving their production systems, boosting their livelihoods, and contributing to regional food security in the future.

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## Authors Contribution

BAK conceived the idea and wrote original manuscript draft, NA supervised the research work and edited manuscript, SA defined methodology, SA executed formal data analysis, AAM collected field data, IAS investigated the experiment and IK arranged resources and collected germplasm.

## Conflict of Interest

All authors declare no conflict of interest.

## Data Availability

Data will be available on request from authors.

## Ethics Approval

Not applicable to this paper

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