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Resilient onions: Adapting onion cultivation to climate change

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ABSTRACT

Background: Global climate change poses serious challenges to shallot cultivation. Rising temperatures, altered rainfall patterns, and reduced soil moisture directly affect plant growth and yield, even leading to crop failure due to flooding or drought. To address these issues, adaptive cultivation strategies are needed, including the use of true shallot seed (TSS), efficient irrigation management, and proper fertilization. This study aims to examine the physiological responses of shallot plants to drought stress caused by climate change, assess the effectiveness of TSS technology as an adaptive planting material, and evaluate irrigation and nutrient management practices to support sustainable cultivation. **Methods:** This study uses a literature review method to synthesize current knowledge on enhancing the resilience of shallot plants to climate variability. Data collection was carried out through a systematic search in scientific databases such as Scopus, Web of Science, PubMed, Google Scholar, and CAB Abstracts, using relevant structured keywords. Data from the selected studies were thematically analyzed to address four main focal points: the physiological and biochemical responses of shallots to drought stress, the development and challenges of adopting True Seed Shallot (TSS) technology, the impact of climate change on nutrient management, and climate-adaptive irrigation management strategies. **Findings:** Based on the review conducted, climate change, particularly drought stress, has a significant impact on the growth and yield of shallots. Physiological responses such as proline accumulation, soluble sugars, and stomatal closure are key mechanisms in coping with water scarcity, although they also limit plant growth and productivity. The use of True Seed Shallot (TSS) technology has been proven to offer advantages in disease resistance, cost efficiency, and adaptation to changing climatic conditions, although it requires specific cultivation techniques and farmer training. Sustainable agricultural practices, such as drip irrigation, organic fertilization, and the selection of climate-resilient varieties, are essential to enhance crop resilience. **Conclusion:** integrating drought-resilient practices, such as True Seed Shallot (TSS) technology, efficient irrigation, and nutrient management, is essential to enhance shallot cultivation sustainability under climate change. **Novelty/Originality of this article:** The novelty of this study lies in its integrated analysis of shallot physiological responses to drought stress, true seed shallot (TSS) technology, and climate-smart irrigation and fertilization practices to enhance shallot resilience under climate change.

KEYWORDS: abiotic stress; drought stress; irrigation management; nutrient management; true seed shallot.

1. Introduction

Shallots are significant horticultural commodities with numerous advantages. Major et al., (2022) demonstrate that shallot bulbs are abundant in functional phytochemicals, including organosulfur compounds, phenolics, polysaccharides, and saponins.

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Consequently, shallots hold potential as drug candidates for the treatment of various respiratory infections, particularly viral infections and pulmonary conditions such as COVID-19 (Setiawan et al., 2021). They modulate oxidative stress and mitigate the risk of bone disorders in healthy middle-aged and postmenopausal individuals, and are regarded as excellent prebiotics with beneficial effects on human health (Law et al., 2015). Furthermore, utilizing onion as a functional ingredient could potentially reduce the impact of hypercholesterolemia on liver inflammation (GonzÃ et al., 2017; Law et al., 2015). Research on shallots is progressing annually, focusing on agronomy and bulb utilization.

The cultivation of shallots may involve the utilization of either bulb shallots or true seed shallots (TSS). Climate change represents a pressing concern impacting environmental crop cultivation. It presents substantial challenges to shallot production, as extreme weather events, such as heavy rainfall, result in flooding, crop failure, and economic losses for farmers (Hasanah et al., 2023). Suitable environmental conditions and agricultural management are required to overcome seed and bulb dormancy, induce bulb sprouting, seed germination, flower stalk development (bolting), flowering, and finally to produce seeds and bulbs with high yield and quality (Askari-Khorasgani & Pessarakli, 2019; Fahrianty et al., 2020). Increases in temperature, altered precipitation patterns, and changes in soil moisture, particularly affecting shallots, pose threats to horticultural production (Pradana et al., 2022). Researchers have examined numerous approaches to alleviate these effects, with particular attention to the implementation of expanded true seed shallot, underscoring the significance of both plant propagation and crop production.

Climate change exerts a substantial impact on agriculture, particularly in regions susceptible to drought. Empirical research indicates that irregular rainfall patterns and rising temperatures contribute to the increased frequency and severity of droughts, which in turn negatively affect crop yields and farmers' incomes (Kumar et al., 2019; Patra et al., 2023). Furthermore, it affects the depletion of soil moisture, which is essential for the growth of upland crops (Hong et al., 2015). Drought stress in garlic chives (Allium tuberosum) results in a decline in both the quantity and functionality of chlorophyll, impacting both chlorophyll a and b (Huh, 2022). Furthermore, drought stress impacts the antioxidant activity and sugar metabolism in garlic plants, with distinct responses evident among different ecotypes (Habuš Jerčić et al., 2023; Kovačević et al., 2023). In response to the challenges posed by drought stress, it is essential to adopt good agricultural practices.

The implementation of effective agricultural practices is crucial for reducing the negative impacts of farming and production on climate change, thereby advancing sustainable agriculture. Agriculture contributes to climate change through the emission of greenhouse gases from fossil fuel consumption, tillage activities, and livestock manure (Yohanes, 2015). Shifts in climate patterns impact the availability of nutrients, as well as the processes of mineralization and leaching within soil systems (Elbasiouny et al., 2022; Saini et al., 2025). To tackle these issues, the adoption of climate-smart agriculture and forestry practices is vital. These practices involve the development of crop varieties that are resilient to heat, drought, and ozone, the selection of cultivars that perform well under increased CO2 concentrations, and the improvement of root morphology and aquaporin regulation to enhance resource-use efficiency (Way & Long, 2015).

Good agricultural practices, including the management of irrigation and plant nutrition, are essential for ensuring the sustainable adaptation of crops to the challenges posed by climate change. Precision irrigation methods, such as micro-sprinklers and drip systems, can enhance water efficiency and minimize waste (Oiganji et al., 2025). In tank irrigation systems, strategies like contour bunds, terracing, and afforestation can improve water retention and soil quality (Rithika et al., 2025). Researchers have explored various strategies to enhance plant resilience and nutrition in response to climate change. Soil carbon sequestration plays a crucial role in mitigating climate change effects while concurrently improving soil fertility and nutrient availability (Elbasiouny et al., 2022; Saini et al., 2025). Additionally, the development of nutrient-efficient crops through both traditional and innovative breeding techniques can result in short-term improvements in agricultural productivity and sustainability (Norton, 2014).

The comprehensive integration of shallots physiological responses to drought stress, true seed shallot technology for plant propagation and cultivation, irrigation and fertilization practices into a singular framework is notably lacking in the realm of sustainable agriculture. This article endeavors to deliver a thorough examination of the physiological adaptations exhibited by shallot plants when exposed to drought stress, a condition exacerbated by climate change. Additionally, it scrutinizes the efficacy of tue seed shallot technology as a practical and solution-oriented planting material amidst climate change challenges, evaluates irrigation management techniques, and investigates the relationship between shallot nutrition and the adversities posed by climate change. Furthermore, it proposes strategies aimed at enhancing the resilience of shallots, thereby contributing to the advancement of sustainable agricultural practices.

2. Methods

This study employed a literature review to synthesize current knowledge on enhancing shallot (Allium cepa L.) resilience to climate variability. The review specifically addressed four interconnected research questions: (1) physiological, biochemical, and morphological response mechanisms of shallots to drought stress; (2) the development, benefits, and adoption challenges of True Seed Shallot (TSS) technology as a climate adaptation strategy; (3) the impacts of climate change (drought, salinity, extreme weather) on shallot nutrient management (N, P, K, organic matter) and effective supplementation strategies; and (4) optimized irrigation water management techniques for climate-variable conditions. A comprehensive search was conducted across Scopus, Web of Science, PubMed, Google Scholar, and CAB Abstracts using structured keyword combinations related to shallots, climate change, drought stress, TSS, nutrient deficiency/management, and irrigation. Identified records underwent rigorous screening based on relevance, methodological quality, and publication date. Data from included studies were extracted and synthesized thematically to identify key adaptive mechanisms, evaluate mitigation strategies, and highlight research gaps within each focus area.

The review process involved identifying and analyzing relevant peer-reviewed articles, research reports, and scholarly publications that addressed the key research objectives of this study. Particular attention was given to research examining the development and application of TSS measurement technologies in climate-stressed onion production, studies investigating the relationship between onion nutritional quality and climate change challenges, research on physiological and biochemical mechanisms of drought stress response in onions, and publications documenting irrigation water management techniques suitable for climate change conditions.

The literature analysis was organized thematically to address the specific research aims, with findings synthesized across multiple studies to identify patterns, trends, and knowledge gaps in the field. The review examined technological advances in TSS measurement and monitoring, nutritional composition changes under various climate stress conditions, drought response mechanisms at physiological and molecular levels, and irrigation management strategies that enhance onion resilience to climate variability. This approach allowed for a comprehensive understanding of current knowledge while identifying areas requiring further research to support climate-adaptive onion cultivation practices.

3. Results and Discussion

3.1 Responses Mechanism of Shallot (Allium cepa L.) under drought stress

The impact of drought stress on shallots (*Allium cepa* L.), is a subject of considerable importance due to its widespread agricultural and economic significance. The resilience of shallot against drought stress has been the subject of numerous studies, focusing on its physiological, biochemical, and morphological responses. These studies have highlighted the plant's adaptive mechanisms for maintaining growth and yield under water-scarce conditions. The analysis reveals both general trends and cultivar-specific mechanisms that contribute to drought tolerance in shallots.

The first observable consequence of drought stress is the reduction in plant growth. Drought results in significant reductions in leaf area, plant height, and bulb size. Several studies indicate that water deficit, especially during critical growth stages such as bulb formation, negatively affects both vegetative and reproductive growth of onions (Ghodke et al., 2018; Pelter et al., 2004). A decrease in leaf area is commonly associated with water stress, as plants prioritize water conservation, often by reducing the surface area available for transpiration. The reduction in leaf area directly contributes to the decreased photosynthetic capacity, which in turn affects overall biomass accumulation and crop yield (Rao et al., 2016).

Moreover, water stress induces significant changes in the onion's root system. Since onions are a shallow-rooted crop, they have limited access to water below the topsoil layers. Water stress exacerbates this issue by further limiting the root's ability to access available water, leading to a decrease in the plant's overall water uptake. As a result, the plants exhibit stunted root growth and reduced root biomass, particularly in genotypes that are sensitive to drought stress. Bhat et al. (2018) reported that drought stress caused a marked reduction in the root dry weight and a decrease in the number of roots in several shallot cultivars.

On a biochemical level, drought stress triggers a suite of physiological mechanisms aimed at mitigating the detrimental effects of water loss. Drought-induced stress prompts the generation of harmful reactive oxygen species (ROS) that result in direct impairment of cellular membranes, subsequently disrupting various cellular metabolic pathways (Das & Roychoudhury, 2014). One of the primary mechanisms involved in drought tolerance is osmotic adjustment, which helps maintain cellular turgor pressure under conditions of water deficit. Proline accumulation plays a critical role in enhancing drought tolerance in shallots. Proline is known to function as an osmoprotectant, stabilizing proteins and cellular structures under stress conditions. Studies have shown that proline levels increase significantly as a response to water stress in shallot plants (Ghodke et al., 2018). Proline, as an osmoprotectant, helps protect cellular structures by stabilizing proteins and cell membranes, thereby maintaining cellular function during dehydration. Furthermore, it acts as a reactive oxygen species (ROS) scavenger, reducing oxidative damage in stressed plants. High proline accumulation indicates that the plant is tolerant and can adapt well to water deficit stress.

In addition to proline, other metabolites such as soluble sugars and total soluble solids (TSS) also accumulate under drought stress. Drought causes an increase in total sugars, total soluble solids, and hydrogen peroxide (H_2O_2) levels in cultivated onion genotypes (Gedam et al., 2021). These compounds contribute to osmotic adjustment and protect plant tissues from dehydration. In contrast, water stress declines the synthesis of secondary metabolites such as flavonoids, phenols, tannins, and pyruvic acid (Ghodke et al., 2018). Pelter et al., (2004) found that drought-stressed onions had higher concentrations of soluble sugars and reduced leaf water potential.

The reduction in stomatal conductance under drought conditions is another mechanism by which shallots cope with water deficit. Purbajanti & Bintang (2023) reported that the stomatal closure, regulated by abscisic acid (ABA), helps conserve water, but it also limits CO_2 uptake, thus reducing photosynthesis. Despite these limitations, the plants can maintain adequate metabolic functions by adjusting their internal osmotic pressure and reallocating resources to vital processes like root development and osmotic regulation (Rao et al., 2016). This adjustment is essential in ensuring survival under prolonged drought conditions. The effect of drought on chlorophyll content is another crucial aspect of the drought response. Water stress declines the chlorophyll content, thereby impairing the photosynthetic capacity of the plant. The tolerant cultivar maintains the higher chlorophyll, so the photosynthesis rate is one of drought tolerant mechanism (Ghodke et al., 2018). However, some cultivars exhibit a degree of functional stay-green, wherein chlorophyll content is retained despite water stress. This phenomenon has been linked to the ability of certain shallot varieties to maintain photosynthetic activity and delay senescence under drought conditions (Tahir et al., 2024).

Arbuscular mycorrhizal fungi (AMF) have been shown to enhance drought tolerance in shallots. Inoculation with AMF species such as *Funneliformis mosseae* and *Claroideoglomus etunicatum* can significantly improve water uptake and nutrient absorption, particularly under drought conditions (El Bergui et al., 2023; Muhsen et al., 2019). AMF colonization enhances root growth, increases the surface area for water and nutrient uptake, and improves the plant's ability to withstand water deficits. In addition, AMF inoculation helps increase the relative water content (RWC) and proline content, thus aiding in osmotic adjustment and reducing the overall impact of drought on plant health (Muhsen et al., 2019).

Despite these adaptive mechanisms, drought stress still results in significant yield losses. Drought during bulb development and enlargement stages caused substantial reductions in bulb fresh and dry mass. This aligns with earlier findings that water stress significantly reduces the overall productivity of onions, particularly due to the plant's shallow root system, which limits its ability to access water beyond the topsoil layers (Bhatt et al., 2019). Similar results were obtained by Purbajanti & Bintang (2023), where drought stress at 20% field capacity caused a notable decrease in onion bulb yield, supporting the notion that water availability directly impacts both vegetative growth and bulb formation. According to the research of Tahir et al., (2024), the prolonged drought stress can reduce onion bulb weight by up to 65%, as the plant's resources are redirected from reproductive processes to survival mechanisms. This is further compounded by the fact that drought conditions can alter the chemical composition of the bulbs, affecting their marketable quality. Specifically, drought stress can lead to a decrease in bulb size, an increase in pungency, and a reduction in certain secondary metabolites such as flavonoids and phenolic compounds (Ghodke et al., 2018). These changes not only reduce the commercial value of the crop but also pose challenges to the food industry, particularly in regions where onion quality is critical.

Several strategies have been proposed to mitigate the effects of drought on shallot production. These include optimizing irrigation practices, such as using deficit irrigation, which has been shown to maintain yield while conserving water (Tahir et al., 2024). Additionally, the use of hydrogel-based soil additives can improve water retention in the soil, thereby reducing the frequency and intensity of irrigation needed. El Bergui et al., (2023) demonstrated that the application of hydrogel improved onion yield even under reduced irrigation regimes, making it a promising solution for drought-prone areas. Moreover, the application of biofertilizers has been shown to enhance drought tolerance in shallots. Lestari & Siswanti (2024) found that biofertilizer treatment improved the anatomical structure of roots, with thicker root cortex and metaxylem diameter, which enhanced water uptake and contributed to better drought resistance. These findings align with studies suggesting that biofertilizers, particularly those containing beneficial microorganisms, can enhance nutrient uptake, promote root growth, and reduce the effects of water stress (Rahmawati & Siahaan, 2024).

The use of drought-tolerant cultivars is another promising approach. Genotypic variation in drought tolerance has been observed among different shallot varieties, with some cultivars exhibiting better resistance to water stress than others (Ghodke et al., 2018). Identifying and breeding such cultivars could significantly enhance the resilience of onion crops to climate change and water scarcity. The response of shallot plants to drought stress involves a complex interplay of physiological, biochemical, and morphological mechanisms aimed at conserving water and maintaining cellular integrity. In terms of practical implications, these findings suggest that a combination of physiological mechanisms, such as osmotic adjustment via proline, improved root structure through biofertilizer application, and regulation of water loss via stomatal closure, are key to enhancing drought resilience in shallots. While drought stress can severely impact onion yield and quality, innovative management strategies, such as deficit irrigation, hydrogel application, and the development of drought-tolerant cultivars, offer promising solutions for mitigating the effects of water scarcity. Future research should focus on further elucidating the genetic basis of drought tolerance in onions and optimizing the use of environmental stress management techniques to ensure sustainable onion production under changing climatic conditions.

3.2. True Seed Shallot as a material plant to promote sustainable agriculture pratice

True seed shallot (TSS) varieties have shown significant potential for enhancing shallot production and promoting sustainable agricultural practices. In Ethiopia, field trials have indicated that TSS varieties outperform local varieties in terms of bulb yield and are preferred by farmers (Gashu & Beyene, 2024). Despite the advantages of TSS, such as reduced seed costs and potentially higher yields, its adoption faces challenges, including longer growing periods and requirements for nursery cultivation (Sayaka et al., 2020). Sustainable practices in shallot cultivation, including organic farming, efficient water management, and integrated pest management, are essential for improving productivity and environmental sustainability (Dewi et al., 2024). Morphological studies of shallot varieties derived from TSS in highland regions have demonstrated that cultivation techniques significantly affect plant growth, with recommendations from seed suppliers leading to improved outcomes (Hasanah et al., 2022). To promote the adoption of TSS and improve sustainable shallot production, it is essential to ensure the availability of seeds, provide education to farmers, and encourage collaboration among stakeholders.

The transition from traditional bulb propagation to the use TSS offers several advantages. TSS technology is emerging as a promising innovation for resilient and sustainable agriculture, particularly in the context of climate change. It provides alternatives to conventional bulb propagation, with the aim of enhancing yield, reducing disease incidence, and lowering production costs, which are crucial for both food security and the livelihoods of farmers (Table 1). Drought during critical growth phases, especially during bulb development, has the most severe impact on plant health and recovery, thereby increasing the risk of pest outbreaks (Pratiwi et al., 2024a, 2024b).

Table 1. Drought, pest risk, and TSS benefits in shallot cultivation

Factor	Bulb Shallot (Traditional)	True Shallot Seed (TSS)	Citations
Drought Vulnerability	High	Lower (with TSS + PGPR)	(Askari-Khorasgani & Pessarakli, 2019; Pratiwi et al., 2024a, 2024b)
Pest/Disease Risk	Increased under drought	Lower with TSS rotation	(Prahardini et al., 2021; Sayaka et al., 2020)
Yield Stability	Variable	More stable	(Manwan et al., 2020; Prahardini et al., 2021; Sayaka et al., 2020)2810
Seed Cost/Storage	High/Short	Low/Long	(Manwan et al., 2020; Sayaka et al., 2020)102

True seed shallot cultivation presents a viable alternative to the conventional practice of bulb planting. Its effectively addressing challenges related to seed scarcity and quality (Pangestuti et al., 2023). Prior research has assessed the performance of TSS across diverse cultivars and environmental conditions. In arid regions, TSS cultivation has resulted in yields ranging from 5.28 to 8.41 tons per hectare, achieving only 20-40% of the potential production capacity, primarily due to farmers' lack of familiarity with this technique (Devy et al., 2020). According to the findings of (Sulistyaningsih et al., 2020), there is a notable diversity in the survival rates and yield potentials among various cultivars, with some cultivars being particularly well-suited for growth in lowland environments. In Ethiopia, the Minjar shallot variety has exhibited superior performance in terms of both marketable and total bulb yield when compared to other varieties (Tsagaye et al., 2021). As an illustration, the true seed shallots of the *A. ascolonicum* L. Tuk-tuk variety successfully germinated within a 21-day period, resulting in the highest fresh bulb weight of 30.8 t ha^{-1}. This yield surpassed that of the bulb-propagated Bima Brebes, Biru Lancor, and Lokal varieties by 25.73%, 18.30%, and 19.77%, respectively, in Buahan village, Kintamani district, Bangli Regency, Indonesia (Buda et al., 2018).

TSS as plant material on shallot presents several advantages over the traditional bulb propagation method. Shallot clones derived from TSS have the potential to produce a high number of tillers. The development of tillers may be associated with bulb aggregation, which could contribute to an increase in bulb yield (Sulistyaningsih et al., 2020). TSS enhanced transportability, prolonged storage life, and a reduction in disease transmission (Askari-Khorasgani & Pessarakli, 2019). Varieties such as Improved Huruta which are capable of producing TSS, have demonstrated superior outcomes in both seed and bulb yields when compared to conventional onion varieties (Mohammed et al., 2018). Studies have highlighted the potential of TSS to significantly increase shallot productivity, with yields ranging from 14.8 to 28.2 t/ha, which notably exceed the national average of 10.48 t/ha for bulb-propagated shallots in Indonesia (Sutardi et al., 2022). The adoption of TSS technology could substantially improve farmers' income and quality of life by addressing the issue of limited planting materials and enhancing overall crop yields.

The effective demonstration and dissemination of TSS production and mini bulb cultivation to farmers in Indonesia suggest a significant potential for widespread adoption. TSS provides economic benefits by markedly decreasing seed costs when compared to bulb propagation methods (Makhziah et al., 2019). For shallots cultivated from true seed shallots, the most effective agricultural practices involve maintaining a high planting density of 100 plants per square meter and employing balanced fertilization with NPK and compost, which can achieve yields reaching up to 9.83 t ha^{-1} (Sopha, 2020). The morphological attributes and growth performance of TSS-derived shallots are contingent upon the variety and cultivation techniques used, with the Lokananta variety exhibiting superior results over Sanren F1 in highland settings (Y. Hasanah et al., 2022). The findings indicate that TSS technology holds significant potential to enhance shallot production and foster sustainable agricultural practices.

The production of TSS requires specific environmental conditions and agricultural management practices. Recent advancements in cultivation techniques, including optimal sowing depth and soil coverage, have significantly enhanced TSS emergence and yield (Brink & Basuki, 2012). Research has shown that TSS plants result in higher flowering and seed production compared to bulb-derived plants (Rosliani et al., 2021). To maximize TSS potential, integrated approaches combining organic and inorganic fertilization, efficient irrigation methods, and proper vernalization techniques are recommended. These advancements in shallot cultivation contribute to increased crop yields, improved livelihoods for farmers, and enhanced agricultural resilience (Askari-Khorasgani & Pessarakli, 2019; Mohammed et al., 2018). However, further research is needed to address breeding challenges and optimize cultivation practices for different varieties and environmental conditions (Prahardini et al., 2021). The implementation of sustainable agricultural techniques, such as integrated fertilization—which encompasses organic, inorganic, and biofertilizers—and efficient irrigation strategies, can significantly enhance the yield of shallot bulbs.

3.3 Shallot nutrient management under climate change: deficiencies and supplementation strategies

Shallot cultivation faces significant challenges due to climate change, particularly in terms of nutrient management, necessitating a comprehensive understanding of how these changes impact shallot growth and productivity. Declining yields in Central Sulawesi between 2017 and 2018 can be addressed through optimizing planting medium composition and incorporating organic matter to enhance nutrient content, aeration, and drainage (Sugianto & Jayanti, 2021). In normal conditions, shallot farmers often rely on traditional fertilization methods, including the application of NPK (nitrogen, phosphorus, and potassium) fertilizers, to ensure optimal nutrient supply for shallot growth (Widiana et al., 2020). These methods are typically based on established guidelines and local experience, often without considering the dynamic changes brought about by climate change. However, under climate change scenarios, these traditional methods may become less effective or even detrimental, leading to nutrient imbalances and reduced yields.

Under climate change scenarios, more extreme weather events such as heat waves, floods, and droughts are projected to become more frequent and intense. These events can disrupt nutrient cycling processes in the soil, leading to nutrient losses through leaching, runoff, or volatilization. In addition, Salinity stress can cause harmful effects through osmotic stress, ion toxicity, and oxidative stress. In many cases, drought and salinity together reduce global crop production as their impacts are intensified by climate change (Jiménez-Árias et al., 2021). The presence of high amounts of salts in irrigation water can increase osmotic potential, preventing water uptake and altering nutrient absorption (Lopes et al., 2019). Plants under salt stress can either prevent, reduce, or overcome salt-induced damages by limiting the entry of salts into roots, or compartmentalizing salts into vacuoles.

Based on the Table 2, shallot nutrient deficiencies (N, P, K), exacerbated by climate change through altered mineralization, leaching (N, K), and drought-limited uptake, constrain productivity in degraded soils (Thangasamy et al., 2024; Amare, 2020). Effective management requires adaptive strategies: precise soil testing and site-specific fertilizer timing/rates (Amare, 2020); organic matter (compost, manure, biochar, carbonized rice hull) to enhance soil resilience and counter salinity/sodicity (Naungayan et al., 2021; Kandil et al., 2020; Sales et al., 2021); liquid organic fertilizers/biofertilizers (4-5 ml/L) for rapid correction (Idaryani et al., 2021); and optimized irrigation with mulching to mitigate water stress and improve access given shallow roots (Hidayat et al., 2019; Murtilaksono et al., 2021). To mitigate the adverse impacts of climate change on shallot nutrient management, adopting climate-smart agricultural practices is essential. These practices include optimizing fertilizer application rates and timing based on real-time weather data and soil moisture levels. Soil testing is the first step in developing a targeted nutrient management plan, providing valuable information on the existing nutrient levels and soil pH. Based on the soil test results, appropriate fertilizers can be selected and applied to correct nutrient deficiencies and optimize soil fertility. Shallots typically require well-drained soils with adequate levels of organic matter and essential nutrients such as nitrogen, phosphorus, and potassium.

Table 2. Shallot nutrient under climate change:

Factor	Deficiency	Climate Change Effect	Authors
Nitrogen (N)	↓ Vegetative growth & vigor	↑ Leaching (rain); ↑ Mineralization (heat); ↓ Uptake (drought)	Thangasamy et al. (2024); Amare (2020)
Phosphorus (P)	↓ Root development & energy transfer	↓ Availability (drought/rain extremes)	Thangasamy et al. (2024); Tandi et al. (2021)
Potassium (K)	↓ Bulb quality, water regulation	↑ Leaching (rain); ↓ Uptake (drought); Critical in salt stress	Thangasamy et al. (2024); Sales et al. (2021)
Organic Matter	Poor soil structure & water holding	Buffers temp/rain extremes; Improves resilience	Naungayan et al. (2021); Kandil et al. (2020)
Water	↑ Stress (shallow roots)	Drought ↓ nutrient mobility; Flooding ↑ leaching	Hidayat et al. (2019); Murtilaksono et al. (2021)

Note: ↑ = Increase or Higher; ↓ = Decrease, Lower, or Impaired

Agronomic management plays a pivotal role in shallot production, impacting bulb yield and quality, which are highly dependent on environmental factors and agricultural practices. Certain nutrients play a pivotal role in enhancing shallot resilience to climate change stresses, acting as protective agents and promoting adaptive responses. Potassium, for instance, is essential for osmoregulation and stomatal control, helping shallots maintain water balance under drought conditions. Calcium is crucial for maintaining cell membrane integrity and preventing ion leakage under salinity stress, while also playing a role in signaling pathways involved in stress response (Hafez et al., 2021). Nitrogen is crucial for amino acid synthesis, impacting chlorophyll, nucleotides, and proteins, and its deficiency in saline soils limits growth (Abdelkhalik et al., 2023). Moreover, proline, glycine betaine, and trehalose are among the exogenous compounds that are both eco-friendly and readily available, offering a sustainable approach to overcoming the negative effects of salt stress on seed germination, plant growth, and productivity (Moukhtari et al., 2020).

Fertilization, involving manure, Ponska, KCl, and Fertifos, is typically administered in multiple stages, starting at planting and continuing at 15, 30, and 45 days after planting to optimize plant height, leaf count, bulb quantity, bulb diameter, and the weight of both fresh and dried bulbs (Tandi et al., 2021). Cultivating shallots on less fertile lands, like peat soils with high organic acid content and low nutrient availability, presents unique challenges requiring specific interventions such as phosphate fertilizer and Trichoderma application to improve growth and yield (Suparman & Nugroho, 2021). The application of plant growth-promoting rhizobacteria, endophytic fungi, or vesicular arbuscular mycorrhiza along with mineral fertilizers enhances plant growth and crop yield through phytohormone secretion, nutrient supplementation, and pathogen suppression (Thangasamy et al., 2024). The precise management of fertilization through balanced NPK application is crucial for achieving high growth and production, with NPK Nitrate fertilization at 700-900 kg/ha showing promising results (Suddin et al., 2021).

To mitigate the adverse impacts of climate change, various strategies can be employed to enhance their resilience and maintain optimal nutrient levels. Selecting climate-resilient shallot varieties with enhanced tolerance to heat, drought, and salinity is a crucial first step. Optimizing irrigation practices to ensure adequate water availability during critical growth stages can improve nutrient uptake and prevent stress-induced deficiencies. The use of soil amendments, such as organic matter and biochar, can enhance soil fertility, water retention, and nutrient availability, promoting healthy shallot growth even under adverse conditions. Furthermore, the application of nutrient management strategies, including foliar feeding and controlled-release fertilizers, can provide shallots with a sustained supply of essential elements throughout their growth cycle (Setiawati et al., 2021). Applying organic ameliorants to saline soils can improve shallot growth and yield (Naungayan et al., 2021). The use of organic liquid biofertilizers, nitrogen or potassium fertilization, or a combination of these in the form of organomineral fertilizers can help to mitigate the effects of salt stress on plants (Sales et al., 2021). Furthermore, the application of plant growth-promoting rhizobacteria can enhance plant tolerance to salinity stress (Ha-Tran et al., 2021). Exogenous application of proline is a sustainable approach that helps plants tolerate salt stress (Moukhtari et al., 2020). Endophytic bacteria alleviate salt stress and increase chlorophyll and N uptake in rice seedlings (Setiawati et al., 2021). Furthermore, the implementation of precision agriculture techniques, such as variable rate fertilization and fertigation, can enable targeted nutrient application based on real-time crop needs and soil conditions.

3.4 Shallot water management and methods under climate change

Climate change has become one of the major challenges in agriculture today. In Indonesia, its impact is becoming increasingly evident, marked by unpredictable seasons, extreme rainfall, and rising air temperatures. These conditions significantly affect agricultural production systems, especially crops that are sensitive to weather fluctuations, such as shallots. The cultivation of shallots from seeds, known as True Shallot Seed (TSS), is increasingly being developed as an alternative to improve production quality and efficiency. TSS is considered more disease-resistant, uniform, and suitable for mass seedling production. However, the success of TSS cultivation still depends on environmental factors, particularly water availability. In practice, water is one of the most crucial factors at every stage of shallot growth, from seeding to harvest. The problem is that climate change has made water distribution unstable. Sometimes, there is heavy rainfall in a short period, while at other times, the land experiences prolonged drought. This, of course, makes it difficult for farmers to maintain the proper soil moisture required for TSS shallots.

Water for agricultural land can be obtained from various sources, such as rainwater, surface water (rivers, lakes, reservoirs, and springs), and groundwater (bore wells). If the availability of rainwater is sufficient to meet the needs of the crops, surface and groundwater are usually not utilized for irrigation. Conversely, in areas where rainwater is insufficient to meet crop requirements, groundwater or surface water is needed to irrigate the cultivated crops. One approach that is beginning to be adopted is the use of drip irrigation systems and the construction of small water reservoirs (embung) near agricultural land. Drip irrigation allows water to be delivered slowly and evenly directly to the root zone, so that water is not wasted. Meanwhile, embung serve as storage for rainwater or irrigation runoff that can be utilized during the dry season.

The cultivation of shallots from true seeds (TSS) often faces various challenges that can affect productivity. One of the influencing factors is the availability of water that does not match the needs of the plants. Water is primarily used by plants to support nutrient uptake, plant tissue development, and cellular metabolism. In addition, water plays an important role in maintaining temperature and humidity at levels that are ideal for plant growth. Therefore, water management is crucial to optimally fulfilling the water requirements in shallot TSS cultivation (Dzikriyah et al., 2024).

The quality of shallots is highly susceptible to environmental factors, and climate change can lead to decreased water availability due to prolonged dry seasons and low rainfall. These conditions can result in drought stress, which affects various parameters of plant growth and yield. Drought stress has been reported to reduce the yield of the Bhima Kiran onion cultivar by up to 65%. Water greatly influences the ability of roots to absorb nutrients. Continuous water deficiency can inhibit growth and even lead to plant death. Therefore, further research is needed to determine the appropriate watering volume for shallot plants. Based on previous findings, only a few studies have explored the effect of irrigation systems on local Indonesian shallot varieties, particularly Bima, Trisula, and Sumenep. Shallot watering is conducted according to the treatment. The volume of water given is adjusted to the field capacity, which is 200 mL per watering session, carried out from two weeks after planting (WAP) until the harvest period (15–17 WAP) (Kusumiyati et al., 2024)

These characteristics can affect land productivity and require specific agricultural management strategies, particularly in addressing the challenges of using water resources efficiently and effectively in the face of climate change. Irrigation systems require special attention in terms of timing and the amount of water used. Irrigation systems that are suitable for changing climatic conditions include sprinkler irrigation and drip irrigation techniques. These irrigation systems are more appropriate for all seasons because they do not rely on water availability during either the rainy or dry seasons. The water source used comes from shallow wells, which is stored in water storage tanks.

3.5 Sprinkler irrigation

Sprinkler irrigation is a method of applying water to the soil surface in the form of water droplets, like rainfall. Water is sprinkled by distributing pressurized water through small holes (sprinklers/nozzles) powered by a water pump. Uniform water distribution can be achieved by considering several factors, such as selecting appropriate sprinkler sizes and spacing, as well as adjusting water pressure to match field conditions. Sprinkler irrigation technology is highly effective and efficient in meeting crop water needs. With this technology, plant water requirements can be fulfilled, thereby increasing crop productivity (Dzikriyah et al., 2024)

Based on a previous study conducted by Fauziah et al., (2016), the application of sprinkler irrigation with a water volume of 100% of the crop evapotranspiration requirement (ETc) was proven to produce the highest harvest weight in plants. Nevertheless, the plants were still able to grow and produce normally up to the 25% ETc threshold, indicating that approximately 81% of the available water had been utilized through the process of evapotranspiration. Compared to the conventional watering method using a watering can (gembor), as commonly practiced by farmers, the use of sprinkler irrigation provided more optimal results in supporting plant growth and crop yield. In line with (Suriadi et al., 2022)

In line with the study by Suriadi et al., (2020) in 2020, a water-saving technology package for shallot cultivation using sprinkler irrigation was able to increase shallot productivity to 31.6 tons per hectare, which is 14% higher compared to package B (furrow irrigation) and 45% higher than package C (farmer practice). Furthermore, in 2022 Suriadi et al. (2022), confirmed that the application of technology package A proved to be highly significant in saving water compared to other shallot cultivation technology packages. Technology package A (sprinkler) was able to save up to 62.1% more water than package B and up to 95.8% more than farmer practice or package C. The total irrigation cost using package A was lower than the other packages, with a cost efficiency of 15.8% compared to package B and 30.4% compared to package C.

3.6 Drip irrigation

Drip irrigation is a technique of gradually applying water directly to the root zone. Drip irrigation can be up to 200% more efficient in water use compared to sprinkler irrigation. The use of drip irrigation combined with soil moisture sensors significantly improves water use efficiency. Soil moisture sensors can save up to 70% of water without reducing crop yields. The application of drip irrigation offers several advantages, including: (1) low water loss due to evaporation or run-off; (2) precise water delivery to the root zone; (3) suppression of weed growth (especially when combined with mulch); and (4) no water contact with the plant canopy, thereby reducing the risk of disease outbreaks (Prathama et al., 2023)

In line with Aryani et al., (2024), who explained that the success of cultivation is highly influenced by the type of crop and land suitability. Shallots, although adaptive to dry land, have a shallow root system that makes them sensitive to drought. Therefore, water availability becomes a crucial factor, especially during the early growth phase and bulb formation stage. The water requirements of shallots vary depending on agroclimatic conditions, season, location, and growth stage. Proper irrigation management not only ensures an adequate water supply but also helps maintain soil temperature and moisture. Systems such as drip irrigation are highly recommended because they are efficient, match the characteristics of shallots, and can minimize the risk of water stress in dry land conditions.

According to a study by Halil et al., (2024), the development of drip irrigation technology for horticulture based on fresh vegetables during the dry season has proven to be efficient and water-saving. This technology can reduce production costs while simultaneously increasing farmers' income and overall profit. The application of drip irrigation in the cultivation of horticultural vegetables and seasonal fruits shows great potential in boosting production and reducing farming costs. This technology is particularly beneficial for large-scale cultivation of high-value commodities, as it enables farmers to grow fresh vegetables outside the rainy season. Drip irrigation significantly reduces water usage, costs, and daily labor requirements. Moreover, drip irrigation is financially more feasible and profitable compared to surface irrigation, as evidenced by lower production costs and higher farm income and profits.

3.7 Water management combined with straw mulch application

In addition to water management in shallot (TSS) cultivation, the use of mulch can also be combined as a strategy to face climate change conditions. Several studies have shown a correlation between water management and the use of mulch as an effective combination for shallot cultivation in both rainy and dry seasons. According to a study by Arifin & Saeri (2019) the use of mulch such as straw mulch produced the highest number of bulbs per clump in the Monjung shallot variety. This is believed to be due to straw mulch providing optimal soil moisture for microbial activity, enabling the decomposed organic matter to be directly utilized by shallot plants.

Straw mulch can lower soil temperature during the dry season, while in the rainy season, it helps retain soil moisture. This is because straw mulch has the ability to protect the planting medium from the direct impact of rainfall, while still allowing water to infiltrate and preventing water evaporation from the soil. Straw mulch can reduce the rate of evaporation, thereby saving up to 41% of water usage. Over time, organic mulch can decompose and mineralize, contributing nutrients that support plant growth and yield. Additionally, straw mulch is an organic material that can influence the number of tillers and bulbs in shallot plants. The addition of organic matter helps form granules that bind without clay, resulting in more porous soil. Porous soil allows roots to penetrate more easily, leading to the formation of larger and more numerous bulbs.

3.8 Fertilizer with irrigation

The implementation of fertigation the application of fertilizer through irrigation water, is a modern agricultural technique that can improve fertilization efficiency and crop yields. Fertigation allows timely and precise nutrient delivery tailored to plant needs, directly to the root zone, thereby reducing fertilizer loss due to leaching or runoff, while also lowering labor and energy costs. This technology has also been proven to double the efficiency of water and fertilizer use, and has the potential to save up to 40% of nitrogen fertilizer without compromising yields. The main advantages of fertigation include high efficiency in water and nutrient use, increased crop productivity, reduced risk of environmental pollution, and support for agricultural automation. This system is particularly effective for high-value crops such as fruits and vegetables. Although it presents technical challenges such as the risk of clogging irrigation equipment and corrosion, these issues can be overcome with proper management and appropriate equipment selection. With the use of automation technology and design software, fertigation has become a sustainable agronomic solution that supports global food security (Pibars et al., 2022).

4. Conclusions

The findings of this review highlight the significant effects of climate change, especially drought stress on shallot (*Allium cepa* L.) cultivation. Drought has been shown to significantly reduce the growth and yield of shallots, primarily by decreasing leaf area, plant height, and bulb size. Shallots have shallow root systems and face particular challenges in accessing deeper soil moisture, making them even more vulnerable to water scarcity. This review also reveals how shallots respond to drought stress at a physiological and biochemical level. A key mechanism for their survival is the accumulation of proline, which acts as an osmoprotectant and helps maintain cellular stability during water stress. Other compounds such as soluble sugars and total soluble solids also accumulate to aid in osmotic balance. Furthermore, the closure of stomata helps conserve water so reduces photosynthesis, further limiting growth and yield. This study also highlights the importance of integrated agricultural practices such as optimal irrigation methods, nutrient management, and the use of biofertilizers to mitigate the impacts of climate change. The use of True Seed Shallot (TSS) technology offers several advantages over traditional bulb propagation. TSS not only reduces seed costs but also improves disease resistance and shows better adaptability to changing climate conditions. The transition from bulb-based propagation to TSS could enhance yield stability and provide a more sustainable approach to shallot farming, particularly in regions facing seed shortages. However, the adoption of TSS comes with its own set of challenges, such as longer growing periods and the need for specialized cultivation techniques, which require further research and education for farmers. Sustainable agricultural practices such as efficient irrigation management, the use of organic fertilizers, and the selection of varieties that are resilient to climate change. The use of drip irrigation and other efficient irrigation systems can help reduce water waste and ensure adequate water availability during critical phases of plant growth. The implications of these findings are critical for both farmers and policymakers. Adopting climate-smart farming practices and technologies such as TSS and efficient irrigation systems can significantly improve the resilience of shallots to drought and other climate-related stresses. Furthermore, continued research into the genetic basis of drought tolerance and the development of new shallot varieties suited to these conditions will be vital in securing future crop yields. This review adds valuable insights to the growing body of knowledge on sustainable agriculture and climate adaptation, setting the stage for future research aimed at ensuring that shallot farming can continue to thrive in the face of an uncertain climate. In conclusion, this review emphasizes the complex challenges that climate change presents to shallot production, while offering practical solutions for mitigating its impact. A combination of improved farming practices, the adoption of TSS technology, and ongoing research into climate adaptation strategies will be key to ensuring that shallot cultivation remains sustainable in the years to come.

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