Water Use Efficiency and Physiological Adaptation of Maize (Zea Mays L.) Under Drought Stress in Dryland Ecosystems

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Abstract : Drought control on dry land is one of the main factors that reduce the productivity of corn plants (*Zea mays* L.) due to disruption of physiological processes and plant metabolism. This study aims to analyze the relationship between *water use efficiency* (*WUE*) and the physiological adaptation of corn plants to water deficit conditions through a literature review approach. The study was conducted using various national and international scientific articles published in the 2022–2025 period. The results of the study showed that drought stress caused a decrease in the rate of photosynthesis, leaf water content, and plant biomass formation due to stomata closure and increased accumulation of *reactive oxygen species* (ROS). Drought-tolerant corn plants have the ability to maintain water use efficiency through stomata regulation, proline accumulation, increased antioxidant activity, and the development of a more adaptive root system. In addition, the application of precision irrigation technology and adaptive agronomic management can improve water use efficiency and support crop productivity on dry land. Thus, the integration of physiological adaptation and adaptive cultivation strategies is an important approach in supporting the sustainability of maize production under climate change conditions.

Keywords : Drought Control, Water Use Efficiency, Physiological Adaptation

Abstrak : *Pengendalian kekeringan pada lahan kering merupakan salah satu faktor utama yang menyebabkan menurunnya produktivitas tanaman jagung (Zea mays L.) karena terjadinya gangguan terhadap berbagai proses fisiologis dan metabolisme tanaman. Penelitian ini bertujuan untuk menganalisis hubungan antara efisiensi penggunaan air (EPA) dan kemampuan adaptasi fisiologis tanaman jagung terhadap kondisi defisit air melalui pendekatan tinjauan pustaka. Kajian dilakukan dengan menggunakan berbagai artikel ilmiah nasional dan internasional yang diterbitkan dalam periode 2022–2025. Hasil kajian menunjukkan bahwa cekaman kekeringan menyebabkan penurunan laju fotosintesis, kandungan air daun, dan pembentukan biomassa tanaman akibat penutupan stomata serta peningkatan akumulasi spesies oksigen reaktif (ROS) di dalam jaringan tanaman. Tanaman jagung yang toleran terhadap kekeringan memiliki kemampuan untuk mempertahankan efisiensi penggunaan air melalui pengaturan stomata, akumulasi prolin, peningkatan aktivitas antioksidan, dan perkembangan sistem perakaran yang lebih adaptif terhadap keterbatasan air.*

Selain itu, penerapan teknologi irigasi presisi dan pengelolaan agronomis yang adaptif dapat meningkatkan efisiensi penggunaan air serta mendukung produktivitas tanaman jagung pada lahan kering. Dengan demikian, integrasi antara adaptasi fisiologis dan strategi budidaya adaptif merupakan pendekatan penting dalam mendukung keberlanjutan produksi jagung di bawah kondisi perubahan iklim yang terus berlangsung pada berbagai wilayah pertanian tropis.

Kata Kunci *: Pengendalian Kekeringan, Efisiensi Penggunaan Air, Adaptasi Fisiologis*

INTRODUCTION

Global climate change has become one of the major challenges in the modern agricultural sector as it has led to an increase in air temperatures, changes in rainfall patterns, and an increasing frequency of drought events in different regions of the world. This condition has a direct impact on the decline in the productivity of food crops, especially in dryland agroecosystems that have limited water resources and relatively low soil fertility levels. Drought stress is one of the main abiotic factors that cause a decrease in the growth and yield of corn plants due to disruption of physiological processes and plant metabolism (Farooq et al., 2023).

Dry land has the main characteristics of low soil capacity to store water, high evapotranspiration rate, and uneven distribution of rainfall throughout the year. This condition causes plants to often experience a water deficit during the growth and development phase. Drought is the main limiting factor in crop production because it affects almost all plant physiological processes, from water and nutrient absorption, photosynthetic activity, to the formation of plant biomass. In drought-stressed conditions, plants experience a decrease in the potential of leaf water which has an impact on disrupting metabolic processes and plant growth (Tariq et al., 2023). In Indonesia, especially in the West Nusa Tenggara (NTB) region, the development of corn cultivation on dry land has an important role in supporting food security and providing raw materials for animal feed. However, corn productivity in drylands still faces major obstacles in the form of limited water availability and increased risk of drought due to climate change. Therefore, a cultivation strategy is needed that is able to increase water use efficiency while maintaining crop productivity in water deficit conditions.

Corn plants (Zea mays L.) are one of the world's strategic commodities that have an important role as a source of food, animal feed, and industrial raw materials. The global demand for corn continues to increase every year in line with population growth and the development of the food industry. However, corn productivity in dryland areas is still relatively low due to water limitations and high intensity of drought stress. Decreased water availability in the vegetative and generative phases can lead to a significant decrease in corn yields due to disruption of plant physiological processes and low water use efficiency (Hussain et al., 2022). Water *Use Efficiency* (WUE) is one of the important indicators in evaluating the ability of plants to use water to produce biomass or crop yields. Plants with high WUE values generally have a better ability to maintain growth and productivity under conditions of limited water availability (Zhang et al., 2024). In addition to being influenced by plant genetic characteristics, WUE is also closely related to the plant's ability to make physiological adaptations to drought stress.

Various studies have reported that corn plants have diverse adaptation mechanisms in dealing with water deficit conditions, both through physiological, biochemical, and morphological responses. In addition, the application of efficient irrigation technology and adaptive agronomic management are known to increase water use efficiency and support crop productivity on dry land (Melkie et al., 2024). Thus, the integration of crop adaptability and water management strategies is an important factor in supporting the sustainability of corn production in drought-stressed conditions. Although many studies have been conducted on drought stress in maize crops, most studies still focus on physiological aspects, crop productivity, or irrigation technology separately. Studies that integrate the relationship between water use efficiency and the physiological adaptation of corn crops under drought-stressed conditions are still relatively limited. Therefore, a comprehensive literature review is needed to understand the relationship between water use efficiency and plant physiological adaptation mechanisms as the basis for developing a more adaptive and sustainable maize cultivation strategy.

Based on the background description and various results of previous research, the formulation of the problem in this study is focused on the relationship between *water use efficiency (WUE)* and the physiological adaptation of corn plants to drought-stressed conditions in dry land. Drought stress is known to cause disruption of photosynthetic activity, decreased leaf water content, and increased oxidative stress due to the accumulation of *reactive oxygen species* (ROS) which has an impact on decreasing the growth and productivity of corn plants (Farooq et al., 2023; Wang et al., 2022). In addition, corn plants have various physiological and biochemical adaptation mechanisms to maintain survival in water deficit conditions, such as stomata regulation, proline accumulation, increased antioxidant activity, and modification of the root system (Ibrahim et al., 2022; Kumar et al., 2023). However, studies that integrate the relationship between water use efficiency, physiological adaptation mechanisms, and water management strategies in maize cultivation in dry land are still relatively limited. Therefore, this study was formulated to examine how the relationship between water use efficiency and the physiological adaptation of corn plants, physiological mechanisms that play a role in increasing plant tolerance to drought stress, as well as water management strategies and cultivation technologies that can increase corn productivity in conditions of water limitation.

METHODS

This study uses a *literature review* method with a descriptive-analytical approach to examine the relationship between water use *efficiency* (WUE) and the physiological adaptation of corn plants (*Zea mays* L.) under drought-stressed conditions in dry land. The literature was obtained from Google Scholar, Scopus, ScienceDirect, SpringerLink, ResearchGate, and Garuda databases using keywords related to drought control, water use efficiency, physiological adaptation, and corn crops. The literature selection process refers to the *guidelines of Preferred Reporting Items for Systematic Reviews and Meta-Analyses* (PRISMA 2020). The articles used are scientific publications for the period 2019–2025 (last seven years) to ensure the novelty, relevance, and up-to-date of the information analyzed. The time range was chosen because it reflects the latest research developments on drought control, *water use efficiency*, and the mechanism of physiological adaptation of corn plants on dry land. The initial search results yielded 85 articles. After going through the stages of identification, screening, and feasibility evaluation based on the criteria that have been set, as many as 32 articles were selected as the main source of the study. The data obtained were then analyzed and synthesized descriptively to identify the relationship between water use efficiency, physiological response of corn crops, and adaptation mechanisms to drought stress on dry land.

RESULTS AND DISCUSSION

Water *Use Efficiency (WUE)* in Corn Plants Under Drought Stress

Water Use Efficiency (WUE) is one of the important indicators in determining the ability of corn plants to adapt to drought-stressed conditions on dry land. WUE describes the ability of plants to produce biomass or crop yields to the amount of water used during the growth process. In water deficit conditions, plants with high WUE values generally have better ability to maintain physiological activity and productivity than plants with low WUE values. Zhang et al. (2024) explain that increased WUE is closely related to the plant's ability to maintain a balance between photosynthesis processes and water loss through transpiration. These conditions show that water use efficiency is one of the main indicators of plant tolerance to drought stress.

Drought control causes a decrease in soil moisture content which has an impact on disrupting the process of water and nutrient absorption by plant roots. Water deficit also causes a decrease in the potential of leaf water so that plants experience physiological disturbances, such as a decrease in the rate of photosynthesis and biomass formation. Farooq et al. (2023) report that drought in both the vegetative and generative phases causes a decrease in water use efficiency due to low diffusion of carbon dioxide into leaf tissues due to stomata closure. The decrease in photosynthetic activity has an impact on the low accumulation of photosynthetic results required in the formation of seeds and biomass of corn plants.

Drought-tolerant corn crops generally have the ability to maintain higher WUE values than sensitive genotypes. This ability is related to the efficiency of stomata regulation and the ability of plants to maintain photosynthetic activity in deficit conditions. These results are in line with the research of Li et al. (2024) who reported that drought-tolerant corn genotypes are able to optimize water use through stomata regulation and carbon metabolism efficiency so that water loss can be suppressed without causing a significant decrease in photosynthesis. However, Farooq et al. (2023) show that in conditions of severe stress, increased water use efficiency is not always followed by increased plant productivity because excessive closure of stomata can inhibit the diffusion of carbon dioxide into leaf tissue. These differences in results show that the relationship between WUE and crop productivity is complex and influenced by drought stress, genotype character, and physiological adaptability of plants. In mild to moderate stress conditions, increased WUE can help plants maintain growth. However, in conditions of severe stress, excessive water use efficiency is often followed by a decrease in photosynthetic activity due to limited gas exchange in the leaves.

The increase in water use efficiency is also influenced by the plant's ability to make osmotic adjustments through the accumulation of compatible osmolites such as proline, dissolved sugars, and betaine glycine. The accumulation of these compounds helps maintain the pressure of the turgor of the cells so that the plant's metabolic activity continues under water deficit conditions. Ibrahim et al. (2022) reported that increased proline content in corn plants is able to improve water use efficiency through cell membrane protection and stabilization of the photosynthetic system during drought-stressed conditions. Thus, the efficiency of water use is not only affected by the availability of water, but also by the physiological and biochemical ability of plants to maintain metabolic stability under water-limited environmental conditions.

In addition to being influenced by the physiological and biochemical mechanisms of plants, the efficiency of water use is also influenced by cultivation management strategies and irrigation systems applied to dry land. Koesmaryono et al. (2014) explained that the implementation of a proper irrigation water management system is able to increase water use efficiency and productivity of corn plants in dry land with a dry climate. Irrigation management carried out according to the physiological needs of plants can reduce water loss due to evaporation and increase water utilization by plants more optimally. In addition, the combination of irrigation arrangements with pruning the lower leaves is known to be able to increase the efficiency of light absorption and photosynthetic distribution so that plant growth becomes more efficient in conditions of water limitation. Corn plants that received optimal water management showed better ability to maintain photosynthetic activity, biomass formation, and productivity compared to treatments without water regulation. The results of the study show that water management strategies and adaptive cultivation techniques have an important role in increasing *Water Use Efficiency* (WUE) and supporting the sustainability of maize cultivation in dryland agroecosystems (Koesmaryono et al., 2014). Thus, the increase in water use efficiency in corn plants is not only influenced by the physiological capabilities of the plants, but also by the level of environmental stress and the ability of the plants to maintain a balance between water conservation and photosynthetic activities.

Physiological Adaptation of Corn Crops to Drought Stress

Drought stress causes disruption of various physiological processes of corn plants, such as decreased photosynthetic activity, decreased tissue water content, and inhibition of vegetative growth of plants. Water deficit conditions cause plants to experience disturbances in the process of absorbing water and nutrients so that the growth of roots, stems, and leaves is not optimal. Asbur et al. (2024) reported that corn plants that experienced drought stress showed a decrease in crop height, leaf area, and biomass accumulation due to decreased plant physiological activity during water deficit conditions. Decreased water availability also leads to reduced chlorophyll formation and disruption of photosynthetic activity so that plant growth becomes slower than normal conditions. In addition, corn plants tend to make physiological adjustments through closure of the stomata to reduce water loss through transpiration. However, the continuous closure of the stomata can reduce the diffusion of carbon dioxide into the leaf tissue, resulting in decreased photosynthesis efficiency and plant productivity. Thus, the physiological response of plants to drought stress is an important factor in determining the adaptability and tolerance of corn plants in dryland agroecosystems (Asbur et al., 2024).

Corn plants have various physiological adaptation mechanisms to maintain survival in drought-stressed conditions. One of the main physiological responses that plants carry out is the regulation of the stomata. Stomata closure is the plant's initial mechanism to reduce water loss through the process of transpiration. However, prolonged closure of stomata also causes a decrease in the diffusion of carbon dioxide into the leaf tissue, resulting in decreased photosynthetic activity. Park et al. (2024) explain that stomata regulation is one of the main physiological responses. Deep plants reduce water loss through the process of transpiration. In addition, Wang et al. (2022) reported that drought-tolerant corn crops have higher antioxidant activity such as *superoxide dismutase* (SOD), catalase (CAT), and peroxidase (POD) than sensitive crops so that cell damage due to the accumulation of *reactive oxygen species* (ROS) can be suppressed.

These results are in line with the research of Syauqi and Amzeri (2023) stating that drought-tolerant corn genotypes have better physiological adaptability to water deficit conditions than sensitive genotypes. This adaptability is shown through the ability of plants to maintain the relative water content of the leaves, maintain photosynthetic activities, and increase water use efficiency during drought-stressed conditions. Tolerant genotypes generally have more efficient stomata regulation mechanisms so that water loss through the transpiration process can be suppressed without causing a drastic decrease in metabolic activity. In addition, drought-tolerant plants also show increased antioxidant activity and the accumulation of compatible osmolites such as proline which play a role in maintaining cell membrane stability and osmotic balance of plants. These conditions allow plants to maintain growth and biomass formation even though the availability of groundwater decreases. Thus, physiological adaptability is one of the important factors in supporting corn plant tolerance to drought stress in dryland agroecosystems (Syauqi & Amzeri, 2023). In addition to stomata regulation, corn plants also show physiological adjustments through increased relative water content of leaves and cellular metabolic efficiency. Drought-tolerant plants generally have a better ability to maintain tissue water content so that the plant's physiological processes continue despite a decrease in soil moisture content. Zhang et al. (2024) stated that the ability to maintain the water status of leaves is one of the main indicators of plant tolerance to drought because it is directly related to the sustainability of photosynthetic activity and plant metabolism.

These conditions indicate that the physiological adaptation mechanism of plants has a certain tolerance limit to the level of environmental stress. Physiological responses such as stomata closure are effective in reducing water loss, but at the same time can decrease photosynthetic activity if it lasts too long. In addition, increased antioxidant activity requires considerable metabolic energy so that the effectiveness of plant defense mechanisms is greatly influenced by environmental conditions and genetic abilities. To overcome these conditions, plants increase the activity of the antioxidant system through the production of enzymes such as superoxide dismutase (SOD), catalase (CAT), and peroxidase (POD). Wang et al. (2022) reported that drought-tolerant corn crops have higher antioxidant activity than sensitive crops so that the rate of cell damage due to oxidative stress can be significantly suppressed.

Thus, the physiological adaptation of corn plants to drought stress is the result of complex interactions between stomata regulation, antioxidant activity, cellular water balance, and the ability of genotypes to maintain metabolic stability during water deficit conditions. Increased antioxidant activity plays an important role in maintaining cell membrane stability and maintaining plant metabolic efficiency during drought-stress conditions. In addition, tolerant plants also have the ability to maintain a higher chlorophyll content so that photosynthetic activity continues in water deficit conditions. These conditions show that the physiological adaptation of plants to drought is the result of a complex interaction between stomata regulation, cellular water balance, antioxidant activity, and plant metabolic efficiency in the face of environmental stresses.

The Role of Proline and Osmoprotection in Drought Tolerance

Proline accumulation is one of the important biochemical mechanisms that plays a role in increasing plant tolerance to drought stress. Proline serves as a compatible osmolyte that helps maintain the osmotic pressure of cells, maintains membrane stability, and protects proteins and enzymes from damage due to environmental stress. In water deficit conditions, an increase in proline content allows plant cells to maintain turgor pressure so that physiological and metabolic processes continue to take place optimally. Renzetti et al. (2024) explain that proline accumulation is a plant's adaptive response in maintaining physiological stability during drought conditions.

The increase in proline content in corn plants is closely related to the plant's ability to maintain tissue water content and photosynthetic activity. Ibrahim et al. (2022) reported that exogenous proline applications were able to increase chlorophyll content, photosynthesis activity, and water use efficiency in corn plants that experienced drought stress. Proline also plays a role in protecting the cell membrane structure from damage due to increased ROS so that plant cell stability is maintained during stressful conditions. These results are supported by Renzetti et al. (2024) who explain that proline accumulation is a plant's adaptive response in maintaining physiological stability and reducing oxidative damage due to ROS accumulation during drought conditions. However, some studies have shown that increased proline content does not necessarily correlate directly with the plant's level of tolerance to drought because the response is also affected by the plant's stress levels and growth phases.

The difference in the results of the study shows that proline accumulation is not the only indicator of drought tolerance in corn plants. The effectiveness of proline in improving plant tolerance is strongly influenced by its interaction with antioxidant systems, stomata regulation, and the plant's ability to maintain metabolic balance during stressful conditions. Thus, proline accumulation plays an important role in the osmoprotection mechanism of maize plants, but its effectiveness in increasing drought tolerance is influenced by the integration of various plant physiological and biochemical mechanisms. Proline accumulation is known to be closely related to the antioxidant activity of plants. The increased proline content helps suppress oxidative damage due to ROS accumulation through cellular protection mechanisms and free radical capture. Therefore, proline not only functions in osmotic adjustment, but also plays an important role in the plant's defense system against oxidative stress during drought stress.

Adaptation of Root Systems to Water Deficits

Corn plants exhibit various forms of morphological adaptation in response to drought-stressed conditions, mainly through modification of root systems. A longer and deeper root system allows plants to absorb water from deeper soil layers so that plants are able to survive water limitations. Kumar et al. (2023) explained that the development of the root system is one of the main strategies of corn plants in increasing tolerance to drought stress in dry land. A well-developed root system helps plants maintain water and nutrient absorption so that the plant's physiological processes continue even when groundwater availability decreases. In water deficit conditions, plants tend to increase the root-crown ratio through a greater allocation of biomass to the roots than the crown of the plant. The strategy aims to increase water absorption capacity and maintain plant water balance. Plants with a more developed root system generally have a better ability to absorb water and nutrients so that the physiological activity of the plant continues even though environmental conditions experience a lack of water.

Aulya et al. (2019) explained that drought-tolerant corn genotypes have more adaptive morphological and physiological characteristics than sensitive genotypes in dry land conditions. Tolerant plants generally show better root system development, such as longer roots, deeper root penetration, and a higher root-to-crown ratio so that water absorption ability is more optimal in water deficit conditions. In addition, tolerant genotypes also have the ability to maintain tissue water content and plant growth stability during periods of drought. These adaptive characteristics allow plants to maintain physiological activity and biomass formation even though groundwater availability decreases. Thus, the characterization of drought-tolerant genotypes is one of the important approaches in the development of adaptive corn varieties to support crop productivity in dryland agroecosystems in Indonesia.

In addition to increasing root length, corn plants also undergo changes in root architecture, such as an increase in the number of lateral roots and the depth of root penetration into the soil. These modifications increase water absorption efficiency and help plants maintain tissue water content in drought-stressed conditions. Kumar et al. (2023) reported that drought-tolerant corn genotypes have a more adaptive root architecture than sensitive genotypes, resulting in higher water use efficiency. Based on the results of these studies, the adaptation of the root system is one of the important mechanisms in increasing the tolerance of corn plants to drought stress in dry land. Deeper root development, increased root-to-crown ratio, and modification of root architecture play a role in improving the plant's ability to absorb water and maintain physiological activity during water deficit conditions. Therefore, the character of the root system can be used as one of the important indicators in the selection of drought-tolerant corn genotypes and the development of adaptive cultivation strategies in dryland agroecosystems.

CONCLUSIONS AND SUGGESTIONS

Drought control in dry land causes a decrease in the growth and productivity of corn plants due to disruption of physiological processes and plant metabolism. Water *Use Efficiency (WUE)* is an important indicator in determining the ability of corn plants to adapt to water deficit conditions. Drought-tolerant corn plants are able to maintain physiological activity through stomata regulation, proline accumulation, increased antioxidant activity, and the development of a more adaptive root system. In addition, the application of cultivation technology such as *precision irrigation* and adaptive agronomic management plays a role in improving water use efficiency and supporting the sustainability of corn production on dry land.

Based on the findings of this study, it is recommended to conduct further experimental research to examine the response of various maize genotypes to drought stress, particularly with regard to water use efficiency and plant physiological adaptation mechanisms. In addition, the development of drought-tolerant corn varieties, the application of water-saving irrigation technology, and cultivation management that is adaptive to climate change need to be continuously improved to support sustainable corn productivity on dry land.

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