Caraka Tani: Journal of Sustainable Agriculture
ISSN 2613-9456 (Print) 2599-2570 (Online)

Caraka Tani: Journal of Sustainable Agriculture, 40(3), 404-424, 2025
URL: https://jurnal.uns.ac.id/carakatani/article/view/100515
DOI: http://dx.doi.org/10.20961/carakatani.v40i3.100515

Prospect for Vegetative Bulbs Productions and Enlargement of Rose Onion (*Allium cepa* L.) Via Agro-Physiological Optimization in Tropical Climate

Mahaletchumy Krishnamoorthy[1], Afiq Kamaruzali[1], Liang Su Toh[1], Nurul Aaliyah Mohd Sahud[1], Khairunnisa Najwa Khairulazlan[1], Mashitah Jusoh[1], Azzami Adam Muhamad Mujab[2], Khalisanni Khalid[3], Andrew Fleming[4] and Nazmin Yaapar[1*]

[1]Department of Crop Science, Faculty of Agriculture, Universiti Putra Malaysia, Serdang, Malaysia; [2]Commercialization and Business Centre, Malaysian Agricultural Research and Development Institute, Perak, Malaysia; [3]Biotechnology and Nanotechnology Research Centre, Malaysian Agricultural Research and Development Institute, Selangor, Malaysia; [4]School of Biosciences, The University of Sheffield, Sheffield, United Kingdom

[*]*Corresponding author:* muhdnazmin@upm.edu.my

Abstract

Rose onion (*Allium cepa* L.), a unique red onion from Karnataka, India, is valued across Asia for its culinary significance. Recent onion supply disruptions have triggered an export ban from India, causing price surges and declining onion quality. This study evaluated two agro-physiological cultivation methods for rose onion under tropical Malaysian conditions to address Malaysia's onion import dependency. The bulbification method aimed at optimizing planting material production utilized open field conditions and resulted in enhanced pseudostem proliferation ($p < 0.001$) and increased bulb counts ($p < 0.001$). In contrast, the bulking method, designed to maximize yield, employed shaded environments and nutrient management, achieving an 86% yield increase (10.78 tons ha^{-1}) and higher economic returns (102,410 MYR ha^{-1}). Key physiological measurements, including chlorophyll content (+30.68%, $p < 0.05$) and water-use efficiency (+87.71%, $p = 0.003$), highlighted the adaptability of both methods to tropical climates. Economic analysis revealed that although pre-harvest costs were 65% higher for the bulking method, it generated 63,715 MYR in net profit, representing a 450% increase in profitability and a benefit-cost ratio (BCR) of 2.65. The findings support targeted cultivation strategies based on production objectives and emphasize the agronomic value of integrating physiological monitoring and cost-benefit analysis in tropical onion systems.

Keywords: bulbification; bulking; forchlorfenuron; red onion; yield improvement

Cite this as: Krishnamoorthy, M., Kamaruzali, A., Toh, L. S., Sahud, N. A. M., Khairulazlan, K. N., Jusoh, M., Mujab, A. A. M., Khalid, K., Fleming, A., & Yaapar, N. (2025). Prospect for Vegetative Bulbs Productions and Enlargement of Rose Onion (*Allium cepa* L.) Via Agro-Physiological Optimization in Tropical Climate. *Caraka Tani: Journal of Sustainable Agriculture*, *40*(3), 404-424. doi: http://dx.doi.org/10.20961/carakatani.v40i3.100515

INTRODUCTION

The rose onion (*Allium cepa* L.) is important in Malaysia. It is a favored ingredient in many beloved national dishes because of its distinctive flavor and aromatic qualities (Gayathri et al., 2016). However, Malaysia significantly relies on imported rose onions from Karnataka, India, to satisfy the local demand. This import dependency is underscored by the Department of Statistics Malaysia's 2021 report, revealing that 622.2 thousand metric tonnes of red onion, shallot, and garlic, amounting to 1,477.6 million MYR, were imported, translating into an import dependency ratio (IDR) of 100% for onion bulbs (DOSM, 2023). This heavy reliance increases

[*] *Received for publication March 15, 2025*
Accepted after corrections June 2, 2025

national vulnerability, especially during periods of supply disruption, such as India's export restrictions, which have historically led to price volatility and compromised onion quality within Malaysian markets (Wong et al., 2019; DOSM, 2023). Addressing this dependency is crucial for economic stability and ensuring food sovereignty and resilience amid climatic and geopolitical uncertainties.

Malaysian authorities actively promote local onion cultivation to reduce import dependency and ensure a stable supply. In efforts to effectively support this national initiative, a thorough understanding of two vital agro-physiological stages in the lifecycle of onions is essential, specifically the process of bulbification and bulking. Bulbification refers to the initiation of bulb formation, characterized by the morphological transformation of the swollen leaf bases into a nutrient-storing organ, while bulking refers to the enlargement phase where carbohydrates and water accumulate in the developing bulb (Taylor et al., 2010; Atif et al., 2020). These stages are controlled by a complex network of environmental and genetic triggers, most notably photoperiodism, which regulates the expression of *FLOWERING LOCUS T* (*AcFT*) genes. *AcFT1* promotes bulb initiation while *AcFT4* suppresses it, ensuring proper developmental timing under varying light regimes (Lee et al., 2013). Phytochromes and circadian clock genes perceive these light signals, coordinating hormonal cascades that reprogram the plant from leaf elongation to bulb swelling (Taylor et al., 2010; Atif et al., 2020). The photothermal requirements for these processes vary by cultivar but often intersect with key hormonal regulators such as gibberellins, abscisic acid, and cytokinins. These hormones modulate assimilate partitioning and cellular expansion, with cytokinin application promising in enhancing chlorophyll retention and stimulating vegetative vigor and bulb size (Pagano et al., 2023, Hamidon et al., 2025).

External factors such as light quality, temperature, and moisture availability determine not only the transition point but also the rate and success of bulb formation. For example, shading changes the ratio of red to far-red light in the spectrum, which can delay or encourage bulb formation depending on how intense and long the shading lasts (Gao et al., 2021a). As the onions proceed to bulb development, applying balanced fertilizers, particularly nitrogen, phosphorus, and potassium, supports the final growth stage, which demands a high nutrient input to maximize bulb size and quality. Generally, a temperature of 13 to 23 °C is optimum for vegetative growth and 20 to 25 °C for bulb development (Sharma and Chauhan, 2022). Therefore, there is a need to optimize cultivation strategies that integrate physiological and environmental domains for a systems-level understanding of bulbification and bulking in onions, especially in tropical settings like Malaysia.

To assess the suitability of Malaysia for onion cultivation, it is essential to consider the climatic conditions relating to the origin of the onion cultivars. The climate of Perak (100.8915° E, 4.4356° N) and Selangor (100.6124° E, 5.2101° N) states in Malaysia shares key similarities with Karnataka, India (75.7139° E, 15.3173° N), the origin of the imported rose onions. Both regions are located in the northern hemisphere, within comparable latitudes between the Equator and the Tropic of Cancer. Furthermore, while Karnataka experiences a subtropical climate with distinct seasons, Selangor has a tropical rainforest climate with consistently high temperatures (25 to 32 °C) and abundant rainfall. Crucially, the optimal temperature range for onion growth (20 to 30 °C) is largely consistent across both locations. This climatic compatibility suggests that cultivating Karnataka-origin rose onions in Selangor is viable.

Despite the promising climatic alignment, current knowledge and established best practices for commercial onion cultivation within Malaysia's specific environmental conditions remain limited. While major global onion producers such as China and India predominantly favor seed-based propagation methods for their extensive operations (Peiwen et al., 1994; Manna, 2016), this research explores the viability of vegetative propagation using sets (immature onion bulbs) as a potential more suitable approach for initiating a local industry in Malaysia. Set-based propagation offers faster crop establishment, shorter production cycles, and higher initial yields (Singh and Singh, 2018; Mubarak, 2021) and may be particularly beneficial in the Malaysian context. Furthermore, with consumer-grade onion bulbs readily available, utilizing sets presents a practical starting point for establishing a local onion industry. Although onion research in Malaysia was conducted in the early 1980s, the results of the study found that the cultivation of onions in the country was uneconomical due to high planting costs, less profitable farm sales prices, and high pest and disease attack (Rozita et al., 2024). However, due to the current issues with inconsistent supply, high import costs, unstable world onion market prices, and increasing domestic demand involving national food security and safety issues, Malaysian authorities actively encourage domestic onion cultivation, making this research timely and relevant to national agricultural goals.

Current literature provides scant empirical evidence addressing the agronomic and economic feasibility of cultivating rose onions under tropical hot and humid conditions. This context-specific knowledge gap is critical, as Malaysia's soil and climatic environments differ substantially from the temperate or arid regions where most onion research has traditionally been situated. Consequently, the absence of adaptive cultivation models tailored to Malaysia's tropical lowland agroecosystems limits policy implementation and farmer adoption of onion production strategies. Recognizing the critical need for locally adapted cultivation techniques, this research demonstrates two distinct methods of cultivating rose onions: one aimed at maximizing planting material production (high bulb number) and the other at optimizing marketable yield (high bulb weight) under tropical conditions. The outcome of this study provides a preliminary foundation for methodological advancements in rose onion cultivation in tropical horticulture. This contribution will significantly support the ongoing national endeavor to promote local onion production and substantially reduce Malaysia's dependence on imports, which similar developing nations can adopt.

MATERIALS AND METHOD

Description of the study sites

The study was carried out for 2 seasons in 2 different locations. The bulbification method was conducted from September to November 2023 at the Malaysian Agricultural Research and Development Institute (MARDI) in Parit, Perak, Malaysia (100.8911° E, 4.4348° N) on Telemong series soil. On the other hand, the bulking method was conducted from December 2023 to February 2024 at Field 15, Faculty of Agriculture, Universiti Putra Malaysia in Serdang, Selangor (101.7026° E, 3.0077 °N) on Serdang series soil. Table 1 presents the monthly climate data used in this study.

Plant material and growth conditions

Store-bought rose onion bulbs originating from Karnataka, India, and commonly available in Malaysian markets were used as planting material for this study. Selected bulbs measuring 25 to 35 mm in diameter and weighing 15 to 25 g were prepped by removing one-third of the top. The bulbs were then placed in a tray covered with plastic film to maintain high humidity for approximately 48 hours to initiate rooting and sprouting.

In both methods, the prepped bulbs were planted directly into 20 cm raised beds (bed area) in a completely randomized layout. Each bed contained 18 bulbs spaced 15 cm apart. The planted bulbs were covered with a thin layer of soil and mulched with dried rice straws to prevent desiccation.

Molluscicide (Siputox® – Agricultural Chemicals) was applied on the seedbed before planting to control snail infestation. Biological control against fungi was biweekly using organic fungicides Phyzoctium F-10 and Alterdew F-11. Additionally, wood vinegar was applied to the plant foliage as an organic pesticide at a 5% (v/v) concentration with a biweekly application frequency. Harvesting occurred 60 to 70 days after planting (DAP) once the plant necks had collapsed, indicating maturity. The BBCH scale was used to identify crop stages (Meier et al., 2009).

Description of bulbification method regimes

Controlled-release fertilizer (CRF), NPK 23:9:13, was applied 3 days before planting at 50 g plot^{-1}. Liquid fertilizer was used as a foliar

Table 1. Monthly climate data for Parit, Perak, and Serdang, Selangor, during the study period

Location	Month	Mean temperature (°C)	Mean relative humidity (RH)	Total rainfall (mm)
Parit, Perak	September	27.3	80	170
	October	27.9	85	256
	November	27.0	88	260
Serdang, Selangor	December	25.2	85	231
	January	25.8	81	188
	February	26.1	83	263

spray containing NPK 10:30:30 (Upsara® – Zeenex) at a concentration of 0.5% (v/v) at 35 DAP (approximately 40 ml plant^{-1}). The seedbeds were irrigated by flooding, as the research plot was situated in an existing paddy field that retained water. A summary of these methods is provided in Figure 2A.

Description of bulking method regimes

Store-bought ice was applied at 1 kg bed^{-1} daily for three consecutive days to enhance bulb formation, and shading was provided using a pongee cloth installed 2 m above the ground. CRF, NPK 23:9:13, was applied 3 days before planting at 50 g plot^{-1}. Liquid fertilizer NPK 16:16:16 + TE (Biogreen, Yi Nong) was applied through foliar application at 0.1% (v/v). It was conducted weekly at 7, 14, 21, and 28 DAP, alongside compost tea prepared with fish emulsion, molasses, microbes, and compost. Liquid fertilizer NPK 10:30:30 (Upsara® – Zeenex) was sprayed at 40 DAP at 0.5% (v/v). A synthetic growth regulator derived from cytokinin, namely forchlorfenuron ($C_{12}H_{10}ClN_3O$, from Dunedin), was applied at the rate of 0.1% (v/v) at 21 DAP and 0.05% (v/v) at 40 DAP to promote bulb formation. Plants were irrigated twice daily for 15 minutes using a drip irrigation system. A summary of these methods is provided in Figure 2B.

Measurements

The light readings at the planting site were recorded at 30 DAP using a spectrometer (LI-180; LI-COR Inc., USA) between 9:00 and 10:00 am. The spectrometer was positioned 110 cm above the ground, and 3 measurements were taken from 3 central points of the planting site.

Progressive measurements were taken fortnightly. Using a measuring tape, plant height (cm) was measured from the ground level to the tip of the longest leaf. The number of leaves and pseudostems was manually counted. Leaf to pseudostem ratio was calculated by dividing the total number of leaves by the total number of pseudostems for each plant using Equation 1.

The chlorophyll content was measured on a healthy leaf using the Soil Plant Analysis Development (SPAD) chlorophyll meter (Chlorophyll meter SPAD-502 Plus, Konica Minolta Inc., Japan). Readings were taken at 3 locations along the midpoints of the leaf, and the average SPAD index was recorded. Measurements were taken fortnightly until harvest.

Leaf gas exchange, including assimilation rate and stomatal conductance, was measured during the vegetative stage at 30 DAP using the LI-6800 photosynthesis system (LI-COR Inc., USA). Five plants were randomly selected, and measurements were taken at the midpoint of a fully expanded leaf. The leaf width was measured and input into the LI-6800 for accurate calculation. The light intensity was set at 1,500 μmol m^{-2} s^{-1}, composed of 10% blue and 90% red light. Temperature and humidity were maintained at 27 to 30 °C and 60%, respectively. The flow rate was set at 600 μmol s^{-1}, with a valve pressure of 0.1 kPa, fan speed set to 10,000 rpm, and CO_2 concentration in the leaf chamber was maintained at 400 ppm.

Yield data were collected at the time of harvest. The number of bulbs per clump was manually counted. The fresh clump weight (g) and fresh bulb weight (g) were measured using an electric weighing scale (FX-1200i, A&D, CO. Ltd., Japan). A vernier caliper measured bulk diameter (mm) at the equatorial position. Dry clump weight (g) and dry bulb weight (g) were recorded after 2 weeks of curing using an electronic weighing scale (FX-1200i, A&D, CO. Ltd., Japan).

Bulb grading was performed according to the formula by Gayathri et al. (2016). The bulb number potential, yield potential, projected plantable area, and forecasted revenue per hectare (in MYR) were estimated based on the bulb yield obtained per square meter. The selling price for rose onions in the bulbification method was set at a wholesale price of 6.25 MYR kg^{-1}. In contrast, the selling price for the bulking method was set at the market price of 9.50 MYR kg^{-1}, as reported on the Federal Agricultural Marketing Authority (FAMA) website (FAMA, 2024).

Economic analysis

The economic analysis was conducted on December 4, 2024, using an exchange rate of 1 MYR = 0.23 USD. Pre-harvest costs included land preparation, labor, bulb inputs, fertilizer, and pesticides. Land preparation, including shading in the bulking method, and labor costs were based on Mohamed Hafeifi et al. (2024). Bulb input costs were obtained from a wholesale distributor's website (Like Best (M) Sdn Bhd, 2024). The harvesting cost was calculated based on a labor cost of RM90 per day for 14 days, while the curing structure cost was set at RM1,000, as mentioned by Mohamed Hafeifi et al. (2024). Yield potential for each method was measured in tons per hectare (tons ha^{-1}), and total revenue was calculated

$$\text{Leaf to pseudostem ratio} = \frac{\text{Number of leaves}}{\text{Number of pseudostems}} \quad (1)$$

Water-use efficiency (WUE) was calculated as the ratio of assimilation rate to stomatal conductance using Equation 2.

$$\text{WUE} = \frac{\text{Assimilation rate}}{\text{Stomatal conductance}} \quad (2)$$

Carboxylation efficiency was calculated as the ratio of assimilation rate to intercellular CO_2 using Equation 3.

$$\text{Carboxylation efficiency} = \frac{\text{Assimilation rate}}{\text{Intercellular } CO_2} \quad (3)$$

Moisture loss percentage was calculated using Equation 4.

$$\text{Moisture loss (\%)} = \frac{\text{Fresh weight-Dry weight}}{\text{Fresh weight}} \times 100 \quad (4)$$

Bulb number potential per hectare was calculated using Equation 5.

$$\text{Bulb number potential (ha}^{-1}\text{)} = \text{Total bulb per plant x Total plants per hectare} \quad (5)$$

Yield potential per hectare was calculated using Equation 6.

$$\text{Yield potential (tons ha}^{-1}\text{)} = \text{Clump weight x Number of plants per hectare} \quad (6)$$

The projected plantable area per hectare was calculated using Equation 7.

$$\text{Projected plantable area (ha}^{-1}\text{)} = \text{Bulb number potential x Planting space} \quad (7)$$

Projected revenue per hectare was calculated using Equation 8.

$$\text{Projected revenue (MYR ha}^{-1}\text{)} = \text{Yield potential per hectare x Selling price} \quad (8)$$

based on yield estimates and current market onion prices. Total production costs were determined by summing pre-harvest and post-harvest costs, representing the total investment required. Profitability for each method was evaluated using three key metrics: net return, net return per MYR investment, and the benefit-cost ratio (BCR). Net return was calculated by subtracting total costs from total revenue, while net return per MYR investment assessed the economic efficiency of resource use. The BCR was applied to evaluate cost-effectiveness, with a ratio exceeding 2.0, indicating strong economic viability. Percentage changes between the bulbification and bulking methods were calculated to facilitate comparative analysis.

Statistical analysis

The Shapiro-Wilk test was conducted to evaluate data normality, and Levene's test was used to assess the homogeneity of variances. Student's t-test was utilized to compare means for the normally distributed data with equal variances. When the normality assumption was violated, the Mann-Whitney U test was applied. For non-normal data with unequal variances, the Brunner-Munzel test was utilized, while Welch's t-test was employed for normally distributed data with unequal variances. Statistical analyses, calculations, and graph generation were performed using Microsoft Excel 365 (Microsoft Corporation, Redmond, WA, USA) and GraphPad Prism 9.2.0 (GraphPad Software, USA). Diagrams were created using Microsoft PowerPoint 365 (Microsoft Corporation, USA).

RESULTS AND DISCUSSION

Environmental compatibility

This study demonstrates the successful cultivation of the rose onion cultivar in the tropical climate of Perak (100.8915° E, 4.4356°

N) and Selangor (100.6124° E, 5.2101° N) state in Malaysia, using imported bulbs originating from the state of Karnataka, India (75.7139° E, 15.3173° N) (Figures 1A and 1B). Both regions are located within the northern hemisphere, between the Equator (0°) and the Tropic of Cancer (23.43602° N). Perak and Selangor exhibit a tropical rainforest climate characterized by consistently high temperatures (25 to 32 °C) and rainfall influenced by maritime factors. Karnataka, in contrast, experiences a subtropical climate with distinct seasons, including warm, dry summers (15 to 35 °C), mild winters, and a monsoon season from June to September. Nevertheless, as the optimal growth temperature for onions typically falls within the range of 20 to 30 °C (Immanuelraj et al., 2014), the climatic compatibility in Perak and Selangor aligns with the bulbs of Karnataka origin, thus providing suitable growth conditions for this particular onion cultivar.

Malaysia's favorable growth temperatures position it as a promising location for cultivating rose onions. During the first season, the bulbs were planted in an intensely moist soil bed in MARDI Parit, Perak, expecting that the combination of aerobic and anaerobic conditions would enhance nutrient absorption and promote larger bulb formation. However, instead of achieving the desired marketable size, the cultivation method resulted in many smaller bulbs, leading to the designation of this method as the bulbification method. To mitigate the issue of excessive pseudostem formation and its associated nutrient competition, a subsequent cultivation trial in Selangor incorporated the application of the plant growth regulator forchlorfenuron (cytokinin) to regulate pseudostem development. The rationale behind this approach was to optimize nutrient allocation by reducing the number of pseudostems, thereby facilitating the growth of larger individual bulbs (Bennett et al., 2012). This bulking cultivation method was implemented by integrating shading, ice application, and frequent foliar and compost tea treatments to encourage bulb enlargement. The key methodological aspects of this approach are summarised in Figure 2.

The bulbification method, conducted under full sunlight, had a high relative humidity (RH) of 89.7% and an average temperature of 27.9 °C due to the standing water body in the paddy field. Photosynthetic photon flux density (PPFD) measurements were 1,288 μmol m^{-2} s^{-1}, and solar radiation was 1,042 (mW m^{-2}). In contrast, the bulking method, performed under pongee cloth shade, resulted in a lower RH of 66.2% and a higher temperature of 32 °C, with a 30% reduction in light intensity. Despite that, the light was more pronounced in the bulking method, with PPFD measurements of 352.4 μmol m^{-2} s^{-1} and solar radiation of 412.5 (mW m^{-2}), particularly in the far-red and UV spectra, which decreased by 45% and 47%, respectively which had been shown to mitigate heat stress, enhance light interception, and improve carbon utilization, contributing to better crop performance (Gunadi and Sulastrini, 2013; Hadid and Febriana, 2022).

Vegetative growth

Plants in the bulbification method exhibited yellowing on the leaf tip compared to those in the bulking method, which retained a green, healthy appearance at 45 DAP (Figures 3A and 3B). This pattern was consistent with differences in plant height (Figure 3C). At 45 DAP, plants in the bulbification method showed a decline in height. In contrast, plants in the bulking method exhibited steady growth, reaching an average height of 36 cm, a 93% increase compared to the bulbification method ($p < 0.001$).

Pseudostem (or neck) number per plant (Figure 3D), a key determinant of the final bulb count at harvest, was consistently higher in the bulbification method compared to the bulking method, with significant differences observed at all time points ($p < 0.001$). At 30 DAP, the pseudostem number in the bulbification method was 44% higher than in the bulking method (Figure 3D, Welch's t-test, $p < 0.001$), which showed the potential of this method to mass-produce bulbs to become planting materials. Similar pseudostem proliferation under stress-prone or resource-limited conditions has been reported in onions, where vegetative propagation tends to be prioritized over sink development (Khokhar, 2017). High pseudostem counts are associated with early bulb initiation and accelerated physiological aging, often reducing biomass accumulation per bulb (Brewster and Salter, 1980). In contrast, the resource-optimized environment in the bulking method tends to promote fewer but more photosynthetically efficient shoot axes, sustaining leaf growth longer into the bulbing phase (Dutta et al., 2024).

Leaf number per plant (Figure 3E) was significantly higher in the bulbification method at 15 and 30 DAP ($p = 0.006$ and $p < 0.001$, respectively). However, leaf number in the bulbification method declined significantly

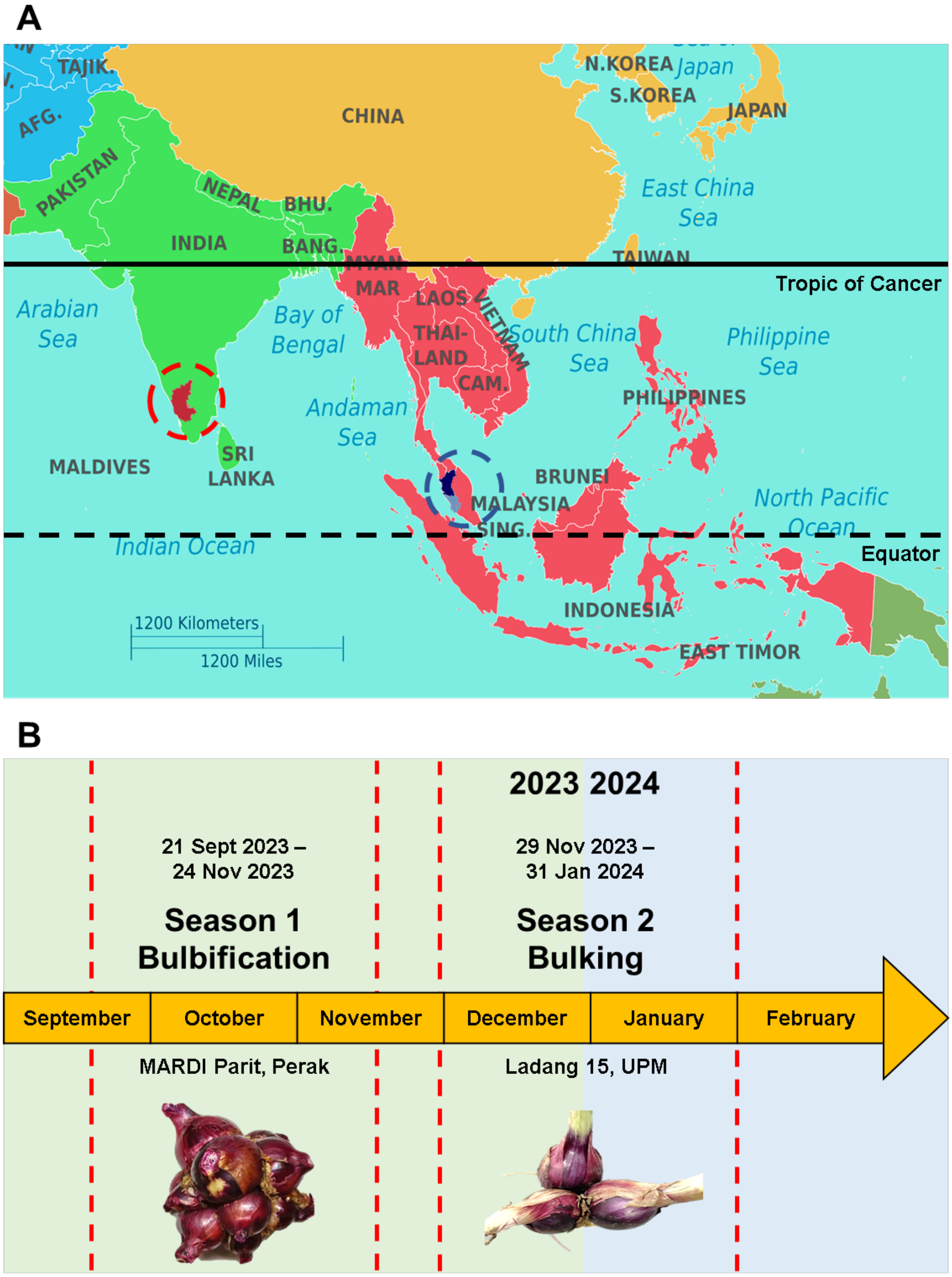

Figure 1. A) Map of Southeast Asia highlighting Selangor state, Malaysia, and Karnataka state, India. Karnataka, India, is marked with a red dashed circle, while Perak and Selangor, Malaysia, are highlighted with a blue dashed circle. The dashed black line indicates the Equator, while the solid black line represents the Tropic of Cancer. The geographical proximity and similar latitudinal positions of Karnataka and Selangor within the Southeast Asia region suggest that these two places share similarities in climate patterns. B) The timeline and the location of the onion cultivation for the two seasons

Source: Map of Asia, in Wikipedia, 2007 (https://en.m.wikipedia.org/wiki/File:Map_of_Asia.svg, CC-BY 4.0)

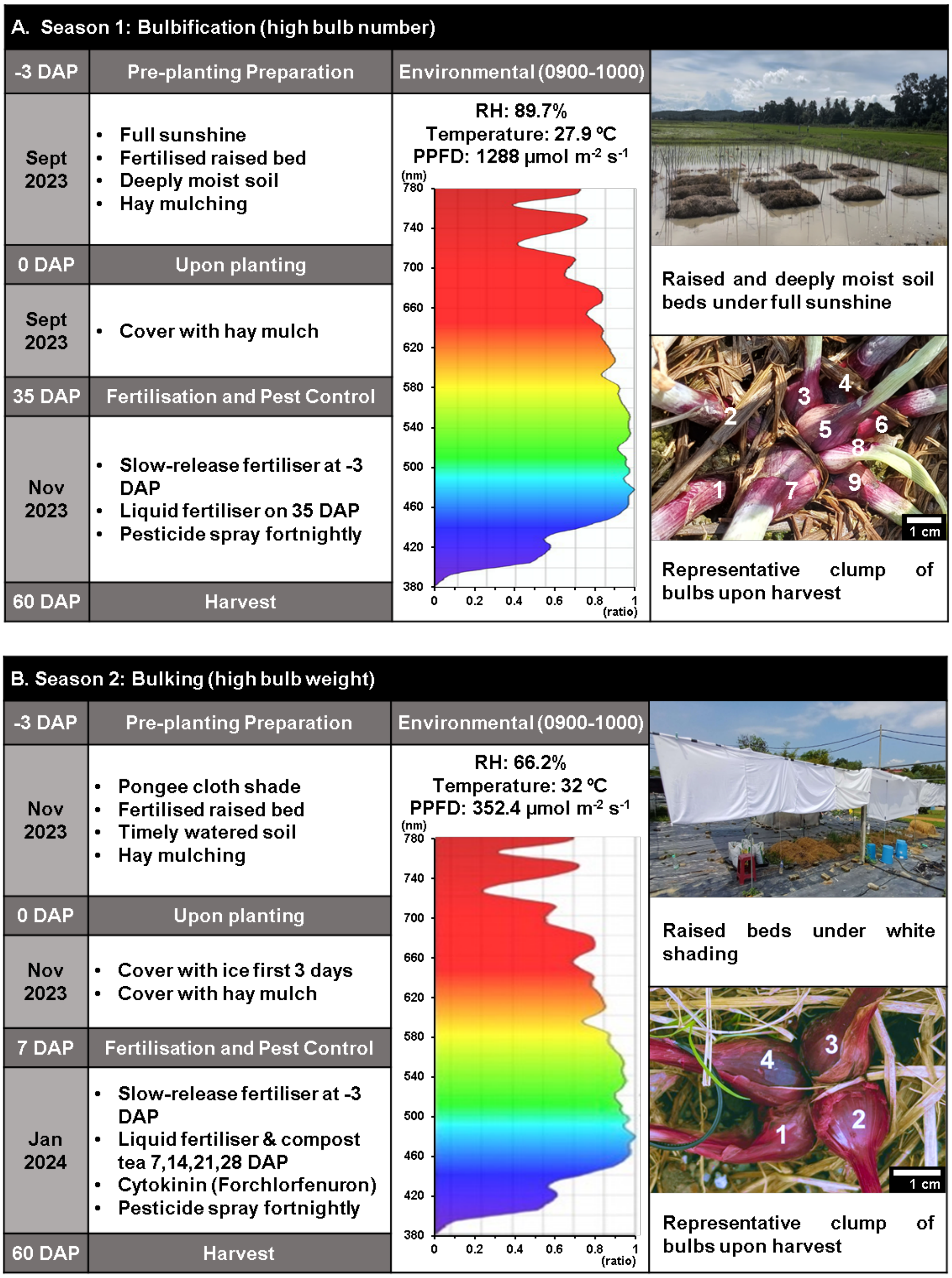

Figure 2. Cultivation practices and key differences between the bulbification and bulking methods. A) The bulbification method focuses on producing many bulbs, its methods, and associated environmental conditions. B) The bulking method, along with its methods and corresponding environmental conditions, focuses on creating high bulb weight

at 45 DAP, whereas plants in the bulking method maintained steady growth in leaf number.

The leaf-to-pseudostem ratio, defined as the number of leaves divided by pseudostem number, suggests that an optimal leaf number per pseudostem is necessary for efficient assimilate translocation from leaves to bulbs. The leaf-to-pseudostem ratio (Figure 3F) displayed a progressive and notable increase under the bulking method as the plants matured, consistent with the effects of cytokinin application, which was known to promote leaf appearance, leaf expansion and overall growth of plants (Benedetto et al., 2020). This reflects the plant's capacity to meet the assimilated demands of bulb enlargement occurring subterraneously. From an agronomic standpoint, the leaf-to-pseudostem ratio may serve as a phenotypic marker of productivity. The higher ratio recorded in the bulking treatment indicates more efficient assimilate translocation and greater yield potential. This observation aligns with previous research in cereals and tuber crops, where similar morphological ratios were linked to the harvest index and sink strength (Lopes and Reynolds, 2012; Zhang et al., 2014).

The vegetative advantage observed in the bulking method can be attributed to the integrated use of multiple physiological enhancers. Weekly foliar applications of a balanced macro and micronutrient blend (NPK 16:16:16 + TE) improved nutrient uptake efficiency by delivering elements directly to metabolically active leaf surfaces. Foliar feeding has been shown to promote rapid nutrient assimilation, particularly under intensive systems or where soil uptake may be constrained (Ishfaq et al., 2022). In parallel, applying compost tea prepared from organic fish emulsion, molasses, microbial inoculants, and compost further supported plant vigor by improving leaf nutrient status and stimulating beneficial microbial colonization as reported in Garg and Rakshit (2024). Shading installation using pongee cloth modulated canopy microclimate, reducing light and temperature stress and maintaining higher RH around the foliage. A study by Gao et al. (2021b) reported that moderate shading with blue and white photo-selective nets could optimize light quality, improve physiological performance, enhance antioxidant defense, and increase yield and quality in green onion cultivation under high light and temperature conditions. Applying forchlorfenuron (CPPU), a synthetic cytokinin, likely contributed to cell expansion, delayed senescence, and enhanced vegetative mass through increased mitotic activity (Farhadi and Salteh, 2017).

Physiological responses

The physiological responses of rose onion plants varied significantly under different cultivation methods, particularly in chlorophyll content, stomatal conductance, and WUE (Figure 4). Total chlorophyll content (Figure 4A) significantly increased by 30.68% in the bulking method at 51.06 compared to the bulbification method at 61.7 (Student’s t-test, $p < 0.05$), indicating enhanced capacity for light capture and energy conversion, which are critical for photosynthetic productivity. This increase aligns with plant adaptations to lower light conditions, where pigment concentration rises to maximize light harvesting (Simkin et al., 2022). The shading used in the bulking method likely moderated light intensity and reduced photoinhibition, consistent with reports demonstrating that controlled shading improves chlorophyll retention and photosynthetic efficiency in onions and other crops (Gao et al., 2021a). However, excessive shading can suppress photosynthesis, emphasizing the need to optimize light levels (Mauro et al., 2011; Dolatkhahi et al., 2013).

Despite a non-significant trend toward higher carbon assimilation in the bulbification method (Figure 4B, Student’s t-test, $p = 0.752$), stomatal conductance was significantly greater by 48.64% compared to the bulking method (Figure 4C, Welch’s t-test, $p = 0.007$). Elevated stomatal conductance under the bulbification method (0.50 mol m^{-2} s^{-1}) reflects increased stomatal opening typical of plants in high-light environments (Shen et al., 2021). However, this increase did not translate into improved carbon assimilation or carboxylation efficiency (Figure 4E, Student’s t-test, $p = 0.934$), suggesting stomatal regulation inefficiencies or physiological stress potentially caused by nutrient limitations or microclimatic factors (Kumari et al., 2022) resulting in reduced resource-use efficiency. Wang et al. (2021) noted that optimal nitrogen availability increased not just stomatal conductance but also the entire biochemical pathway for photosynthesis, aligning with the idea that environmental and nutrient conditions critically influence stomatal function and photosynthesis.

WUE was markedly higher (87.71%) in the bulking method (Figure 4D, Mann-Whitney U test, $p = 0.003$), indicating more effective carbon fixation per unit water loss. This improvement likely results from better stomatal control and reduced transpiration, consistent with research showing shading mitigates photoinhibition and improves water conservation in water-stressed plants (Montanaro et al., 2009; Shen et al., 2021). Carboxylation efficiency remained stable across both methods (Figure 4E, Student’s t-test, $p = 0.934$), indicating that biochemical CO_2 fixation capacity via Rubisco was not a limiting factor (Cocon and Luis, 2024). Thus, differences in photosynthetic performance mainly arise from stomatal and environmental regulation rather than enzymatic activity.

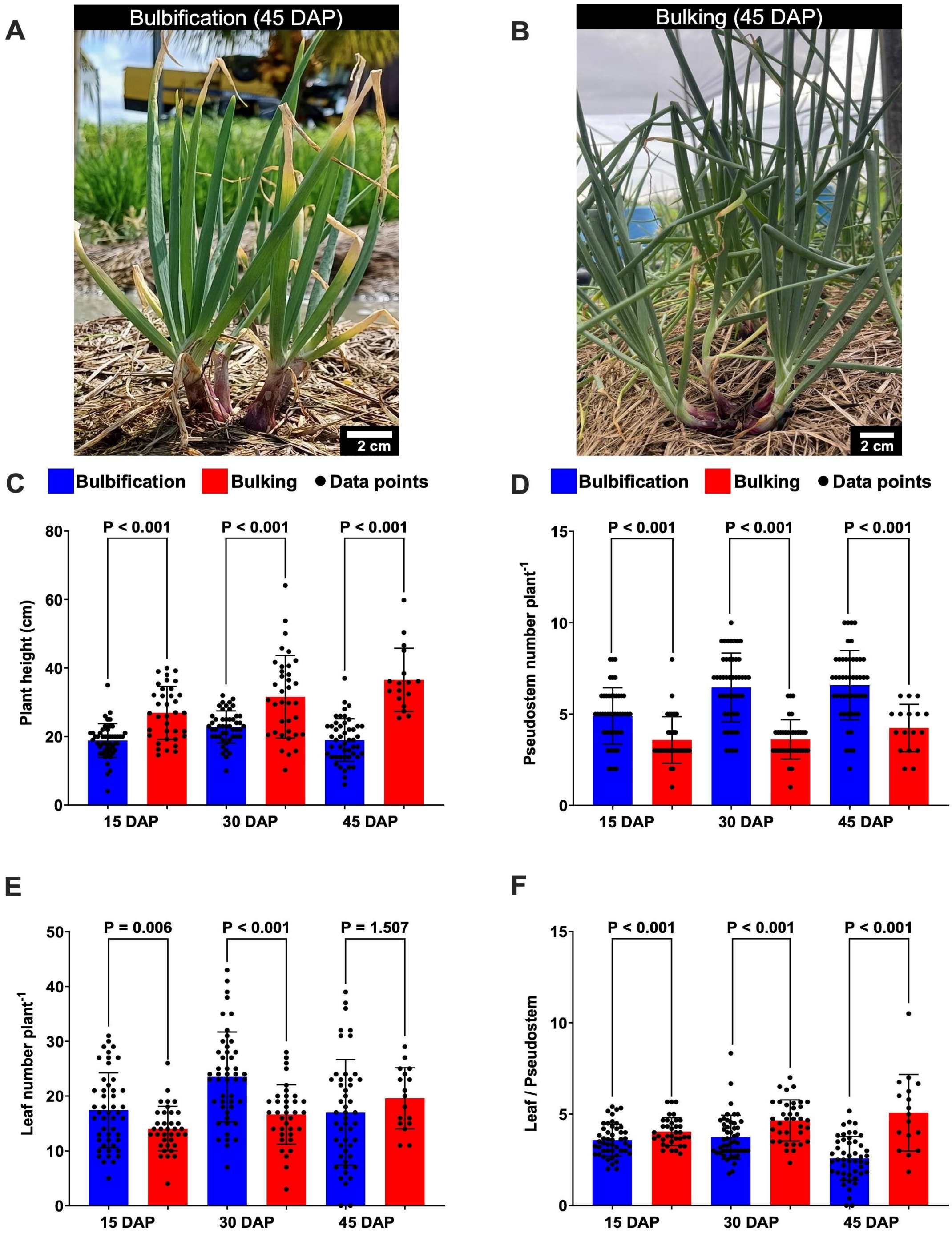

Figure 3. Visual appearance at 45 DAP and growth parameters of rose onion in bulbification and bulking methods. A) Images of rose onion plants at 45 DAP in bulbification method, B) Images of rose onion plants at 45 DAP in bulking method. White scale bar = 2 cm. C) Progressive growth of plant height at 15, 30, and 45 DAP. D) Progressive growth of pseudostem number at 15, 30, and 45 DAP. E) Progressive growth of leaf number at 15, 30, and 45 DAP. F) Leaf/pseudostem ratio at 15, 30, and 45 DAP

Note: Statistical tests: C) Brunner-Munzel test for 15 DAP, Welch's t-test for 30 DAP, and Student's t-test for 45 DAP, *p*-values as shown. D) Welch's t-test for 15, 30, and 45 DAP, *p*-values as shown. E) Mann-Whitney U test for 15 DAP, Brunner-Munzel test for 30 DAP, and Student's t-test for 45 DAP, *p*-values as shown. F) Student's t-test for 15 DAP, Mann-Whitney U test for 30 DAP, and Welch's t-test for 45 DAP, *p*-values as shown. Sample size: Bulbification = 48 and Bulking = 36

Although leaf temperature remained stable across both methods in this study (Figure 4F, Mann-Whitney U test, p = 0.467), earlier research indicates that shading can reduce leaf temperatures in heat-sensitive crops but may have minimal effects on heat-tolerant species (Alves et al., 2022; Mensah et al., 2022).

Using foliar biostimulants such as compost tea and cytokinin enhanced chlorophyll content, stomatal conductance, and WUE. Previous studies have demonstrated that cytokinins increase chlorophyll accumulation and stomatal activity in wheat and maize (Lazova and Yonova, 2010; Islam et al., 2021), while compost tea improves plant health and photosynthetic efficiency (Pane et al., 2014). These results suggest that combining shading with foliar biostimulants may be an effective strategy for optimizing rose onion cultivation. The findings indicate that the bulking method enhances chlorophyll retention, improves WUE, and maintains photosynthetic efficiency, making it potentially advantageous for cultivation in tropical climates. However, the greater stomatal conductance observed in the bulbification method indicates potential benefits for rapid gas exchange and CO_2 uptake in high-light environments, but at the cost of WUE efficiency. These results highlight the value of incorporating physiological trait monitoring into agronomic management to optimise tropical onion production.

Bulbs productivity

The results of this study reveal a significant trade-off between bulb number and individual bulb size, influenced by the chosen cultivation method (Figure 5). The bulbification method produced 33.7% more bulbs per plant (7.5 bulbs set^{-1}), supporting its suitability for generating planting material (Figure 5A, Welch's t-test, $p < 0.001$). In contrast, the bulking method yielded larger bulbs (7 g bulb^{-1}), with a 55.4% greater equatorial diameter of 20 mm (Figure 5B, $p < 0.001$), a 223.8% increase in fresh bulb weight (Figure 5E, $p < 0.01$) and a 192.1% increase in dry bulb weight (Figure 5F, $p < 0.001$). These findings align with the well-documented inverse relationship in bulbous crops, where increased bulb number is typically associated with reduced individual size (Deng et al., 2021). This trade-off is attributed to constraints in assimilate partitioning. Simultaneous bulb formation in the bulbification method appears to have limited the carbon allocation to each sink, thereby restricting individual biomass accumulation (Lambers and Oliveira, 2019). In contrast, the bulking method seems to have promoted assimilate consolidation into fewer sinks, enabling greater bulb enlargement. Comparable results in potato and onion citrus suggest reduced sink competition and sustained photosynthetic activity favor increased bulb mass (Paul and Foyer, 2001).

Environmental and nutritional management contributed to the enhanced bulb biomass under the bulking method. Shading and regular foliar applications of compost tea and cytokinin were central to this method. Shading delays senescence, increasing assimilate availability (Xie et al., 2023). These benefits, however, may not be universal. Mettananda and Fordham (1999) found that shading reduced bulb size and yield in specific onion cultivars, highlighting genotype-specific responses. Similarly, Kurosaki and Yumoto (2003) observed yield declines in soybeans under shading, contrasting with the benefits seen in tropical crops like rose onion, which may tolerate moderate shade more favorably (Bhatt et al., 2002). Cytokinin application is thought to delay senescence, enhance sink strength, and promote cell expansion (Rademacher, 2015). Yet, excessive cytokinin use can disrupt hormonal balance and reduce stress resilience, as reported by Wang et al. (2015) in Arabidopsis. The addition of compost tea also contributed to the improved bulb biomass in the bulking method, consistent with reports linking it to enhanced soil fertility and productivity (Hatungimana et al., 2024). Scheuerell and Mahaffee (2006) cautioned that compost tea efficacy depends on microbial composition and environmental conditions, suggesting variability across systems. The increased biomass accumulation in the bulking method further supports research indicating that CO_2 assimilation and stomatal conductance influence resource allocation to bulbs (Merkebu, 2021).

The marketability of onion bulbs depends on size distribution, post-harvest stability, and consumer preferences. The distribution of bulb sizes between the two methods is shown in Figure 6. The bulbification method produced bulbs exclusively in the < 25 mm size category (100%), making them suitable as planting material rather than direct sale. In contrast, the bulking method produced a wider range of bulb sizes, with 2.41% exceeding 30 mm in diameter, making it more suitable for commercial markets, aligning with market preferences for larger, uniform bulbs, which are valued for their culinary applications and fructooligosaccharide content

(Azeem et al., 2024). However, contrasting evidence shows that higher bulb counts, even at the expense of size, can be economically viable under specific market contexts. Smaller-sized onions are also reported to contain higher phenolic compounds and simple sugars, which may provide nutritional advantages in niche markets (Major et al., 2023). Increasing local production could reduce import dependency, stabilize prices, and offer fresher, nutritionally superior alternatives to imported onions (Berni et al., 2019; Khan et al., 2022).

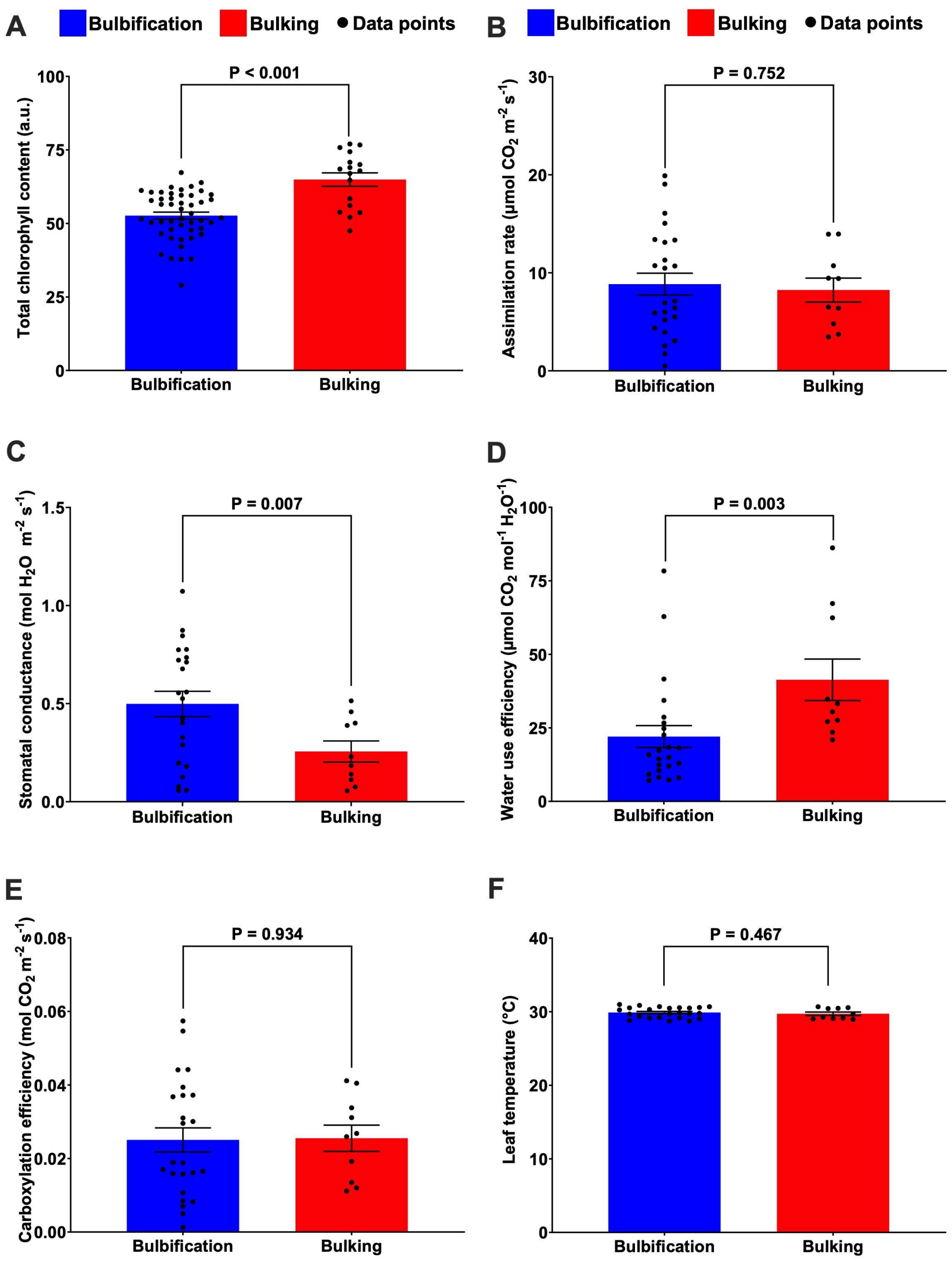

Figure 4. Physiological parameters of rose onion at 36 DAP: Comparison between bulbification and bulking methods. A) Total chlorophyll content at 45 DAP, B) Assimilation rate, C) Stomatal conductance, D) Water-use efficiency, E) Carboxylation efficiency, F) Leaf temperature

Note: Statistical tests: A, B, E) Student's t-test, *p*-values as shown, C) Welch's t-test, *p*-values as shown, D, F) Mann-Whitney U test, *p*-values as shown. Sample sizes: bulbification = 24 and bulking = 10, except for total chlorophyll content, where bulbification = 48 and bulking = 36

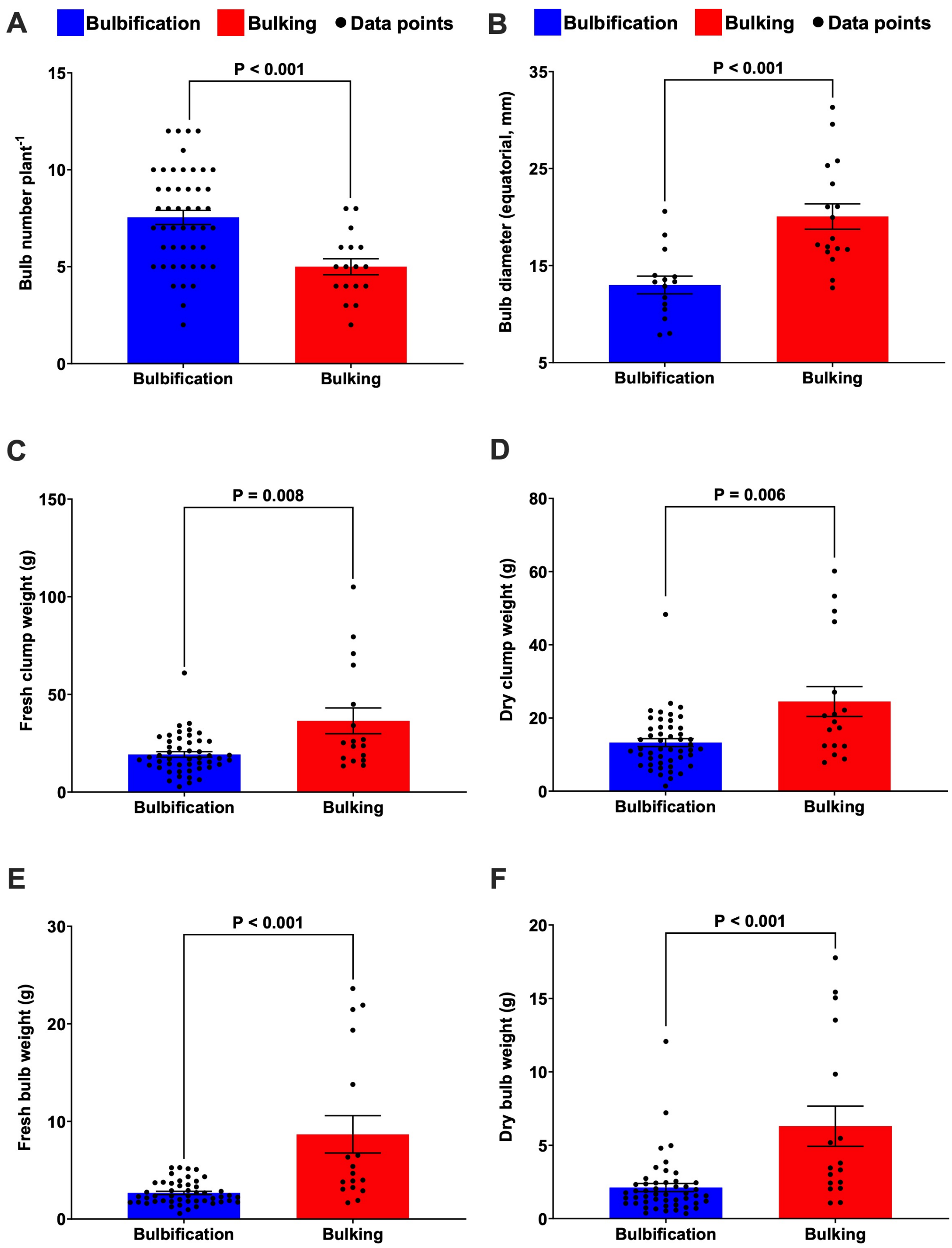

Figure 5. Yield analysis of rose onion at harvest: Comparison between bulbification and bulking methods. A) Bulb number per plant, B) Bulb equatorial diameter, C) Fresh clump weight, D) Dry clump weight, E) Fresh bulb weight, F) Dry bulb weight

Note: Statistical tests: A) Welch's t-test, *p*-values as shown; B) Student's t-test, *p*-values as shown; C, D, E, F) Brunner-Munzel test, *p*-values as shown. Sample sizes: bulbification = 48 and bulking = 17, except for bulb equatorial diameter, where bulbification = 15 and bulking = 17

Projection and feasibility

The economic viability of onion production depends on multiple interacting factors, including yield potential, input costs, and market pricing dynamics. Statistical analysis revealed significant differences between the bulbification and bulking methods across key parameters: bulb number potential, yield potential, projected plantable area, and projected revenue per hectare (Figure 7). The bulbification method increased bulb numbers per hectare by 33% (Figure 7A, $p < 0.001$), while the bulking method produced a 68.3% higher yield per hectare (Figure 7B, $p = 0.024$), leading to a 180.6% rise in projected revenue (Figure 7D, $p < 0.001$). The higher bulb number potential in the bulbification method also translated into a significantly larger projected plantable area, covering 33% more planting area than the bulking method (Figure 7C, p = 0.0007). This significant improvement highlights the economic benefits of producing larger, marketable bulbs under the bulking method, contributing to greater revenue generation per unit area. In contrast, while the bulbification method produced more bulbs and a larger projected plantable area, its revenue potential was constrained by the dominance of smaller bulbs, which are typically suited for use as planting material rather than for direct market sale.

The economic advantage of the bulking method was primarily due to its higher bulb weight and marketability, resulting in a net return of 63,715 MYR ha^{-1} (Table 2), a 450% increase over the bulbification method. Larger bulbs typically command higher prices in wholesale and retail markets (Hussaini and Amans, 2000), reinforcing the importance of producing market-preferred sizes. However, the bulbification method remains valuable for seed stock production, as it produces 33% more plantable bulbs per hectare, supporting a larger cultivation area in subsequent cycles. This aligns with studies suggesting that bulb seed-based onion farming can be economically sustainable, particularly for propagation-focused producers (Sri et al., 2023).

The economic analysis of the bulbification and bulking methods shows significant disparities in production costs, yield output, and overall profitability (Table 2). Despite its higher profitability, the bulking method required significantly greater input costs, with land preparation costs amounting to 13,000 MYR ha^{-1} due to the addition of shading installation and fertilizer expenses of 9,865 MYR ha^{-1}, increasing by 160% and 157%, respectively. These factors contributed to a 65% rise in total pre-harvest costs, making cost management critical. Although compost tea was used to enhance productivity, the reliance on purchased inputs raised costs. As studies suggest, integrating 50:50 organic and inorganic fertilizer regimes or producing compost tea from farm wastes could reduce input costs while maintaining yield (Singh and Ram, 2014), thereby enhancing the long-term feasibility of the bulking approach.

These results indicate that the substantial increase in profitability economically justifies the additional expenditures on inputs such as fertilizers and land preparation. The net return per MYR investment under the bulking method also rose to 1.65, reflecting a 250% improvement. Furthermore, the bulking method's economic feasibility was further supported by its higher BCR of 2.65, indicating that its financial returns significantly exceeded production expenses. This is consistent with studies showing that high-input farming systems can yield high returns, with large farms achieving cost-benefit ratios of up to 1:2.22 (Piyush et al., 2024).

The projected revenue for both cultivation methods, 36,250 MYR ha^{-1} for the bulbification method and 102,400 MYR ha^{-1} for the bulking method, demonstrates the lucrative income for farmers wanting to venture into rose onion

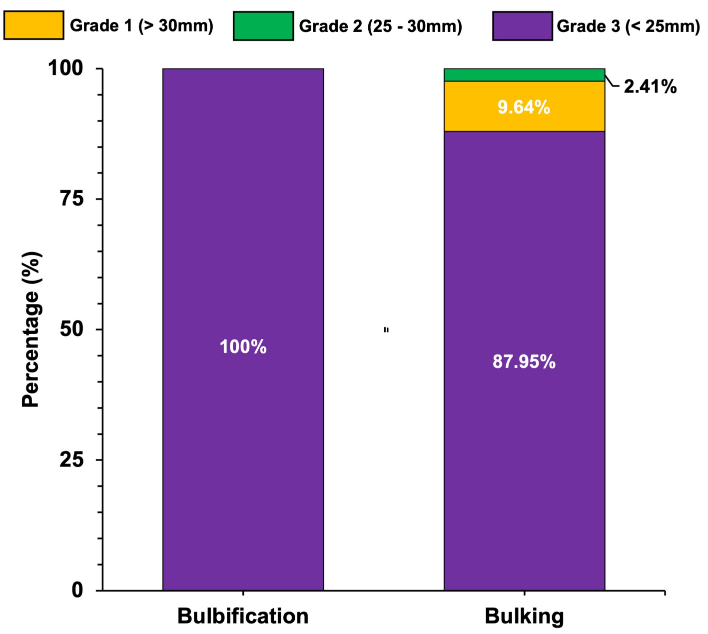

Figure 6. Bulb grading comparison between bulbification and bulking methods

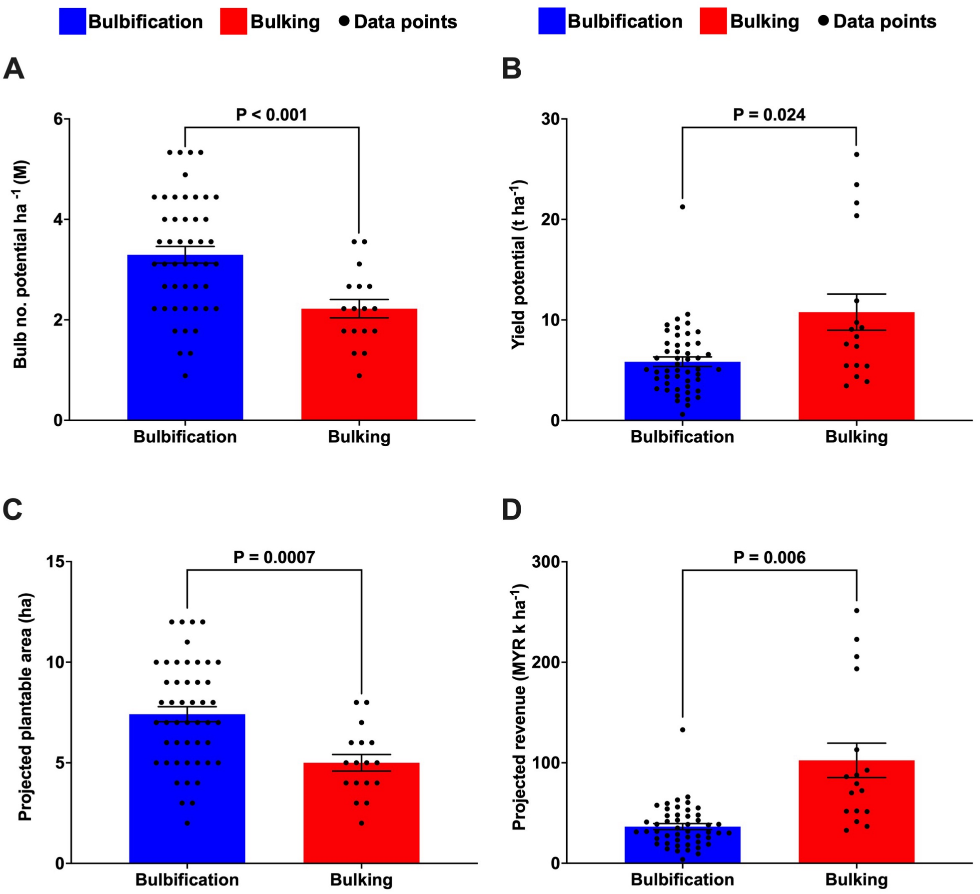

Figure 7. Economic parameters of rose onion at harvest: Comparison between bulbification and bulking methods. A) Bulb number potential, B) Yield potential, C) Projected plantable area, D) Projected revenue per hectare

Note: Statistical tests: A) Welch's t-test, p-values as shown; B, C, D) Brunner-Munzel test, p-values as shown (ns $p > 0.05$, *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$). Sample sizes: bulbification = 48, bulking = 17

farming in Malaysia. As Malaysia remains a major importer of the rose onion, there is already an established market for the produce. The bulbification method incurs significantly lower pre-harvest costs of 21,684 MYR ha^{-1} compared to the bulking method at 35,717 MYR ha^{-1}, making it more accessible for smallholder farmers with limited financial resources. Its higher bulb count supports propagation and decentralized seed system development, contributing to long-term supply chain sustainability (Sri et al., 2023). On the other hand, although the bulking method has higher pre-harvest costs, its efficient net return per investment ratio (1.65) delivers significantly higher financial returns, making it ideal for focused farmers.

The successful commercialization of onion cultivation depends on the broader supply chain infrastructure. Onion production in tropical regions frequently suffers from inadequate storage, fragmented marketing networks, and price volatility linked to import dependency (Khan et al., 2022). By expanding local production, particularly through high-yield, high-value systems using the bulking method, domestic markets can reduce dependency on imports, stabilize prices, and offer consumers fresher, more nutrient-dense produce (Berni et al., 2019; Khan et al., 2022). Locally grown onions avoid long-distance transport, preserving flavor and bioactive compound integrity. This transition supports national food security and resilience. Global disruptions due to trade restrictions, climate shocks, or geopolitical tensions can threaten onion imports (Kuma and Alemu, 2015). Domestic cultivation provides a buffer, reducing vulnerability and enhancing local self-sufficiency (Yeshiwas et al., 2023). However, enabling policies and infrastructure, such as cold storage, market information systems, and cooperative aggregation, is essential to realize these benefits. Successful value chain participation by

Table 2. Economic comparison of bulbification and bulking methods: Production costs, yield, revenue, and profitability

Economic table	Bulbification	Bulking	%Δ
Land preparation	5,000	13,000	160
Labor cost	5,852	5,852	0
Bulb	3,000	3,000	0
Fertilizer	3,832	9,865	157
Pesticide	4,000	4,000	0
Total pre-harvest costs (A)	21,684	35,717	65
Yield potential (tons ha^{-1}) (B)	5.80	10.78	86
Harvesting	1,078	1,078	0
Curing structure	1,000	1,000	0
Utility	900	900	0
Total post-harvest costs (C)	2,978	2,978	0
Total costs (A+C) (D)	24,662	38,695	57
Total return (MYR ha^{-1}) (B x price) (E)	36,250	102,410	183
Net return (MYR ha^{-1}) (E-D) (F)	11,588	63,715	450
Net return per MYR investment (F/D)	0.47	1.65	250
Undiscounted benefit-cost ratio (E/D)	1.47	2.65	80

Note: The wholesale price for rose onion in the bulbification method was set at 6,250 MYR ton^{-1}, while the market price in the bulking method was set at 9,500 MYR ton^{-1}, based on FAMA prices as of December 5, 2024

smallholders also depends on access to affordable inputs, storage facilities, reliable market information, and training. Strengthening linkages among producers, aggregators, and retailers, potentially through cooperative models or digital platforms, will be essential to fully realize the economic potential of improved cultivation methods (Nourbakhsh and Cramer, 2022).

This study provides valuable preliminary insights into rose onion cultivation under tropical Malaysian conditions. However, several methodological limitations warrant consideration. The study was conducted over a limited number of growing seasons and locations, potentially restricting the generalisability of the results across Malaysia's diverse agro-ecological zones. Although physiological and yield parameters were assessed, molecular analyses of gene expression associated with bulbification and bulking were not performed, which could provide a mechanistic understanding of the observed differences. Future research incorporating multi-location trials, comprehensive environmental monitoring, and molecular approaches would enhance the robustness and applicability of these findings.

CONCLUSIONS

This study establishes the first successful method for cultivating rose onion under tropical conditions using bulb-based propagation. Based on production goals, growers can choose between bulbification for propagation (7.54 bulbs set^{-1}, 3 g) or bulking for market production (5 bulbs set^{-1}, 7 g). Different outcomes were achieved by tailoring agronomic practices, such as shading and foliar fertilization, to local conditions. The findings support sustainable horticulture by enhancing local production, reducing import reliance, and improving food security. Future research should focus on varietal adaptability, resource efficiency, and economic viability to support wider adoption and align with climate resilience objectives.

ACKNOWLEDGEMENT

The authors would like to sincerely thank Mr. Azahar, Mr. Helmy, and Mr. Haris, the science officers from the Department of Crop Science at Universiti Putra Malaysia, for their valuable assistance and support. This project was supported by a Putra IPM Grant (code: 9739500) from Universiti Putra Malaysia, titled "The Role of Vernalisation and Gibberellic Acid on the Growth of Shallots (*Allium ascalonicum*)," awarded to N.Y. Authors would also like to thank the Royal Society for their invaluable support towards this study.

REFERENCES

Alves, C. M. L., Chang, H.-Y., Tong, C. B. S., Rohwer, C. L., Avalos, L., & Vickers, Z. M. (2022). Artificial shading can adversely affect heat-tolerant lettuce growth and taste, with concomitant changes in gene expression. *Journal of the American Society for Horticultural Science*, *147*(1), 45–52. https://doi.org/10.21273/JASHS05124-21

Atif, M. J., Ahanger, M. A., Amin, B., Ghani, M. I., Ali, M., & Cheng, Z. (2020). Mechanism of Allium crops bulb enlargement in response to photoperiod: A review. *International Journal of Molecular Sciences*, *21*(4), 1325. https://doi.org/10.3390/ijms21041325

Azeem, M. T., Tahir, M. T., Ilyas, S., Parveen, S., & Badar, H. (2024). Assessment of consumer segmentation and value preferences for onion in Pakistan. *Journal of Economic Impact*, *6*(3), 278–285. https://doi.org/10.52223/econimpact.2024.6313

Benedetto, A. D., Galmarini, C., & Tognetti, J. (2020). Differential growth response of green and variegated *Ficus benjamina* to exogenous cytokinin and shade. *Ornamental Horticulture*, *26*(2), 259–276. https://doi.org/10.1590/2447-536X.v26i2.2089

Bennett, E., Roberts, J. A., & Wagstaff, C. (2012). Manipulating resource allocation in plants. *Journal of Experimental Botany*, *63*(9), 3391–3400. https://doi.org/10.1093/jxb/err442

Berni, R., Romi, M., Cantini, C., Hausman, J. F., Guerriero, G., & Cai, G. (2019). Functional molecules in locally-adapted crops: The case study of tomatoes, onions, and sweet cherry fruits from Tuscany in Italy. *Frontiers in Plant Science*, *9*, 1983. https://doi.org/10.3389/fpls.2018.01983

Bhatt, R., Misra, L. P., Vandana, & Tiwari, H. (2002). Growth and biomass production in tropical range grasses and legumes under light stress environment. *Indian Journal of Plant Physiology*, *7*, 349–353. Retrieved from https://www.cabidigitallibrary.org/doi/full/10.5555/20033024233

Brewster, J. L., & Salter, P. J. (1980). The effect of plant spacing on the yield and bolting of two cultivars of overwintered bulb onions. *Journal of Horticultural Science*, *55*(2), 97–102. https://doi.org/10.1080/00221589.1980.11514909

Cocon, K. D., & Luis, P. (2024). The potential of RuBisCO in CO_2 capture and utilization. *Progress in Energy and Combustion Science*, *105*, 101184. https://doi.org/10.1016/j.pecs.2024.101184

Deng, H., Wang, P., Xiao, R., Zhang, H., Li, F., Zhang, Y., ..., & He, W. (2021). Effect of different irrigation patterns and covering methods on the growth characteristics of onions in the Hexi Corridor. *IOP Conference Series: Earth and Environmental Science*, *643*(1), 012139. https://doi.org/10.1088/1755-1315/643/1/012139

Dolatkhahi, A., Matloobi, M., Motallebi-Azar, A., & Vahdati, N. (2013). Shading impact on qualitative characteristics and chlorophyll content of cut rose (*Rosa hybrida* cv. Avalanche). *Journal of Ornamental Plants*, *3*(4), 215–220. Retrieved from https://citeseerx.ist.psu.edu/document?repid=rep1&type=pdf&doi=d636add81918efa7273856b5c09e707c33004952

DOSM. (2023). *Ringkasan penemuan* (Issue Table 1). Department of Statistical Malaysia. Retrieved from https://www.dosm.gov.my/portal-main/release-content/selected-agricultural-indicators-malaysia-

Dutta, M., Gupta, D., Juneja, S., Nauman, A., & Muhammad, G. (2024). Comparative growth analysis of onion in deep water culture and soil based systems: Enhancing medicinal plant cultivation in urbanized environments. *Ieee Access*, *12*, 38202–38218. https://doi.org/10.1109/access.2024.3373787

FAMA. (2024). *Panduan harga harian*. Federal Agricultural Marketing Agency. Retrieved from https://www.fama.gov.my/harga-pasaran-terkini

Farhadi, N., & Salteh, S. A. (2017). The effect of forchlorfenuron on bulblet formation, antioxidant characteristics and phytochemicals compounds of Persian shallot (*Allium hirtifolium*). *Journal of Horticultural Science*, *31*(3), 565–576. https://doi.org/10.22067/jhorts4.v31i3.56997

Gao, S., Liu, X., Liu, Y., Cao, B., Chen, Z., & Xu, K. (2021a). Response of growth, photosynthetic electron transfer, and chloroplast ultrastructure to different LED light combination in green onion (*Allium fistulosum* L.). *Physiologia Plantarum*, *172*(3), 1662–1672. https://doi.org/10.1111/ppl.13381

Gao, S., Liu, X., Liu, Y., Cao, B., Chen, Z., & Xu, K. (2021b). The spectral irradiance, growth, photosynthetic characteristics, antioxidant system, and nutritional status of green onion (*Allium fistulosum* L.) grown under different photo-selective nets. *Frontiers in Plant Science*, *12*, 650471. https://doi.org/10.3389/fpls.2021.650471

Garg, J., & Rakshit, A. (2024). Compost tea: An emerging nature-based supplement strengthening options for durable agriculture. *Journal of Soil Science and Plant Nutrition*, *24*(4), 8075–8098. https://doi.org/10.1007/s42729-024-02100-5

Gayathri, G., Harshanjali K.V., Rupavathi, K., Kumar, D. V., Kumaran, G. S., Kumari, A. C. R., & Ramana, M. V. (2016). Design, development and evaluation of a manually operated onion grader for rose onion. *International Journal of Agricultural Engineering*, *9*(2), 121–129. https://doi.org/10.15740/has/ijae/9.2/121-129

Gunadi, N., & Sulastrini, I. (2013). Penggunaan netting house dan mulsa plastik untuk meningkatkan pertumbuhan dan hasil tanaman cabai merah. *Jurnal Hortikultura*, *23*(1), 36–46. Retrieved from https://repository.pertanian.go.id/items/5c4b2569-406b-4eb7-84ee-6a117bd6ecc5

Hadid, A., & Febriana. (2022). Effect of shading level the growth and yield of shallot plants seed. *Agroland: The Agricultural Sciences Journal*, *9*(1), 44–51. https://doi.org/10.22487/agroland.v9i1.1219

Hamidon, A., Shah, R. M., Razali, R. M., Lob, S., & Aziz, F. A. A. (2025). Plant growth regulators application to enhance flowering and fruit production in gac (*Momordica cochinchinensis*). *Pertanika Journal of Tropical Agricultural Science*, *48*(2), 339–357. https://doi.org/10.47836/pjtas.48.2.01

Hatungimana, D., Abduel, M. T., Chakeredza, S., & Kurehwatira, M. (2024). Effect of vermicompost and compost tea on the growth and yield of onions. *International Journal of Plant Pathology and Microbiology*, *4*(1), 41–47. https://doi.org/10.22271/27893065.2024.v4.i1a.76

Hussaini, M. A., & Amans, E. B. (2000). Yield, bulb size distribution, and storability of onion (*Allium cepa* L.) under different levels of N fertilization and irrigation regime. *Tropical Agriculture*, *77*(3), 145–149. Retrieved from https://journals.sta.uwi.edu/ojs/index.php/ta/article/view/1460

Immanuelraj, T. K., Dastagiri, M. B., & Sajesh, V. K. (2014). Growth and instability of onion production in Maharashtra, India. *Journal of Global Economics*, *02*(01), 107. https://doi.org/10.4172/2375-4389.1000107

Ishfaq, M., Kiran, A., ur Rehman, H., Farooq, M., Ijaz, N. H., Nadeem, F., ..., & Wakeel, A. (2022). Foliar nutrition: Potential and challenges under multifaceted agriculture. *Environmental and Experimental Botany*, *200*, 104909. https://doi.org/10.1016/j.envexpbot.2022.104909

Islam, M. R., Islam, M. S., Akter, N., Mohi-Ud-Din, M., & Mostofa, M. G. (2021). Foliar application of cytokinin modulates gas exchange features, water relation and biochemical responses to improve growth performance of maize under drought stress. *Phyton-International Journal of Experimental Botany*, *91*(3), 633–649. https://doi.org/10.32604/phyton.2022.018074

Khan, M. N., Malik, A. M., Hameed, G., & Asad, S. (2022). Prospects and constraints of onion production and marketing: A case study of District Tando Allahyar, Sindh-Pakistan. *Proceedings of the Pakistan Academy of Sciences B Life and Environmental Sciences*, *59*(3), 97–109. https://doi.org/10.53560/ppasb(59-3)728

Khokhar, K. M. (2017). Environmental and genotypic effects on bulb development in onion–a review. *Journal of Horticultural Science and Biotechnology*, *92*(5), 448–454. https://doi.org/10.1080/14620316.2017.1314199

Kuma, A. N. Y., & Alemu, A. A. T. (2015). Onion production for income generation in small scale irrigation users agropastoral households of Ethiopia. *Journal of Horticulture*, *2*(3), 1000145. https://doi.org/10.4172/2376-0354.1000145

Kumari, A., Sharma, B., Singh, B. N., Hidangmayum, A., Jatav, H. S., Chandra, K., ..., & Mohapatra, K. K. (2022). Physiological mechanisms and adaptation strategies of plants under nutrient deficiency and toxicity conditions. *Plant perspectives to global climate changes* (pp. 173–194). Academic Press. https://doi.org/10.1016/B978-0-323-85665-2.00012-1

Kurosaki, H., & Yumoto, S. (2003). Effects of low temperature and shading during flowering on the yield components in soybeans. *Plant Production Science*, *6*(1), 17–23. https://doi.org/10.1626/pps.6.17

Lambers, H., & Oliveira, R. S. (2019). Growth and allocation. *Plant Physiological Ecology* (pp. 385–449). Springer International Publishing. https://doi.org/10.1007/978-3-030-29639-1_10

Lazova, G., & Yonova, P. (2010). Photosynthetic parameters were modified in wheat (*Triticum aestivum* L.) flag leaves by two phenylurea cytokinins. *International Journal of Plant Sciences*, *171*(8), 809–817. https://doi.org/10.1086/655857

Lee, R., Baldwin, S., Kenel, F., McCallum, J., & Macknight, R. (2013). *FLOWERING LOCUS T* genes control onion bulb formation and flowering. *Nature Communications*, *4*(1), 2884. https://doi.org/10.1038/ncomms3884

Like Best (M) Sdn Bhd. (2024). *Red onions (Rose)*. Retrieved from https://likebest.com.my/grocery/onions/red-onions-rose/

Lopes, M. S., & Reynolds, M. P. (2012). Stay-green in spring wheat can be determined by spectral reflectance measurements (normalized difference vegetation index) independently from phenology. *Journal of Experimental Botany*, *63*(10), 3789–3798. https://doi.org/10.1093/jxb/ers071

Major, N., Išić, N., Kovačević, T. K., Anđelini, M., Ban, D., Prelac, M., ..., & Goreta Ban, S. (2023). Size does matter: The influence of bulb size on the phytochemical and nutritional profile of the sweet onion landrace "Premanturska Kapula" (*Allium cepa* L.). *Antioxidants*, *12*(8), 1596. https://doi.org/10.3390/antiox12081596

Manna, D. (2016). Quality seed production of onion (*Allium cepa* L.) cv. Sukhsagar as influenced by bulb size and date of planting. *Agricultural Research & Technology: Open Access Journal*, *2*(3), 555589. https://doi.org/10.19080/ARTOAJ.2016.02.555589

Mauro, R. P., Occhipinti, A., Longo, A. M. G., & Mauromicale, G. (2011). Effects of shading on chlorophyll content, chlorophyll fluorescence and photosynthesis of subterranean clover. *Journal of Agronomy and Crop Science*, *197*(1), 57–66. https://doi.org/10.1111/j.1439-037x.2010.00436.x

Meier, U., Bleiholder, H., Buhr, L., Feller, C., Hack, H., Heß, M., ..., & Zwerger, P. (2009). The BBCH system to coding the phenological growth stages of plants-history and publications. *Journal für Kulturpflanzen*, *61*(2), 41–52. Retrieved from https://ojs.openagrar.de/volltexte/Kulturpflanzenjournal/2009/Heft02/Web-Daten/01_meier_et_al/meier_et_al.html

Mensah, E. O., Asare, R., Vaast, P., Amoatey, C. A., Markussen, B., Owusu, K., ..., & Ræbild, A. (2022). Limited effects of shade on physiological performances of cocoa (*Theobroma cacao* L.) under elevated temperature. *Environmental and Experimental Botany*, *201*, 104983. https://doi.org/10.1016/j.envexpbot.2022.104983

Merkebu, A. (2021). Water, nutrients, radiation and CO_2 use efficiency of bulb crops: A review. *Advances in Life Science and Technology*, *90*, 5–11. https://doi.org/10.7176/alst/90-02

Mettananda, S. A., & Fordham, S. (1999). The effects of plant size and leaf number on the bulbing of tropical short-day onion cultivars (*Allium cepa* L.) under controlled environments in the United Kingdom and tropical field conditions in Sri Lanka. *The Journal of Horticultural Science and Biotechnology*, *74*(5), 622–631. https://doi.org/10.1080/14620316.1999.11511164

Mohamed Hafeifi, B., Wan Rozita, W. E., Zulaikha, M., Suhanna, A., Nur Syafini, G., & Suhana, S. (2024). *Manual of red onion production technology for lowland areas*. Malaysian Agricultural Research and Development Institute, Ministry of Agriculture and Food Security.

Montanaro, G., Dichio, B., & Xiloyannis, C. (2009). Shade mitigates photoinhibition and enhances water use efficiency in kiwifruit under drought. *Photosynthetica*, *47*(3), 363–371. https://doi.org/10.1007/s11099-009-0057-9

Mubarak, I. (2021). Response of onion crop to bulb set size and planting date under mulching in dry Mediterranean environment. *Acta Agriculturae Slovenica*, *117*(3), 1–9. https://doi.org/10.14720/aas.2021.117.3.818

Nourbakhsh, S. S., & Cramer, C. S. (2022). Onion germplasm possesses lower early season thrips numbers. *Horticulturae*, *8*(2), 123. https://doi.org/10.3390/horticulturae8020123

Pagano, A., Macovei, A., Xia, X., Padula, G., Hołubowicz, R., & Balestrazzi, A. (2023). Seed priming applied to onion-like crops: State of the art and open questions. *Agronomy*, *13*(2), 288. https://doi.org/10.3390/agronomy 13020288

Pane, C., Palese, A. M., Celano, G., & Zaccardelli, M. (2014). Effects of compost tea treatments on productivity of lettuce and Kohlr abi systems under organic cropping management. *Italian Journal of Agronomy*, *9*(3), 596. https://doi.org/10.4081/ija.2014.596

Paul, M. J., & Foyer, C. H. (2001). Sink regulation of photosynthesis. *Journal of Experimental Botany*, *52*(360), 1383–1400. https://doi.org/ 10.1093/jexbot/52.360.1383

Peiwen, X., Huisheng, S., Ruijie, S., & Yuanjun, Y. (1994). Allium production and research in China. *Acta Horticulturae*, *358*, 127–134. https://doi.org/10.17660/ActaHortic.1994.358 .19

Piyush, P., Mukesh, M., & Rishabh, P. S. (2024). An economic analysis of onion production in Nalanda District of Bihar, India. *International Journal of Agriculture Extension and Social Development*, *7*(5), 331–334. https://doi.org/ 10.33545/26180723.2024.v7.i5e.626

Rademacher, W. (2015). Plant growth regulators: Backgrounds and uses in plant production. *Journal of Plant Growth Regulation*, *34*(4), 845–872. https://doi.org/10.1007/s00344-015-9541-6

Rozita, W. W., Hazlina, N. M., & Zamri, M. K. (2024). Adaptation and selection study of shallot (*Allium cepa* L. var. Aggregatum) varieties for lowland cultivation using mineral soil. *International Journal of Agriculture, Forestry and Plantation*, *15*, 69–74. Retrieved from https://ijafp.org/wp-content/uploads/ 2024/12/IJAFP15_042.pdf

Scheuerell, S. J., & Mahaffee, W. F. (2006). Variability associated with suppression of gray mold (*Botrytis cinerea*) on geranium by foliar applications of nonaerated and aerated compost teas. *Plant Disease*, *90*(9), 1201–1208. https://doi.org/10.1094/PD-90-1201

Sharma, D., & Chauhan, A. (2022). Kharif onion production in India-Present status and future potential: A review. *Agricultural Reviews*, *45*(4), 653–660. https://doi.org/10.18805/ag.r-2455

Shen, Y. B., Zhang, J. F., & Li, T. (2021). Effect of shading based on functional leaf saturated light intensity on the yield and water consumption of winter wheat (*Triticum aestivum* L.). *Applied Ecology and Environmental Research*, *19*(4), 3303–3321. https://doi.org/10.15666/aeer/1904_33033321

Simkin, A. J., Kapoor, L., Doss, C. G. P., Hofmann, T. A., Lawson, T., & Ramamoorthy, S. (2022). The role of photosynthesis related pigments in light harvesting, photoprotection and enhancement of photosynthetic yield in planta. *Photosynthesis Research*, *152*(1), 23–42. https://doi.org/10.1007/s11120-021-00892-6

Singh, A., & Ram, R. B. (2014). Evaluation of the performance of onion cv. NHRDF red 2 in response to inorganic, organic and bio–fertilizers. *Indian Journal of Applied Research*, *4*(11), 263–265. Retrieved from https://www.worldwidejournals.com/ indian-journal-of-applied-research-(IJAR)/ fileview/November_2014_1492774158__75. pdf

Singh, H. M., & Singh, S. K. (2018). Evaluation of technology dissemination through demonstration on the yield of Kharif onion bulb production. *The Asian Journal of Horticulture*, *13*(1), 5–7. https://doi.org/ 10.15740/has/tajh/13.1/5-7

Sri, A., Hairin, F., & Muhammad, F. (2023). Comparative study of shallot farming income using bulb seeds in Tabalong Regency of Indonesia. *Russian Journal of Agricultural and Socio-Economic Sciences*, *135*(3), 128–135. https://doi.org/10.18551/rjoas.2023-03.14

Taylor, A., Massiah, A., & Thomas, B. (2010). Conservation of *Arabidopsis thaliana* photoperiodic flowering time genes in onion (*Allium cepa* L.). *Plant and Cell Physiology*, *51*(10), 1638–1647. https://doi.org/10.1093/ pcp/pcq120

Wang, Y., Anderegg, W. R. L., Venturas, M., Trugman, A. T., Yu, K., & Frankenberg, C. (2021). Optimization theory explains nighttime stomatal responses. *New Phytologist*, *230*(4), 1550–1561. https://doi.org/10.1111/nph.17267

Wang, Y., Shen, W., Chan, Z., & Wu, Y. (2015). Endogenous cytokinin overproduction modulates ROS homeostasis and decreases salt stress resistance in *Arabidopsis thaliana*. *Frontiers in Plant Science*, *6*, 166381. https://doi.org/10.3389/fpls.2015.01004

Wong, K. K. S., Lee, C., & Wong, W. L. (2019). Impact of climate change and economic factors on Malaysian food price. *Journal of the International Society for Southeast Asian Agricultural Sciences*, *25*(1), 32–42. Retrieved from http://issaasphil.org/wp-content/uploads/2019/06/4.-WONG-et-al-2019-Malaysia-Food-Price-FINAL.pdf

Xie, A., Lv, M., Zhang, D., Shi, Y., Yang, L., Yang, X., ..., & Sun, X. (2023). Effects of slight shading in summer on the leaf senescence and endogenous hormone and polyamine contents in herbaceous peony. *Scientific Reports*, *13*(1), 18714. https://doi.org/10.1038/s41598-023-46192-y

Yeshiwas, Y., Alemayehu, M., & Adgo, E. (2023). The rise and fall of onion production; Its multiple constraints on pre-harvest and post-harvest management issues along the supply chain in Northwest Ethiopia. *Heliyon*, *9*(5), e15905. https://doi.org/10.1016/j.heliyon.2023.e15905

Zhang, Y., Sun, F., Fettke, J., Schöttler, M. A., Ramsden, L., Fernie, A. R., & Lim, B. L. (2014). Heterologous expression of *AtPAP2* in transgenic potato influences carbon metabolism and tuber development. *FEBS Letters*, *588*(20), 3726–3731. https://doi.org/10.1016/j.febslet.2014.08.019