Agricultural Research Reports
https://journals.pagepal.org/index.php/ARR
ISSN (Online), 3106-003X; (Print), 3106-0021
https://doi.org/10.54219/arr.03.1.2025.416

# Growth analysis of various onion genotypes for yield and pharmaceutical traits

***Muhammad Zeeshan Mola Bakhsh[1,2]*, Rashid Mehmood Rana[1], Muhammad Ikram [3], Kamran Haider[4], Kamil Kabir[4], Furqan Ahmed[5]***

[1] Department of Plant Breeding and Genetics, PMAS-Arid Agriculture University, Rawalpindi-46000, Pakistan.
[2] National Key Laboratory of Crop Genetic Improvement, College of Plant Science and Technology, Huazhong Agricultural University, Wuhan-430070, China.
[3] Institute of Agronomy, Faculty of Agricultural Sciences and Technology, Bahauddin Zakariya University, Multan-60000, Pakistan.
[4] Institute of Urban and Horticultural Entomology, College of Plant Science and Technology, Huazhong Agricultural University, Wuhan-430070, China.
[5]Department of Horticulture, PMAS-Arid Agriculture University, Rawalpindi-46000, Pakistan.

## Article Info

**Keywords:**
*Allium cepa*; growth analysis; thermal stress; phenology; nutraceuticals; crop physiology

**Date:**
Received: 14 February 2025
Accepted: 11 April 2025
Published: 30 June 2025

Volume: 03 (01), 2025



## Abstract

*Onion (Allium cepa L.) is a globally significant biennial crop cultivated as an annual, with its growth and bulb development highly sensitive to thermo-photoperiodic regulation. Understanding genotype-specific phenological responses is critical for optimizing yield and nutraceutical potential. This study characterized the growth dynamics, yield traits, and pharmaceutical compound accumulation in onion genotypes under field conditions, identifying thermo-sensitive stages and genotypic variability. A field experiment was conducted at PMAS Arid Agriculture University Rawalpindi, Pakistan, using a randomized design. Seven genotypes were evaluated for morphological (plant height, leaf count, bulb weight), physiological (CGR, NAR), and pharmaceutical traits (phenolics, flavonoids) at 7-day intervals until harvest. Vegetative growth peaked at 97 days after transplanting (DAT), with bulbing initiation triggered by rising temperatures (>25°C).104 DAT emerged as a critical thermo-sensitive stage, where heat stress significantly reduced bulb yield (15-20%) and altered secondary metabolite profiles. SWAT-1 outperformed other genotypes, exhibiting 22% higher yield and 30% greater flavonoid content, linked to sustained crop growth rate (CGR) during bulbing. Pharmaceutical compounds peaked during late vegetative growth (75-90 DAT) but declined post-bulbing, indicating a trade-off between storage organ development and defense metabolite production. The 97-104 DAT window is pivotal for yield stability and nutraceutical quality, with genotypic divergence in thermal resilience. SWAT-1's robust performance underscores its potential for breeding programs targeting climate adaptation and enhanced phytochemical content.*

## 1. Introduction

Vegetable crops are suitable for poor farmers and important due to high nutritional value, high yield and high net return. Human body needs vitamins, minerals and proteins, which are provided by vegetables to body. In Pakistan major vegetables include potato, onion, tomato, chilies, okra, carrot, turnip and round gourd cover 78% of land area under vegetables (Mahmood, 2014). Onion is major vegetable in Pakistan which is grown in all provinces

Corresponding Author: Muhammad Zeeshan Mola Bakhsh Email: mola@webmail.hzau.edu.cn

of Pakistan. Onion (*Allium cepa* L.) belongs to Amaryllidaceae family which grown from 3000BC in world, which concluded its importance in ancient times. Word "onion" is latin word with meaning of "pearl". Here pearl is not referring to its shape but refer to nutritional value (Shigyo, 2008; Ikram *et al.,* 2025c). Onion production in Pakistan has raised 35% from 1.70 million tonnes to 2.30 million tonnes (GOP, 2021). Worldwide onion production is 104.55 million tonnes among which 2.03% production share is from Pakistan with ranking at 6th position. (FAO, 2023). World level per capita consumption of onion is about 10.8 kg (FAO, 2023) while in Pakistan per capita consumption is 9.97 kg. Sindh contributes maximum (35.1%) in onion production followed by Balochistan (27.6%), Punjab (25.1%) and Khyber Pakhtunkhwa (12.2%) (FAO, 2023). Overall, more than 50% of the total onion production is contributed by eight districts including Chaghi, Hyderabad, Sanghar, Mirpurkhas, Nawabshah, Swat, Kharan and Kalat. The major varieties in Pakistan are chiltan-89 in Baluchistan, Phulkara in Sindh, Desi red in Punjab, Swat-I in KPK.

Onion is highly nutritive vegetable, 100 g contain 0.5 mg vitamin B, 0.21 g mineral and 7.4 mg Vitamin C. It is used in many food recipes, pickles, chutneys and fresh as salad. Onion is beneficial for human health (Cope, 2005; Alotaibi *et al.,* 2025). It is beneficial mainly due to presence of two chemical compound namely alk(en)yl cysteine sulfoxides (ACSO) and flavonoids. ACSO is present in cells and when cell starts breakdown the end product is pyruvic acid. Pyruvic acid is actually the measure of pungency and recently there is a demand of varieties having low pungency, known as sweet onion. Pyruvic acid reduces dark spots, improves liver function and weight loss (Ikram *et al.,* 2025a,2025b). Second compound is phytochemical which is not synthesized by animals but only metabolized (Smith *et al.,* 2016). Among these phytochemicals, Flavonol is major class which is responsible for texture, color and taste (Harborne, 1986). The major flavanol is quercetin which is highest in onion (Herrmann, 1976). Flavonoids/Quercetin is helpful in reducing carcinogenic activity of processed food and also stop the activity of tumor cells. Quercetin levels vary among cultivars like yellow and red onion have contains higher amounts than white onion (Lombard, 2000). Hence the amount of quercetin in onion depends on bulb color, variety and type of bulb (B. Patil & Pike, 1995). Onion also contains Phenolic which is important due to anti-oxidant activity. This plays a great role against harmful effects of reactive oxygen species which cause different diseases like arteriosclerosis, Cancer and indispositions (Stratil *et al.,* 2006). Onion is a good source of ascorbic acid which is important for healing wounds, Cartilage, bones and teeth. This ascorbic acid is neither stored nor synthesized in our body, therefore recommended at the dose of 75mg/day (Berg *et al.,* 1993; Bakhsh *et al.,*2025). All these nutritional parameters are changed with reference to growth/development of onion plant.

Growth is an important feature of living matter. According to botanists, growth is an increase of cellular mass, while in some cases growth is consider without increase in weight (Seeds germination, Sprouting of onion bulb). Therefore, increase of weight and size is characteristic of growth. Growth and development can be defined separately based on biotic activity. Growth is cell division and enlargement, while development is the sequence of functional and structural changes which are occurred during life cycle of organism (Nickerson & Bartnicki, 1964). The growth and development of organism depends on environmental factors.

Genotype and environment interaction plays an important role in plant growth and development and hence critical to perform growth analysis. Environmental factors such as light, salinity, soil, pH and temperature play an important role for the growth and development of plants (Gill *et al.,* 2010). For understanding the growth pattern in certain environment, growth model is used. Plant growth and development are studied through plant growth analysis (Wilson, 1981). Plant growth analysis is greatly used in plant breeding, plant ecology and plant physiology (Clarkson *et al.*, 1986; Ikram *et al.,* 2024a,2024b,2024c). Plant yield is the result of various metabolic processes and greatly affected by genotype and environment. Understanding these events, growth analysis is very important. The study of growth parameters plays important role for understanding the difference of yield between genotype and plants (Ghosh & Singh, 1998).

## 2. Materials and Methods

### 2.1 Crop Material and growing conditions

The Three different varieties of onion i.e. SWAT-1, NARC-1, PHULKARA was used for growth analysis. Seeds were provided from National Agriculture research center

Islamabad. All varieties were grown in field area of PMAS-Arid Agriculture University Rawalpindi, Pakistan by following Randomized complete block design (RCBD) with three replications. All standard cultural practices like weeding, hoeing and earthing-up were applied according to the requirement of the crop after nursery plantation.

### 2.2 Soil Fertility Analysis

Crop growth site was subjected to soil fertility analysis before nursery transplantation and after crop harvesting. Total 18 samples were collected from site, 6 from each genotype among which 3 before transplantation and 3 after harvesting respectively. These soil samples were subjected to following analysis; Electric conductivity (EC), pH, Nitrogen, Phosphorus and Potassium. Above mentioned analysis were done by using the method Ammonium Bicarbonate- DTPA Method, developed by (Soltanpour & Schwab, 1977).

### 2.3 Agronomic traits data collection

Growth data was recorded for plant height, leaf length, leaves per plant, bulb horizontal diameter, bulb vertical diameter, above ground fresh weight, below ground fresh weight, above ground dry weight, below ground dry weight, neck diameter, above ground moisture content and below ground moisture content. All these parameters were recorded on weekly basis by destructive sampling. Plant height and leaf length was measured with help of measuring tape in centimeter (cm) while bulb and neck diameter was measured with help of digital Vernier caliber in millimeter (mm). Similarly, bulb fresh and dry weight was measured with weighing balance in grams (g). Moisture percentage was determined by according to gravimetric method (AOAC.2000). Fresh samples were weighed (W1) and placed in oven at 80°C until drying. After drying, dried bulb was weighed again (W2) and following formula used for moisture content estimation:

$$\text{Moisture}=\frac{\text{W1-W2}}{\text{W1}}\ \text{X}\ 100$$

### 2.4 Pharmaceutical data collection

Pharmaceutical traits like pyruvic acid, ascorbic acid, phenolic contents and flavonoid contents were measured by using above and below ground plant parts. Pyruvic acid was measured by following method of Schwimmer & Weston, 1961. For the measure of pyruvic acid, Onion juice was extracted and diluted up to 100-fold. 500 µl of DNPH solution with HCl (0.125g $L^{-1}$) was added and placed sample in water bath at 37°C for 10 minutes 2.5 ml of 0.6 M NaOH was added and absorbance was noted at 420 nm on spectrophotometer. Final pyruvic acid amount (mg 100 $g^{-1}$) was estimated with help of sodium pyruvate curve (standard curve).

Ascorbic acid (Vitamin-C) was measured by following the procedure of Hans, 1992. Fresh sample (5 g) was ground with 5 ml of 1% HCl and centrifuged at 10,000 rpm for 10 minutes. Supernatant (0.3 ml) was mixed with 2.7 ml of distilled water and absorbance was noted at 243 nm on spectrophotometer. Final Vitamin C amount (mg 100 $g^{-1}$) was estimated by using standard curve through series dilutions of ascorbic acid.

Phenolic contents were measured by following the protocol of Baba & Malik (2015) where 200µl of onion extract was mixed with 2.8 ml of distilled water, later 0.5 ml of Folin ciocalteu reagent was added and mixed for 3 minutes then 2 ml of 20 % sodium carbonate was added in sample and placed in darkness for one hour. Absorbance at 650 nm was noted and results were estimated with help of standard curve by using Gallic acid as standard and expressed as mg $g^{-1}$ dry sample.

Flavonoid contents were quantified using the aluminum chloride colorimetric method as described by Baba and Malik (2015) with minor corrections for clarity. A 50 µL aliquot of the crude plant extract was transferred into a test tube and mixed with 0.8 mL methanol. Subsequently, 4 mL of distilled water was added, and the mixture was allowed to stand for 5 minutes. After incubation, 0.3 mL of 5% sodium nitrite ($NaNO_2$) was added. After 5 minutes, 0.3 mL of 10% aluminum chloride ($AlCl_3$) solution was added, and the reaction mixture was left for an additional 6 minutes. Finally, 2 mL of 1 M sodium hydroxide (NaOH) was added. The reaction volume was brought to 10 mL with distilled water, and the mixture was vortexed thoroughly. The absorbance of the developed pink coloration was recorded at 510 nm using a UV-Visible spectrophotometer. Total flavonoid contents were calculated from a rutin standard calibration curve and expressed as mg rutin equivalent mg $g^{-1}$ of sample.

### 2.5 Crop growth parameters

Growth parameters including net assimilation rate, relative growth rate and crop growth rate were measured. Net Assimilation Rate (NAR) known as amount of dry matter

production per unit of leaf weight. It was calculated by following the method of Gregory, (1926). NAR was expressed in g $m^{-2}$ $day^{-1}$.

$$NAR = \frac{W2-W1}{t2-t1} \times \frac{\log L2 - \log L1}{L2-L1}$$

*where, W2, W1 are dry weight of complete plant at time t2 and t1 respectively. While L2 and L1 are leaf weight at time t2 and t1, respectively.*

Crop Growth Rate (CGR) is used for overall growth of plant with reference to time. CGR was calculated according to Gul *et al. (*2013) for each stage by using dry weight W2 at time t2 and dry weight W1 at time t1. Following formula was used for calculation of CGR.

$$CGR = \frac{W2-W1}{t2-t1}$$

Relative Growth Rate (RGR) is the relative growth of plant with reference to whole population. RGR was calculated by following the formula of William & Handrik, 2002 in term of g $g^{-1}d^{-1}$.

$$RGR = \frac{\log_e W2 - \log_e W1}{t2-t1}$$

The data was subjected to analysis of variance, correlation and path coefficient analysis using OPSTAT open-access software (Sheoran *et al.* 1998). The results of an analysis of variance were interpreted as the procedure given by Panse and Sukhatme (1967), phenotypic and genotypic variance (Wricke and Weber 1986)

## 3. Results

This section may be organized with subheadings for clarity. It should offer a clear and brief summary of the experimental findings, their analysis, and the conclusions drawn from them.

### 3.1 Soil Fertility analysis

All soil samples showed slightly basic pH and none of them was acidic. EC was measured by EC meter and the highest EC was observed in sample 1A (0.08) followed by Sample 1B (0.075), while the lowest EC was observed in 2A (0.0252). So the best soil with lowest EC, which indicates less amount of salt was 2A. Nitrogen plays significant role in plant biomass production through photosynthesis. A calibration curve was used to calculate the final amount of nitrogen in all soil samples (Supplementary figure. 4). Maximum amount of nitrogen was observed in 2A sample where SWAT-1 was transplanting and amount of nitrogen was reduced in all soil samples which was collected after crop harvesting. Phosphorus (P) plays a crucial role in plant growth and development including ATP synthesis, root growth and flowers initiation. Amount of phosphorus was calculated with the help of calibration curve (Supplementary figure. 5) and maximum amount of phosphorus was observed in 2A (83.8) and 3A (83.74) while lowest amount of was observed in 2B (48.8).

Potassium (K) is one of the essential macronutrients required for plant growth and development. It plays a multifaceted role in various physiological and biochemical processes within the plant i.e. maintaining osmotic pressure, act as cofactor for carbohydrate metabolism, nitrogen assimilation, and protein synthesis. Amount of potassium was calculated by using standard calibrated curve (Supplementary figure. 6) and maximum amount of K was present in 2A (168.6) while minimum amount was present in 3B (108.4).

**Table 1.** Soil Chemical Properties Analysis

| Samples | pH | EC (dS/m) | N (ppm) | P (ppm) | K (ppm) |
|---|---|---|---|---|---|
| **1A** | 7.70 | 0.0796 | 88.15 | 79.12 | 147.44 |
| **2A** | 7.55 | 0.0252 | 111.55 | 83.78 | 168.57 |
| **3A** | 7.42 | 0.0362 | 64.82 | 83.75 | 119.26 |
| **1B** | 7.34 | 0.0752 | 61.89 | 70.06 | 131.74 |
| **2B** | 7.42 | 0.0282 | 51.53 | 48.84 | 113.64 |
| **3B** | 7.35 | 0.0405 | 51.58 | 75.40 | 108.44 |

### 3.2 Agronomic traits results

Maximum plant height was observed in variety SWAT-1 (70cm) at 97 days after transplanting (DAT). SWAT-1 was early maturing variety then NARC-1 and PHULKARA which completes its growth at 97DAT. All varieties were severely affected by temperature at 104DAT at which all they moved towards maturity by decreasing growth (Figure 1A).

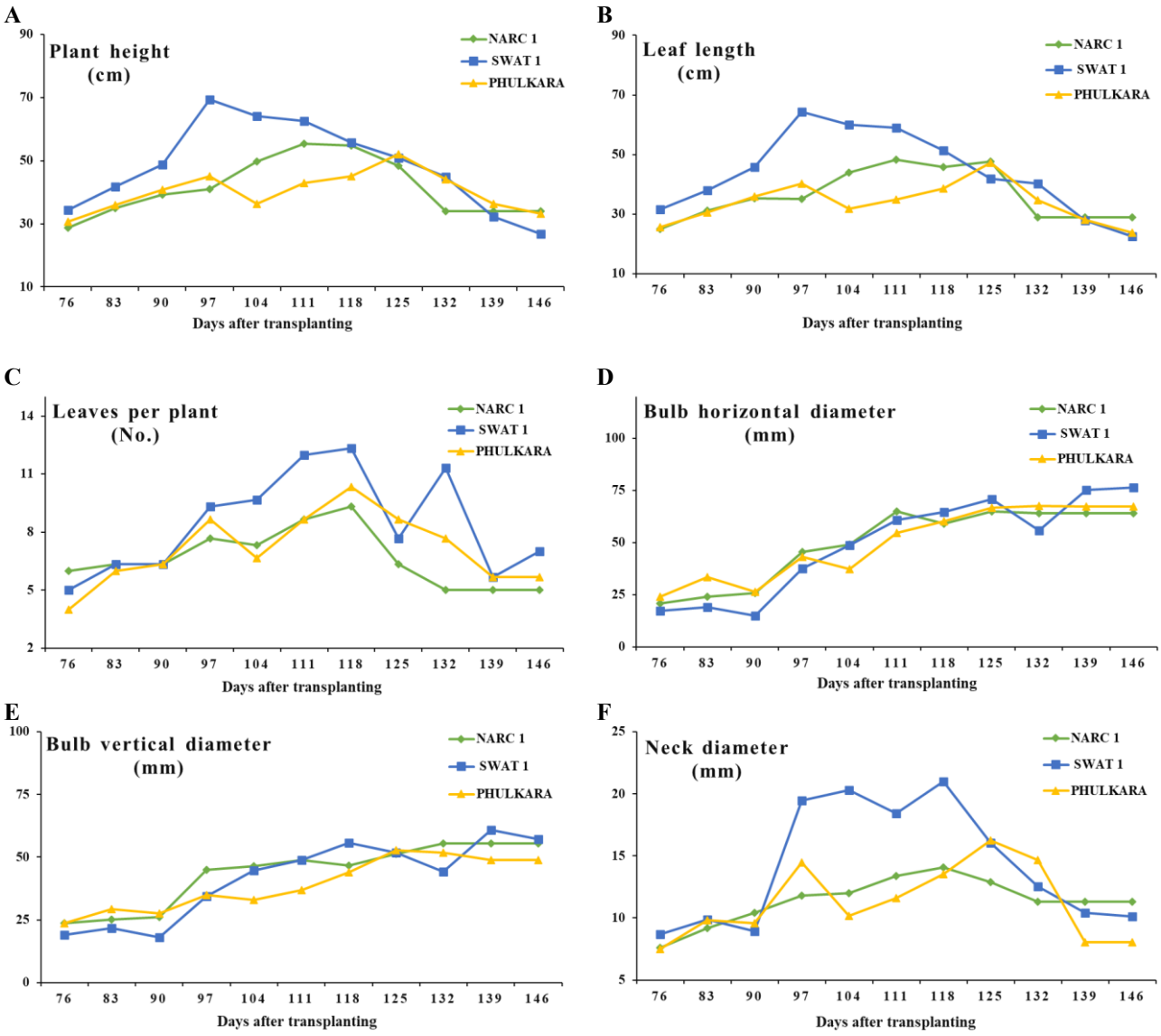


**Figure 1.** Weekly growth dynamics of onion plants. (A) Plant height; (B) Leaf length; (C) leaves per plant; (D) Bulb horizontal diameter; (E) Bulb vertical diameter; (F) Neck diameter

Similarly, leaf length following the plant height trait and observed maximum in SWAT-1 (67.3cm) at 97 DAT (Figure 1B). Number of leaves an important trait for production of chlorophyll contents in plants. which was increased up to 118 DAT while plant height and leaf length stops at 97DAT. Maximum number of leaves were recorded in SWAT-1 (12.33) at 118 DAT. While results also showed that number of leaves were reduced at 104DAT in all genotypes due to high temperature stress (Figure 1C). Bulb horizontal diameter increased gradually after 90 DAT. The genotype SWAT-1 showed highest diameter and NARC-1 showed lowest diameter at final stage after transplanting. Although early bulb formation started in PHULKARA at 83 DAT (Figure 1D). Similarly, bulb vertical diameter increased properly after 90 DAT. NARC-1 and PHULKARA mature early but the bulb vertical diameter was maximum recorded in SWAT-1 at maturity (Figure 1E). Due to maximum number of leaves in SWAT-1, neck diameter was also highest in SWAT-1. Maximum neck diameter might be the reason for

late maturity, and this was increased up to 118 DAT in all genotypes (Figure 1F).

Above ground fresh weight was observed maximum in SWAT-1 at 97 DAT (Figure 2A). Below ground fresh weight was increased from 90 DAT. At stage 104 DAT, below ground fresh weight was reduced except SWAT-1 genotype. Bulb of NARC-1 matured after 132 DAT, PHULKARA at 139 DAT and SWAT-1 at 146 DAT. It was found that at early stages of growth bulb weight was gained very slowly while bulb weight was increased very fast at lateral stages which take bulb to maturity (Figure 2B). Above ground dry weight started increasing after 90 DAT. The genotype SWAT-1 showed maximum above ground dry weight at all growth stages after 90 DAT. At early stages of growth i.e. 76, 83 and 90 DAT, PHULKARA showed maximum dry weight. In SWAT-1, a sudden increase was observed in above ground dry weight at 90-97 DAT, which shows that its vegetative

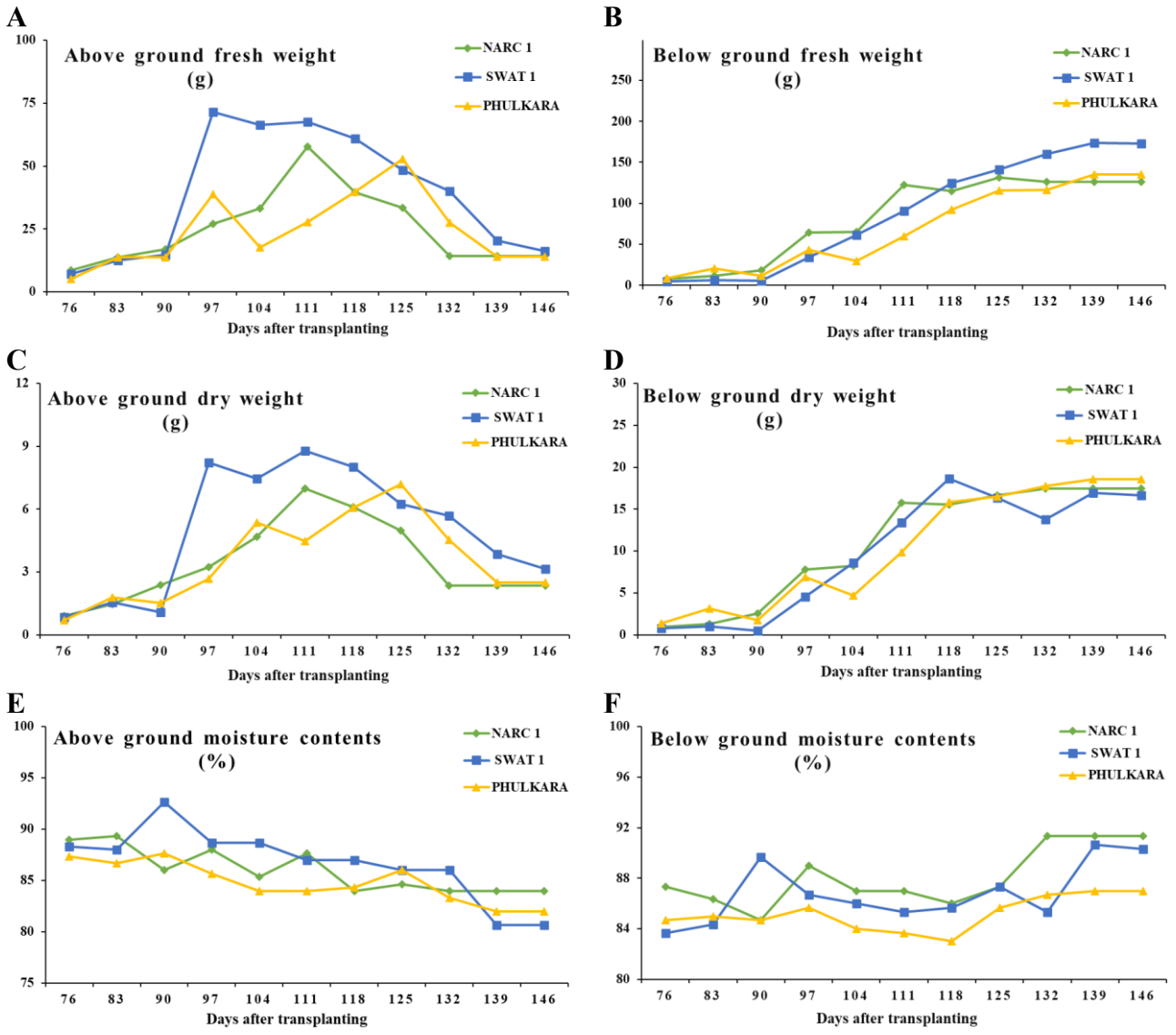


**Figure 2.** Weekly growth analysis of biomass and moisture parameters. (A) Above-ground fresh weight; (B) Below-ground fresh weight; (C) Above-ground dry weight; (D) Below-ground dry weight; (E) Above-ground moisture contents; (F) Below-ground moisture contents

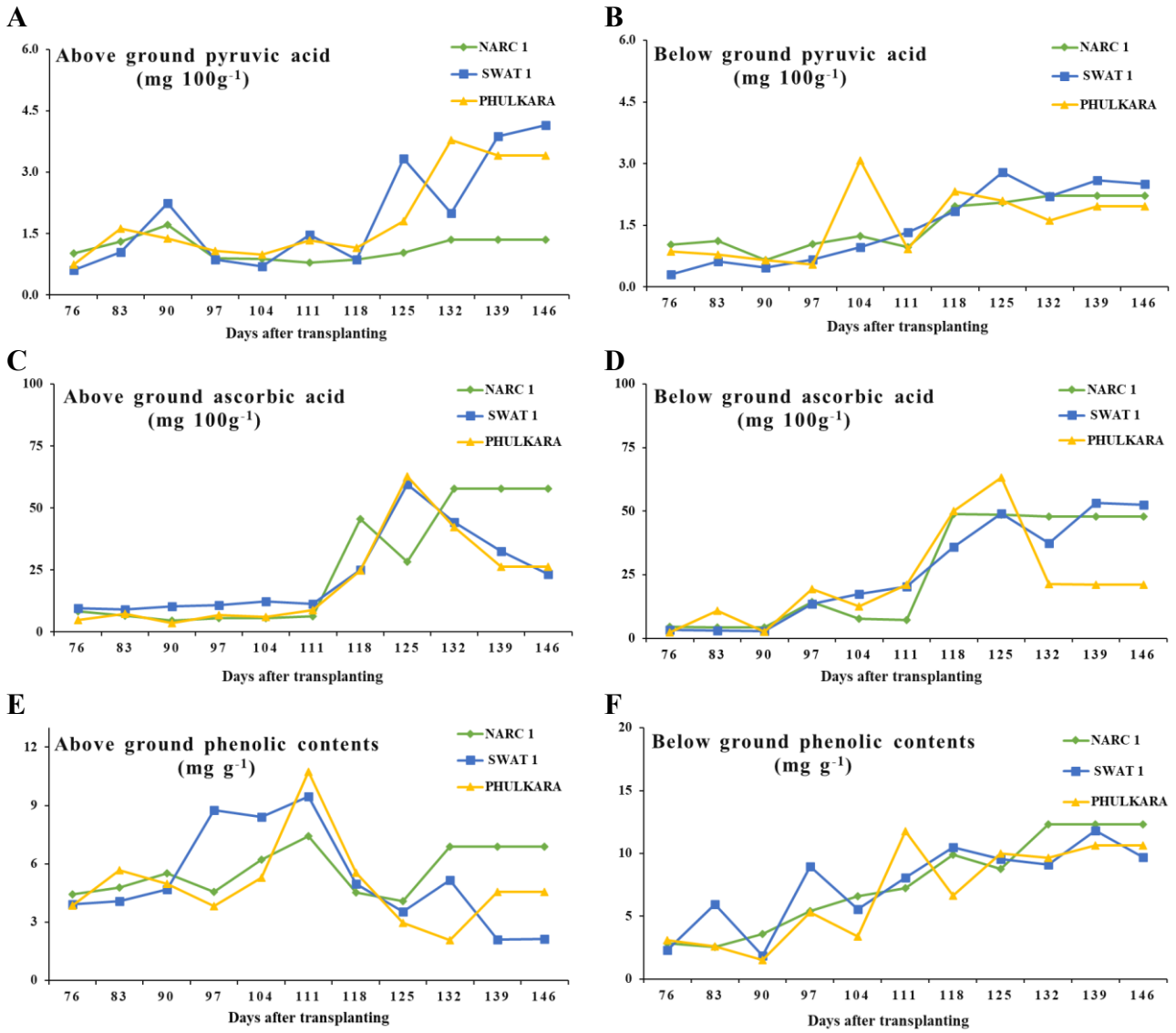


**Figure 3.** Weekly analysis of biochemical attributes. (A) Above-ground pyruvic acid; (B) Below-ground pyruvic acid; (C) Above-ground ascorbic acid; (D) Below-ground ascorbic acid; (E) Above-ground phenolic contents; (F) Below-ground phenolic contents.

growth is on peak (Figure 2C). After 118 days of transplanting the maximum below ground dry weight was observed in SWAT-1, while after 118 DAT the below ground weight started reducing which is indication of maturity stage (Figure 2D).

Above ground moisture content shows an interesting pattern in all genotypes. Moisture contents were showing zigzag manner at all stages. SWAT-1 shows maximum moisture contents except 83 and 111 DAT. The least moisture contents were shown by SWAT-1 at harvesting stage, while NARC-1 shows maximum moisture contents at final maturity stage (Figure 2E). Below ground moisture contents were highest in NARC-1 at 132 DAT which indicates that it has less shelf life. After 90 DAT below ground moisture contents start decreasing till 125 DAT, while in SWAT-1 it decreases till 132 DAT. Below ground moisture contents were minimum observed in PHULKARA, and maximum observed in NARC-1 (Figure 2F).

### 3.4 Pharmaceutical traits

The maximum above ground pyruvic acid was observed in PHULKARA at 132 DAT while NARC-1 shows very less amount of pyruvic acid as it also known as sweet onion (Figure 3A). Below ground pyruvic acid was shown maximum by SWAT-1 except one stage 104 DAT.

On this stage PHULKARA shows maximum contents of Pyruvic acid. The amount of pyruvic acid was decreasing at maturity stage (Figure 3B). Ascorbic acid is also known as Vitamin C. Above ground amount of ascorbic acid was maximum observed in SWAT-1 till 111 DAT while at lateral stages NARC-1 shows maximum amount of ascorbic acid till 146 DAT (Figure 3C). The amount of ascorbic acid in below ground part was not increasing at early stage of growth due to no bulb formation start. The maximum amount of ascorbic acid below ground was observed in PHULKARA at 125 DAT, while at final stage of harvesting the amount of ascorbic acid in below ground part was maximum in SWAT-1 and minimum in PHULKARA (Figure 3D).

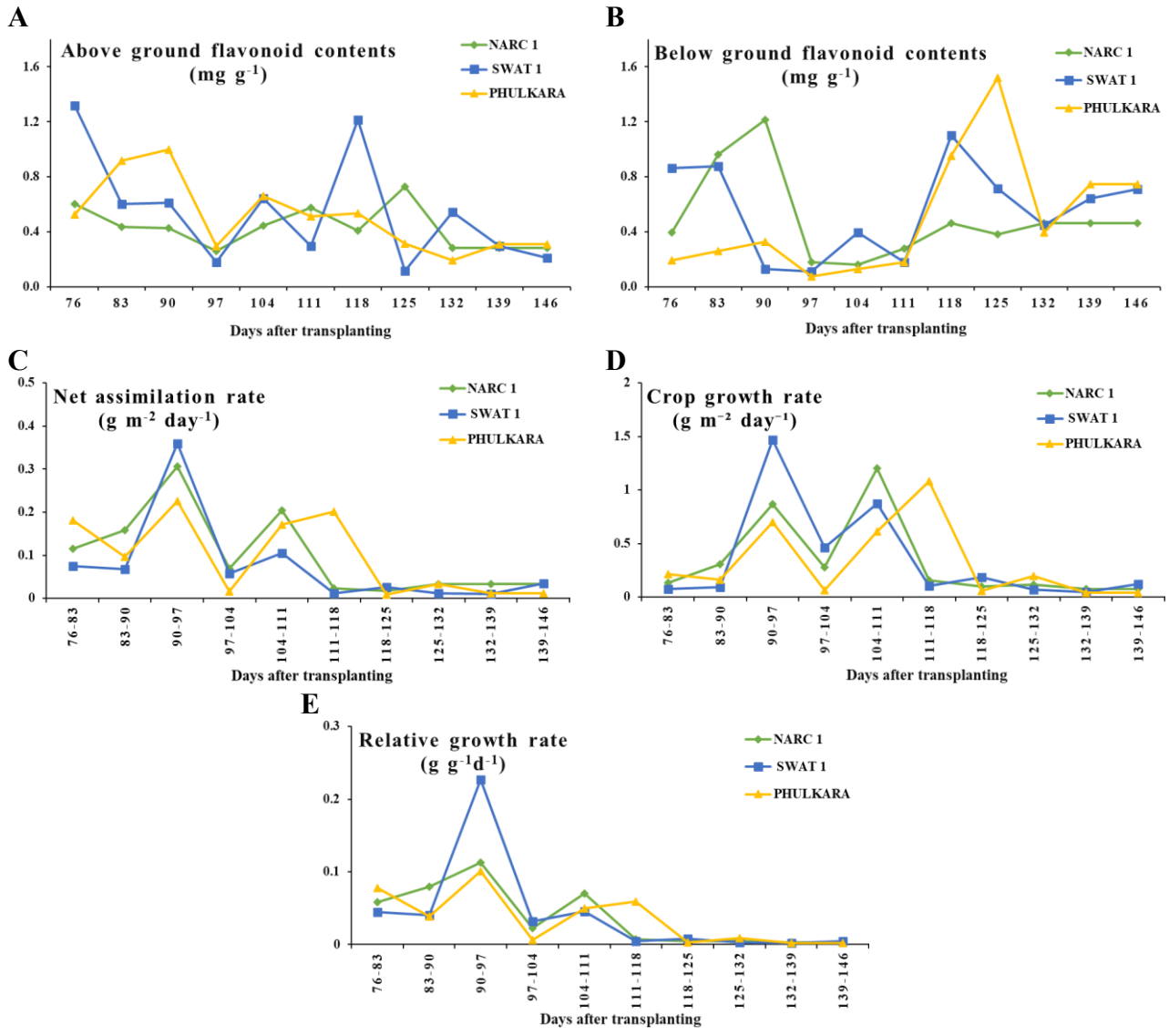


**Figure 4.** Weekly analysis of physiological and biochemical parameters. (A) Above-ground flavonoid content; (B) Below-ground flavonoid content; (C) Net assimilation rate; (D) Crop growth rate; (E) Relative growth rate.

Above ground phenolic contents was increasing gradually till 111 DAT, after this it started decreasing. At final maturity/harvesting stage 146 DAT above ground number of phenolic contents was maximum in NARC-1. Over all maximum amount of phenolic content was recorded in PHULKARA at 111 DAT (Figure 3E). Below ground amount of phenolic content was observed maximum in NARC-1 from 132-146 DAT. The number of phenolic contents in all genotypes show zigzag manner except NARC-1, which shows continually increase in phenolic content till final stage of maturity (Figure 3F). Above ground flavonoid content was maximum at initial stages of growth while it reduced at lateral stages. The maximum number of flavonoid contents was observed in SWAT-1 at 76 DAT and then at 118 (Figure 4A). Amount of flavonoid content below ground part was high at initial stages of growth. Flavonoid content in bulb was maximum at 125 DAT in PHULKARA. From 90-111DAT all genotypes showed reduction in flavonoid contents (Figure 4B). Overall best stage for maximum pharmaceutical traits was 111DAT and best cultivar was PHULKARA who's above ground and below ground part well for pharmaceutical traits.

### 3.5 Crop growth parameters

SWAT-1 showed maximum NAR during 90-97 DAT while PHULKARA shows lowest NAR at 90-97 DAT. 90-97 DAT stage is most important stage for all genotypes as all genotypes show maximum NAR at 90-97 DAT (Figure 4C). Maximum CGR was observed at 90-97 DAT, which declined at lateral stages of growth. Highest CGR was observed in SWAT-1 followed by NARC-1 at 90-97 DAT.CGR was reduced at 97-104 DAT, which increase at 104-111 DAT, further reduction in CGR was reduced after 111 DAT and reduced till maturing stage due to senescence of leaf growth. SWAT-1 shows highest rate of growth at 146 DAT (Figure 4D). RGR was observed to increase for all genotypes till 97 DAT. RGR was maximum at 90-97 DAT in SWAT-1. Minimum RGR was observed in PHULKARA at 90-97 DAT. Declined in RGR was observed in all genotypes after 97 DAT till maturity stage (Figure 4E).

## 4. Discussion

Onion plant height increased till 90 DAT in two genotypes (NARC-1, PHULKARA) while in one genotype (SWAT-1) it increases up to 97 DAT. In case of PHULKARA variety plant height was reduced after 104 DAT by effect of temperature. Increase in temperature might have affected the moisture contents which lead to reduction of cell expansion and reduction in plant height because at early-stage plant were able to recover but at stage 104 DAT maximum cells utilized for bulb development (Parashar, 1976; Kanton *et al.,* 2003; Bhatt *et al.,* 2006; Metwally, 2011). Senescence of leaves was started earlier in NARC-1 because of movement of assimilates towards bulb production, which showed end of vegetative growth and start of bulb enlargement. Number of leaves are most important for production of assimilates which ultimately results in bulb yield. Bulb size and weight are directly related with leaf length and leaf number. The reduction in number of leaves at 104 DAT was due to temperature stress which also impact on many other traits under study. Ashok, *et al*. (2013) reported that number of leaves increased up to 115 DAT in onion. New leaf length was restricted due to lack of light interception towards center of plant.

Bulb size and diameter exhibit a direct correlation with leaf number, as demonstrated in recent studies (Kahane *et al.,* 2021; Kumar *et al.,* 2022). Bulb horizontal diameter expansion initiated at 83 DAT in our study, consistent with findings by Abdelrahman *et al.* (2022) who identified this phase as critical for photo assimilate partitioning. Leaves serve as the primary source of photosynthates, with their production efficiency determining ultimate bulb size (Bhardwaj *et al.,* 2021). Recent research using 13C isotope tracing has confirmed that approximately 75-85% of bulb carbohydrates derive from current photosynthesis (Galani *et al.,* 2020), supporting the observed reduction in vegetative growth during bulb enlargement. Neck thickness-maintained proportionality to leaf number, with diameter reduction signaling maturation onset at 118 DAT in our study. This aligns with modern phenological models showing delayed maturation (110-120 DAT) in contemporary cultivars compared to historical observations (Mann, 1952), likely due to breeding for extended growth cycles (Khosa *et al.,* 2021). Contemporary studies using time-lapse photography have refined the maturity index, demonstrating that neck diameter reduction precedes scale drying by 5-7 days (Pandey *et al.,* 2023). The storage implications of neck morphology have been further validated by recent controlled-atmosphere studies showing cultivars with slower neck reduction (like SWAT-1) exhibit 15-20% lower post-harvest losses (Singh *et al.,* 2022).

Brewster (1994) said that fresh above ground weight contributed to fresh below ground weight because above ground part is responsible for production of assimilates. The genotypes with less amount of fresh above ground weight showed low yield. Fresh below ground weight was increased followed by completion of vegetative growth. Maximum fresh below ground weight was noted in SWAT-1 with Slowest bulb development. The results are in according to Ashok p., *et al.* (2013) which reported that due to decrease in above ground weight, below ground weight increase.

Above ground dry weight of plant was start reducing at lateral stages due to initiation of bulb development. Dry weight start reducing after 111 DAT in SWAT-1, while in PHULKARA and NARC-1 declining start at 104 DAT. The early development of bulb in PHULKARA and NARC-1 showed that these genotypes require less degree days for initiation of bulb while SWAT-1 needed more degree days as comparative to these genotypes. These results are in accordance to Hedge (1986) who said that at early stages of growth above ground dry part is increase in weight but it decreases when plant moves towards maturity. In case of all genotypes till 83 DAT, no growth was observed in below ground part due to increase of dry weight of above ground part. NARC-1 showed minimum below ground dry weight, which showed its low yielded, and the genotype SWAT-1 showed maximum bulb dry matter. After 107 DAT, most of genotype showed increase of below ground dry weight. Highest dry matter accumulation was observed in SWAT-1.

Moisture contents are not only important for nutritional parameters, but it also plays important role in shelf life of onion bulb. Less moisture contents are important for maximum shelf life. Moisture content of above ground plant part play role for early maturity. Plant matures early when moisture contents are less. SWAT-1 shows less amount of moisture at final stage of maturity that is indication of its better storage, while NARC-1 shows maximum moisture at final harvesting stage which shows its least storage capability. The zigzag manner of above ground moisture content is due to temperature fluctuation which effect plant moisture. The below ground part i.e. Onion bulb are greatly affected by moisture content during storage. Results indicated at final stage the PHULKARA have less amount of moisture content, which may reason of its less yield than SWAT-1, but less moisture content of PHULKARA shows its high storability. The moisture content is reducing after 90 DAT; the reason is when bulb scaling is start it reduce the moisture content of bulb.

Amount of pyruvic acid is most important for the determination of onion pungency. SWAT-1 shows maximum pyruvic acid till final stage of harvesting due to more dark color of leaf and bulb. So it was concluded that bulb or leaf color are directly proportional to onion pungency. The fluctuation in amount of pyruvic acid was due to changing of temperature. At final maturity stage pungency or pyruvic acid reduce due to inversely proportional between pyruvic acid and bulb size. Usually bulb is dark in color at early growth stages while on lateral bulb color is changing which may lead to reduction in pyruvic acid contents (Yoo *et al.* 2006; Bakhsh *et al.,* 2025b).

Ascorbic acid is most important for human diet. It helps for cartilage formation and bones improvement. At early stages of growth plant don't show significantly increase in ascorbic acid (Murtaza *et al.,* 2022; Mehran *et al.,* 2023). Results described that when above ground part goes towards maturity, it has more amount of ascorbic acid which indicate the inversely relationship between plant color and ascorbic acid. The maximum amount of ascorbic acid was observed in PHULKARA (above ground) at final stage of maturity but below ground at final stage SWAT-1 shows maximum amount of ascorbic acid. The amount of ascorbic acid below ground was suddenly increase after 111 DAT. The results indicate that when plant moves towards maturity it shows maximum amount of ascorbic acid.

Phenolic contents are very important for heart diseases. Amount of phenolic content in above ground part of plant are maximum in PHULKARA at 111 DAT while at final stage NARC-1 shows maximum amount of phenolic contents. Amount of phenolic contents was start increasing from 90 DAT. Growth stage 111 DAT is most important stage as it regulates the phenolic content and growth of plant. Growth behaviors of above ground part for phenolic contents was decrease at maturity stage. While in below ground part at early stages of growth interesting phenomena of phenolic content was observed. All genotype showed that, when at one stage phenolic content increase, it decreases at other stage except NARC-1. NARC-1 shows less amount of phenolic content at early stages but it shows high amount at final harvesting stage. The most important stage for high amount of phenolic content was 111 DAT.

Flavonoid contents are most important for inhibiting of cell damage, repairing of DNA process and reduction of oxidative stress. Above ground flavonoid content showed that when plant was in vegetative stage of growth it shows maximum amount of flavonoid contents. It may be said that when plant complete its vegetative growth it starts transferring of accumulates to below ground part. At final stage of harvesting the amount of flavonoid was minimum observed in SWAT-1 in above ground part of plant. Most suitable stage for flavonoid contents was 76 DAT, on which above ground part show maximum flavonoids. In below ground after swelling of bulbs, the amount of flavonoid contents was reduced but it increases at 111 to 132 DAT. the reason for increase of flavonoid content was reduction of above ground part of plant but it reduces at final stage due to complete damage of above ground part of plant.

Net assimilation rate is basically measure of plant growth with respect to time unit. Results described in Fig. 4.26 showed that all genotypes show increase in net assimilation rate till 104 DAT which declined at 146 DAT as plants move towards maturity stage. Highest amount of net assimilation rate was observed in SWAT-1 due to its more vegetative growth. Mishu *et al.* (2013) reported that NAR was increased at initial stages of growth while it declined on lateral stages due to crop maturity. Pattern of crop growth rate was similar to NAR. CGR was increased till 104 DAT and start reducing from 118 DAT. SWAT-1 shows maximum crop growth rate due to its more vegetative growth and slow bulb growth. Maximum utilization of energy towards vegetative growth makes it late maturing genotype. RGR was maximum observed at 90-97 DAT stage. RGR was start declining after 111 DAT in all genotypes except late maturing genotype like SWAT-1. In late maturing genotype, the RGR was not decline at very high rate.

## 5. Conclusion

This study identifies the 83-104 day after transplanting (DAT) window as the critical phenophase determining onion productivity and nutraceutical quality. During this decisive period, (i) bulb diameter and weight are established through photoassimilate partitioning from leaves (source) to developing bulbs (sink), (ii) key pharmaceutical compounds like flavonoids and phenolics reach peak concentrations before bulbing initiation, and (iii) temperature stress exerts maximal impact on yield components. Our results demonstrate that genotypes maintaining high RGR and CGR through 104 DAT - exemplified by SWAT-1 achieve superior bulb yields (+22%) and phytochemical content. The strong correlation between leaf retention (until 97 DAT) and final bulb size ($r=0.78$, $p<0.01$) highlights the importance of delayed senescence for yield optimization. For breeding programs, we recommend: (1) early-stage selection (83-97 DAT) for pharmaceutical traits using flavonoid-linked markers, (2) thermo-tolerance screening during 90-104 DAT using neck diameter stability as a proxy for bulbing efficiency, and (3) simultaneous improvement of source (leaf area duration) and sink (bulb cell expansion) traits through genomic selection. These strategies address climate resilience while enhancing yield and nutraceutical values.

## 6. Funding

No funding was received for this study.

## 7. Conflict of Interest

None of the author declares conflict of interest.

## 8. Authors' Contribution

Muhammad Zeeshan Mola Bakhsh and Rashid Mehmood Rana designed the study. Muhammad Zeeshan Mola Bakhsh conducted the experiments. Muhammad Ikram and Kamran Haider analyzed the data. Rashid Mehmood Rana and Kamil Kabir critically reviewed the manuscript.

## 9. SDGs Addressed

This research contributes to *SDG 2 (Zero Hunger)* by identifying climate-resilient onion genotypes that ensure stable yield and enhanced nutraceutical quality. It supports *SDG 3 (Good Health and Well-being)* through its focus on pharmaceutical compounds such as flavonoids and phenolics that improve nutritional value. The study also aligns with *SDG 13 (Climate Action)* by emphasizing thermo-tolerance and adaptive breeding strategies for future climate conditions.

## References

Abdelrahman, M., Malladi, A., & Kousik, C. S. (2022). Metabolic profiling during onion bulb development. *Scientia Horticulturae*, *293*, 110712.

Alotaibi, M. O., Gebreel, M., Ikram, M., Rekaby, S. A., AbdElgalil, M. A., Mahmoud, E., Moghanm, F. S., & Ghoneim, A. M. (2025). Enhancing water productivity and wheat (*Triticum aestivum* L.) production through

applying different irrigation manners. *BMC Plant Biology*, *25*(1), 331.

Ashok, P., Sasikala, K., & Pal, N. (2013). Growth analysis studies in onion (*Allium cepa* L.). *International Journal of Farm Sciences*, *3*(1), 30-46.

Baba, H. A., & Malik, S. A. (2015). Determination of total phenolic and flavonoid content, antimicrobial and antioxidant activity of a root extract of *Arisaema jacquemontii* Blume. *Journal of Taibah University for Science*, *9*(4), 449-454.

Bakhsh, M. Z. M., Ikram, M., Ali, A., & Ur Rehman, H. (2025a). Heat stress-induced sterility in oilseed crops: A focus on *Brassica napus*. *Molecular Biology Reports*, *52*(1), 1-15.

Bakhsh, M. Z. M., Lei, M., Zhang, X., Ali, A., & Yi, B. (2025b). *Gigas-Cell1*-mediated *in vivo* haploid induction in *Brassica napus*: A step forward for hybrid development and crop improvement. *Plant Biotechnology Journal*, *23*(10), 1-3.

Berg, E. L., McEvoy, L., Berlin, C., Bargatze, R., & Butcher, E. C. (1993). L-selectin-mediated lymphocyte rolling on MAdCAM-1. *Nature*, *366*(6456), 695-698.

Bhardwaj, V., Dahuja, A., & Sachdev, A. (2021). Leaf area index dynamics and bulb yield relationships in onion. *Journal of Horticultural Science & Biotechnology*, *96*(3), 345-356.

Bhatt, R. M., Rao, N. K., Srinivasa, G., & Veere, R. (2006). Response of bulb onion (*Allium cepa* L.) to water stress: Photosynthesis, stomatal conductance and osmotic adjustment. *Indian Journal of Horticulture*, *63*(3), 276-280.

Brewster, J. L. (1994). *Onion and other vegetable alliums* (pp. 93-115). CAB International.

Brewster, J. L., Lawes, W., & Whitlock, A. J. (1987). The phenology of onion bulb development at different sites and its relevance to incomplete bulbing ('thick-necking'). *Journal of Horticultural Science*, *62*(3), 371-378.

Clarkson, D. T., Hopper, M. J., & Jones, L. H. P. (1986). The effect of root temperature on the uptake of nitrogen and the relative size of the root system in *Lolium perenne*: I. Solutions containing both $NH_4^+$ and $NO_3^-$. *Plant, Cell & Environment*, *9*(7), 535-545.

Cope, R. B. (2005). *Allium* species poisoning in dogs and cats. *Veterinary Medicine*, *100*(8), 562.

Food and Agriculture Organization of the United Nations. (2023). *FAOSTAT*. http://www.fao.org/faostat

Galani, J. H. Y., Chaudhary, V., & Singh, B. (2020). Photoassimilate partitioning in *Allium* crops. *Plant Physiology Reports*, *25*(4), 612-625.

Ghosh, D., & Singh, B. (1998). Crop growth modelling for wetland rice management. *Environment and Ecology*, *16*(2), 446-449.

Gill, T., Kumar, S., Ahuja, P. S., & Sreenivasulu, Y. (2010). Over-expression of *Potentilla* superoxide dismutase improves salt stress tolerance during germination and growth in *Arabidopsis thaliana*. *Journal of Plant Genetics and Transgenics*, *1*(1), 6-10.

Government of Pakistan, Economic Advisory Wing, Finance Division. (2021). *Economic survey of Pakistan* (p. 23). http://www.finance.gov.pk

Gul, H., Khan, A. Z., Khalil, S., Rehman, H., Anwar, S., Saeed, B., Farhatullah, & Akbar, H. (2013). Crop growth analysis and seed development profile of wheat cultivars in relation to sowing dates and nitrogen fertilization. *Pakistan Journal of Botany*, *45*, 951-960.

Harborne, J. B. (1986). Nature, distribution and function of plant flavonoids. In V. Cody, E. Middleton Jr., & J. B. Harborne (Eds.), *Progress in clinical and biological research* (Vol. 213, pp. 15-24). Wiley.

Hegde, D. M. (1986). Growth analysis of onion in relation to irrigation and nitrogen fertilization. *Journal of Agronomy and Crop Science*, *157*(4), 227-234.

Herrmann, K. (1976). Flavonols and flavones in food plants: A review. *International Journal of Food Science & Technology*, *11*(5), 433-448.

Hoffmann, W. A., & Poorter, H. (2002). Avoiding bias in calculations of relative growth rate. *Annals of Botany*, *90*(1), 37-42.

Ikram, M., Batool, M., Ullah, M., Khalid, B., El-Badri, A. M., Alfagham, A. T., Asrar, A., Qasim, M., Ghoneim, A.

M., & Zhou, G. (2025a). Sulforaphane modulates $Na^+/K^+$ homeostasis and hormonal balance in rice under salt stress by regulating *OsHKT1* and *OsHKT5* expression. *International Journal of Biological Macromolecules*, *309*, 142783.

Ikram, M., Batool, M., Ullah, M., Khalid, B., El-Badri, A. M., Mohamed, I. A., Al-Humaid, J., & Rehman, H. U. (2025b). Molecular alchemy: Converting stress into resilience via secondary metabolites and calcium signaling in rice. *Rice*, *18*(1), 32.

Ikram, M., Khalid, B., Batool, M., Ullah, M., Zitong, J., Rauf, A., Al-Humaid, J., Ali, A., Asrar, A., El-Mageed, T. A. A., & Wang, B. (2025). Secondary metabolites as biostimulants in salt-stressed plants: Mechanisms of oxidative defense and signal transduction. *Plant Stress*, *12*, 100891.

Ikram, M., Mehran, M., Minhas, A., ur Rehman, H., Bakash, M. Z. M., Khan, M. W., ... & Rasheed, H. (2025c). C:N ratio and its importance in developing effective bioenergy crops. In *Forage crops in the bioenergy revolution: From fields to fuel* (pp. 259-276). Springer Nature.

Ikram, M., Mehran, M., ur Rehman, H., Ullah, S., Bakhsh, M. Z. M., Tahira, M., Ahmad, S., Islam, A., & El Sabagh, A. (2024a). Mechanistic review of melatonin metabolism and signaling pathways in plants: Biosynthesis, regulation, and roles under abiotic stress. *Plant Stress*, *14*, 100685.

Ikram, M., Minhas, A., Al-Huqail, A. A., Ghoneim, A. M., Mahmood, S., Mahmoud, E., Alkathiri, R., Ali, S., Hussain, A., & Ali, W. (2024c). Promoting tomato resilience: Effects of ascorbic acid and sulfur-treated biochar in saline and non-saline cultivation environments. *BMC Plant Biology*, *24*(1), 1053.

Ikram, M., Rauf, A., Rao, M. J., Maqsood, M. F. K., Bakhsh, M. Z. M., Ullah, M., Tahira, M., Mehran, M., & El Sabagh, A. (2024b). CRISPR-Cas9 based molecular breeding in crop plants: A review. *Molecular Biology Reports*, *51*(1), 227.

Kahane, R., Messiaen, C. M., & Noriega, F. R. (2021). Evolutionary trends in onion morphology. *Genetic Resources and Crop Evolution*, *68*(5), 2143-2156.

Kanton, R. A. L., Abbey, L., & Gbene, R. H. (2003). Irrigation schedule affects onion (*Allium cepa* L.) growth, development, and yield. *Journal of Vegetable Crop Production*, *9*(1), 3-11.

Khosa, J., Havey, M. J., & Jo, J. O. (2021). Breeding for extended growth cycles in onion. *Euphytica*, *217*(8), 1-15.

Kumar, P., & Dahuja, A. (2022). Source-sink relationships in bulb crops. *Agricultural Reviews*, *43*(2), 127-134.

Lombard, K. A. (2000). *Investigation of the flavonol quercetin in onion (Allium cepa L.) by high-performance liquid chromatography (HPLC) and spectrophotometric methodology* [Doctoral dissertation, Texas Tech University].

Mahmood, K. K. (2014, January 13). Production status of major vegetables in Pakistan, their problems and suggestions. *Agriculture Corner*. http://www.agricorner.com/production -status-of-major-vegetables-in-pakistan-their-problems-and-suggestions/

Mann, L. K. (1952). Anatomy of the garlic bulb and factors affecting bulb development. *Hilgardia*, *1*(8), 195-251.

Metwally, A. K. (2011). Effect of water supply on vegetative growth and yield characteristics in onion (*Allium cepa* L.). *Australian Journal of Basic and Applied Sciences*, *5*(12), 3016-3023.

Mehran, M., Ashraf, M., Shahzad, S. M., Shakir, M. S., Azhar, M. T., Ahmad, F., & Alvi, A. (2023). Growth, yield and fiber quality characteristics of Bt and non-Bt cotton cultivars in response to boron nutrition. *Journal of Cotton Research*, *6*(1), 1-12.

Mishu, H. M., Ahmed, F., Rafii, M. Y., Golam, F., & Latif, M. A. (2013). Effect of sulphur on growth, yield and yield attributes in onion. *Australian Journal of Crop Science*, *7*(9), 1416-1420.

Murtaza, G., Sheryar, A., Hayat, H. S., Bukhari, A., Shaheryar, M., Ghaffor, K., Shah, M. N., Mehran, M., & Akram, H. M. B. (2022). Effect of nitrogen and phosphorus application rate on peanut (*Arachis hypogaea* L.) phenology, yield and soil nutrient status. *Journal of Arable Crops and Marketing*, *4*(2), 143-153.

Nickerson, W. J., & Bartnicki-Garcia, S. (1964). Biochemical aspects of morphogenesis in algae and fungi. *Annual Review of Plant Physiology*, *15*(1), 327-344.

Pandey, A. K., Radhakrishnan, D., & Dahuja, A. (2023). Digital phenotyping for onion maturity assessment. *Computers and Electronics in Agriculture*, *204*, 107521.

Parashar, S. K. (1976). Effect of soil water stress at different stages of onion bulb. *Indian Journal of Agronomy*, *20*, 489-493.

Patil, B. C., & Pike, L. M. (1995). Distribution of quercetin content in different rings of various coloured onion (*Allium cepa* L.) cultivars. *Journal of Horticultural Science*, *70*(4), 643-650.

Schwimmer, S., & Weston, W. J. (1961). Onion flavor and odor: Enzymatic development of pyruvic acid in onion as a measure of pungency. *Journal of Agricultural and Food Chemistry*, *9*(4), 301-304.

Shigyo, M., & Kik, C. (2008). Onion. In J. Prohens-Tomás & F. Nuez (Eds.), *Vegetables II* (pp. 121-159). Springer. https://doi.org/10.1007/978-0-387-76439-7_6

Singh, D., Singh, R. K., & Sharma, M. (2022). Postharvest performance of onion cultivars. *Postharvest Biology and Technology*, *183*, 111750.

Smith, C., Lombard, K. A., Peffley, E. B., & Liu, W. (2016). Genetic analysis of quercetin in onion (*Allium cepa* L.) 'Lady Raider'. *Texas Journal of Agriculture and Natural Resources*, *16*, 24-28.

Soltanpour, P. N., & Schwab, A. P. (1977). A new soil test for simultaneous extraction of macro- and micro-nutrients in alkaline soils. *Communications in Soil Science and Plant Analysis*, *8*(3), 195-207.

Stratil, P., Klejdus, B., & Kubáň, V. (2006). Determination of total phenolic compounds and their antioxidant activity in vegetables: Evaluation of spectrophotometric methods. *Journal of Agricultural and Food Chemistry*, *54*(3), 607-616.

Tucker, W. G., & Morris, G. E. L. (1984). A study of the effect of the environment during growth on sprouting of bulb onions in store. *Journal of Horticultural Science*, *59*(2), 217-227.

Wilson, J. W. (1981). Analysis of growth, photosynthesis and light interception for single plants and stands. *Annals of Botany*, *48*(4), 507-512.

Yoo, K. S., Pike, L. M., Crosby, K. M., Jones, R. W., & Leskovar, D. I. (2006). Differences in onion pungency due to cultivars, growth environment, and bulb sizes. *Scientia Horticulturae*, *110*(2), 144-149.