

**Xyway LFR[®]FMC fungicide: Improving corn (*Zea Mays* L.) water use efficiency and
productivity under water-deficit stress and dryland conditions**

**A Dissertation presented for the
Doctor of Philosophy
Degree
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ABSTRACT

Triazole fungicide has the ability to protect crops from varying water stresses. Xyway LFR^{@FMC} is a triazole, at-plant fungicide and has been observed to improve plant performance under limited water conditions. A greenhouse study was conducted to assess the potential of Xyway LFR^{@FMC} in altering the ability of corn plants to control transpiration rates under water deficit-stress (DS) conditions. Greenhouse grown plants were treated with Xyway LFR^{@FMC} at 0.56, 0.77, 1.11, 1.26 L ha⁻¹. Plants treated with 1.11 L ha⁻¹ reduced the amount of water loss in response to DS and had the highest fraction of transpirable soil water (FTSW) thresholds. There was an increase in shoot hydraulic conductance (K_{shoot}) and plants had higher leaf water potential (LWP) by 1.11 L ha⁻¹ under DS conditions. Therefore, in 2022 and 2023, a field study was initiated to assess the Xyway LFR^{@FMC} contribution to plant growth and yield improvement under different water regimes. Xyway LFR^{@FMC} at 1.11 L ha⁻¹ and no fungicide/check were the main plots. Within each main plot there were three water regimes, high (HI) and low (LO) number of irrigation events and rainfed (RF). Plants treated with Xyway LFR^{@FMC} had significantly higher plant height, stem diameter, LWP, and yield compared to no- fungicide under all three water regimes in 2022. Due to a favorable growing condition in 2023 i.e., less disease pressure, frequent rainfall, and lower vapor pressure deficit (VPD, kPa) rates there was no significant separation for yield among the water regimes. But the yield was significantly higher across multiple years for the fungicide treated plots compared to no-fungicide. The results indicate that Xyway LFR^{@FMC} has the potential to improve plant growth and protect yield under varying water regimes. But environmental conditions and assessment of disease levels should be used as a guide to determine the fungicide application's benefit. Furthermore, the fungicide treated RF plants had almost \$122.56 average net return rate per hectare in 2022 compared to RF plants without fungicide. This indicates that the application

of Xyway LFR^{@FMC} at planting is one possible way to protect the corn yield under a limited water scenario (i.e., RF).

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CHAPTER I

INTRODUCTION

Review of Literature

Background

Corn (*Zea mays* L.) is serving as a vital staple crop all over the world. It can play an imperative role in guaranteeing food and nutritional security due to its high productivity and production potential (Tanumihardjo et al., 2020). It is produced and consumed as a fundamental food in areas where nourishment and sustenance frailties are the major challenges (Welch, 2001). The crop is also utilized as a major feed ingredient for commercial poultry and livestock (Lakshmi, Kumari, and Reddy, 2017). Hence, corn is a dual-purpose crop broadly utilized as a food for humans and feed for livestock (Erenstein, Blümmel, and Grings, 2013). Likewise, corn is also used for ethanol production (Pimentel et al., 2005). It can be cultivated in all three crop seasons, across all ecological regions, and fits well into crop rotations either as a single or in rotation/mixed/multi-cropping. It is picking up a critical position in cropping systems due to higher yield potential, short growing period, higher food value, and diversified use (Taipodia and Shukla, 2013).

However, corn production is significantly impacted by environmental factors, with water deficit stress being identified as one of the most crucial factors that negatively affect it (Zhang et al., 2018). Drought stress in corn can affect anatomical, morphological, physiological, and biochemical processes, restricting corn growth (Cakir, 2004; Kapoor et al., 2020; Noein and Soleymani, 2022). Drought stress impacts corn yield and yield attributing features in addition to its effect on vegetative growth and development (Moser et al., 2006; Rivera-Hernandez et al., 2010).

Several agronomic strategies have been developed to minimize the effect of drought stress in corn. In case of limited water availability, applying available water in the crucial stages like

knee high, flowering, and grain filling can help minimize the negative impact to some extent (Campos et al., 2004; Sah et al., 2020). Under conditions of limited water availability, the selection and cultivation of drought-tolerant corn hybrids can assist in sustaining high yields (Messina et al., 2015; Shekoofa et al., 2015; Mounce et al., 2016; Zhao et al., 2018; Schwartz et al., 2022).

Similarly, drought stress can be mitigated by using bio-stimulators. Pre-treatment with melatonin (bio-stimulant) at a concentration of 100 μ M was found to mitigate the negative impact of drought stress in tomato plants (*Solanum lycopersicum* L.) (Altaf et al., 2022).

Additionally, plant health/protection products were found to improve the water saving potential of the crops and improve the crop performance and yield. Plant health product Daconil Action[®] was found to limit the transpiration rate under high vapor pressure deficit (VPD, kPa) in creeping bent grass (*Agrostis stolonifera* L.) (Shekoofa et al., 2016). Seed treated with *Trichoderma asperellum*, a plant protection product improved leaf relative water content, water use efficiency and photosynthesis of corn under drought conditions (Estévez-Geffriaud et al., 2020). Some classes of fungicide such as triazoles and strobilurins not only alleviate fungal diseases but they also regulate various physiological and biochemical phenomena. As a result, they have been found to improve the growth and yield of plants under abiotic stresses (Venancio et al., 2003; Amaro et al., 2020; Ijaz et al., 2022).

Triazole fungicides are also called stress protectants because of their natural ability to induce abiotic stress tolerance by increasing antioxidant enzymes and molecules in stress-affected plants. They also have plant growth-regulating properties apart from disease protectants (Jaleel et al., 2007; Hassanpour et al., 2012; Desta and Amare, 2021). A new triazole class of fungicide, Xyway LFR^{®FMC} is also called demethylation inhibitor (DMI) fungicide. It is a systemic fungicide and the active ingredient in Xyway brand fungicides is flutriafol. It will be extremely beneficial to

assess and determine if Xyway LFR^{@FMC} can reduce the drought damages and can have positive impact on corn grain quality, yield, and profitability under water limited conditions.

Corn production in the USA

Corn production is highly concentrated in certain regions like North America, Asia, and South America (Grote et al., 2021). The United States is the largest corn producer globally with approximately 39-million-ha land reserved for corn production. In 2022, U.S. corn growers produced 411 billion kg, down 9% from 2021. Corn yield in the United States is estimated at 11654.6 kg ha⁻¹, 102 kg below the 2021 record high yield of 11883.3 kg ha⁻¹ in 2022. The area harvested for grain in 2022, at 32.1 million ha, is down 7% from 2021 (USDA 2023).

According to USDA, Economic Research Service, 2023, the United States is the world's largest producer, user, and exporter of corn (USDA 2023). Every year, around 36.4 million ha of corn are planted by American farmers. Although corn is grown in most U.S. States, the Heartland region (from the Great Plains through Ohio) produces the majority of the crop. The two States that produce the most corn, Iowa, and Illinois, typically make up roughly one-third of the national harvest (USDA, Economic Research Service 2023).

Corn production in Tennessee, USA

Tennessee is ranked 16th in the country for the corn production. More than 343983 ha are typically used to cultivate grain and silage each year. In Tennessee more than 80% of field corn are grown under no-till system (McClure, 2020). The majority of field corn is planted in rotation with soybeans or cotton, and planting area varies according to commodity and fertilizer prices as well as the weather. Tennessee's west and central counties produce the most corn (University of Tennessee, 2023). With 13208.11 kg ha⁻¹, Overton County had the highest average county yield for corn in 2022. Maury County reported the lowest average county production at 6604.06 kg ha⁻¹ in 2022 (Smith A. 2023 March 30).

Effect of drought on corn production

Effect on agro-morphological and yield parameters

Drought stress is one of the most significant environmental variables limiting plant growth, development, and productivity (Prasad, Staggenborg, and Ristic, 2008). Drought stress in corn is a serious issue that affects anatomical, morphological, physiological, and biochemical processes, restricting corn growth (Cakir, 2004; Kapoor et al., 2020; Noein and Soleymani, 2022). The severity of drought damage is determined by the length of the stress and the stage of crop development (Setter, Flannigan, and Melkonian, 2001). Under both mild (80.1%) and severe drought (93.6%), grain yield significantly decreases when compared to normal irrigation. Corn suffers the greatest yield loss during drought conditions that start during the vegetative stage and are followed by tasseling and silking (Grant et al., 1989; Gopalakrishna et al., 2023). Elevating temperature has been shown to have a negative impact on corn yield by reducing silk elongation activity and rate, extending the time between anthesis and silking, and ultimately reducing grain number at the ear tip, as reported by Shao et al. (2021).

Drought stress at different stages of corn growth can lead to varying degrees of yield loss, with both the amount of stress and the growth stage affecting yield, according to Cakir (2004). For instance, drought stress during the vegetative and flowering stages reduced output by 28% and 29%, respectively, compared to regular irrigation (Hajibabaei, Azizi, and Zargari, 2012). Additionally, Pandey, Maranville, and Chetima (2000) found that deficit irrigation at the beginning of the vegetative growth phase can moderately reduce leaf area index, plant height, plant growth rate, and dryness.

Drought stress can have a significant impact on corn yield and yield attributing features. For example, Moser et al. (2006) found that corn subjected to three levels of nitrogen dose (0, 80

and 160 kg N ha⁻¹) and drought stress yielded 32%, 13%, and 21% less than corn grown under normal conditions. Another study by Khalili et al. (2013) showed that increasing water stress resulted in a decrease in the number of rows in the ear, the number of grains per row, and the weight of 1000 kernels, ultimately leading to lower grain yield and biological yield.

The negative effects of drought stress on yield attributing traits are severe. Mostafavi, Ghaemi, and Khorasani (2013) found that corn grown under drought stress conditions had a decrease of up to 67.2% in 10 ear weight (kg) compared to normal growing conditions. Additionally, there was a decrease of up to 13.9%, 54.82%, 27.81%, 23.43%, 17.05%, and 71.51% in 1000 kernel weight, kernels number per row, ear length, ear diameter, cob diameter, and total yield, respectively, in corn subjected to drought stress compared to corn grown under normal conditions. Sah et al. (2020) reported that yield losses due to water stress could be as high as 25%, 50%, and 21% during vegetative, silking (flowering), and ear (grain filling) stages respectively.

Effect on physiological parameters

Drought stress is physiologically linked to induced osmotic stress and metabolic reactions in plants (Djibril et al., 2005). According to a study by Lauer (2003), the ability of plants to absorb and transport resources is disrupted by drought stress, which has an impact on food availability. Drought conditions reduce turgor pressure, which affects normal plant functions (Hsiao, 1973). Bänziger, Edmeades, and Afitte (2002) noted that under water-stress conditions, root weight increases while shoot weight decreases. Water availability affects stomata opening, and drought disrupts stomata activity, which in turn affects plant physiological systems. Enzyme activity is also influenced by water availability, and reduced water availability leads to a decrease in the production of reactive oxygen species (ROS), which can damage chloroplasts and cell membranes (Wahab et al., 2022).

Under stress conditions, chloroplasts in plants produce high amounts of ROS, which can cause necrosis and chlorosis (Asada, 2000). Jones and Thornton (2003) noted that the photosynthetic process of the plant is particularly vulnerable to damage from drought. However, according to Kang, Shi, and Zhang (2000), corn is able to tolerate water-deficit stress during early vegetative growth when less water is available, but complete irrigation is necessary during reproductive stage.

Drought stress management in corn

Several agronomic strategies have been developed to minimize the effect of drought stress in corn. Irrigating the crop is one of the best options for drought management in arid and semi-arid regions. Irrigation has reduced corn yield loss risk by 10%, 17%, 22%, and 27% under moderate, extreme, severe, and exceptional droughts in western US, respectively (Leng, 2021). In case of limited water availability, applying available water in the crucial stages like knee high, flowering, and grain filling can help minimize the negative impact to some extent (Campos et al., 2004; Sah et al., 2020; Sheldon et al., 2023; Poudel and Shekoofa, 2024).

The water scarcity problem is more critical by factors such as uneven terrain, inadequate drainage systems, and a shortage of water channels. To address this issue, researchers are working on developing crop cultivars that require less water (Nafziger, Carter, and Graham, 1991; Messina et al., 2015; Shekoofa et al., 2015; Mounce et al., 2016; Zhao et al., 2018; Schwartz et al., 2022). Rainfed agriculture accounts for more than 80% of global agricultural land therefore, developing genotypes that are better suited to water-scarce conditions is essential (Berzsenyi et al., 2006).

The competition for available water resources has increased dramatically due to the growth of irrigated crop and rising water demands from non-agricultural users (Schaible and Aillery, 2012). In this circumstance it is important to implement water management strategies that save

water while preserving adequate production levels (Zwart and Bastiaanssen, 2004; Costa, Ortuño, and Chaves, 2007). Several strategies such as efficient irrigation scheduling methods and improved irrigation technologies can be implemented for better use of water resources that are limited (Kirda, 2002). Soil water sensors and variable rate irrigation (VRI) system are some of the improved irrigation technologies that can make irrigation scheduling more practical and accurate in terms of the water application within-field variability (Henry and Krutz, 2016; Sheldon et al., 2023).

In addition to the irrigation management strategies, in the recent years, many studies have been carried out to investigate how to improve the crop performance under water stress or drought condition using the complementary properties of certain agrochemicals normally used for plant protection such as triazole (Arivalagan and Somasundaram, 2015; Rajasekar, Rabert, and Manivannan, 2016).

Irrigation scheduling for drought management in corn

Cropland where rainfall is insufficient to meet the water demand of crop, efficient irrigation is among the most viable options. Under limited water availability, effective irrigation scheduling strategies are crucial for mitigating the negative effects of drought and ensuring viable corn yields (Nandan et al., 2021). Irrigation scheduling involves determining the timing and quantity of water application to meet crop water demands while minimizing waste and maximizing water use efficiency (Taghvaeian et al., 2020). In corn, one should account for various factors, including soil characteristics, crop growth stage, evaporative demand, and the severity of drought conditions to decide irrigation scheduling (Djaman et al., 2018).

Irrigation scheduling could rely on several approaches. However, weather-based, soil water based, and plant-based approaches are most widely used in corn (Sui, Pringle and Bames, 2019). A fundamental aspect of irrigation scheduling is monitoring soil moisture levels through

techniques such as neutron probes, time-domain reflectometry, or tensiometers. These tools provide real-time data on plant-available water in the root zone, enabling informed decisions on when irrigation is necessary to prevent drought stress and over-watering plants (Datta and Taghvaeian, 2023). Use of soil water sensors have been recognized as a most prevalent approach for scheduling irrigation in various crops (Taghvaein et al., 2020; Henry and Krutz, 2016; Sheldon et al., 2023).

By coordinating irrigation with plant water demand, irrigation scheduling based on in-situ measurements of soil water potential via soil water sensors could enhance crop productivity, economic viability, and environmental parameters. Sensor-based scheduling can increase on-farm profitability by lowering power consumption, even in the absence of increased crop productivity (Bryant et al., 2017). Utilizing soil water sensors can sometimes result in an increase in irrigation water use efficiency (IWUE) of as much as 274% and increases nitrogen use efficiency up to 40% through reduced leaching (Zotarelli et al., 2011). Irrigation using soil water sensors in the Delta region of Mississippi reduced water applied and increased the corn yield and partial net returns above irrigation cost (Spencer et al., 2019). Similarly, in a study by Sheldon et al. (2023) irrigation scheduling using soil water sensors increased the gross revenue and generated higher partial net returns.

Crop growth stage is a critical consideration in irrigation scheduling for drought management in corn. During the vegetative growth stages, water deficits can stunt plant development and reduce leaf area expansion, subsequently limiting the crop's ability to intercept solar radiation and produce biomass (Aslam, Maqbool and Cengiz, 2015).

In addition to timing, the quantity of water applied through irrigation is equally important. Excessive irrigation can lead to unnecessary water consumption, nutrient leaching, and potential

waterlogging, while insufficient irrigation exacerbates drought stress. Employing techniques such as deficit irrigation, which involves strategically under-irrigating during less drought-sensitive growth stages, can conserve water resources without substantially compromising yields (Payero et al., 2009; Spencer et al., 2019; Sheldon et al., 2023).

By combining soil water monitoring, variable rate irrigation, growth stage considerations, and appropriate irrigation quantities, growers can optimize water use efficiency, mitigate drought stress, and sustain economically viable yields even during periods of limited water availability.

Role of plant health products/fungicide under limited water availability and stress

Along with irrigation scheduling, plant health/protection products were found to improve the water saving potential of the crops and improve the crop performance and yield under drought or water limited conditions. Plant health product Daconil Action® was found to limit the transpiration under high vapor pressure deficit (VPD, kPa) in creeping bent grass (*Agrostis stolonifera* L.) (Shekoofa et al., 2016). Seed treated with *Trichoderma asperellum* L., a plant growth-promoting fungus, improved leaf relative water content, water use efficiency, and photosynthesis of corn under drought conditions (Estévez-Geffriaud et al., 2020). Some classes of fungicide such as triazoles and strobilurins not only alleviate fungal diseases but they also regulate various physiological and biochemical phenomena under water stressed conditions (Ijaz et al., 2022; Thind, 2022).

Various active ingredients present in the fungicide can play a positive physiological role in water stress management. Strobilurin-fungicides, as azoxystrobin, in addition to controlling diseases, have additional effects on crop physiology, which may influence yield response (Venancio et al., 2003; Amaro et al., 2020; Ijaz et al., 2022). Giuliani et al. (2010) reported that the application of azoxystrobin in drought conditions had a positive influence on water status, on water use efficiency (WUE) and yield response in tomato (*Solanum lycopersicum* L.) (Giuliani et

al., 2010). Fungicide having the micro elements Potassium and Zinc can play a positive role in improving the use of water in corn in drought stress condition (Hussain et al., 2020). Foliar application of Azoxystrobin fungicide has a positive physiological effect on tomatoes in drought stress conditions. Azoxystrobin treatment reduced drought stress in tomato plants and enhanced cell membrane stability, free proline content, catalase, peroxidase, and polyphenol oxidase activities, and total and free phenol content (Ali, Desoky, and Rady, 2019).

Similarly, triazole fungicides are also called stress protectants because of their natural ability to induce abiotic stress tolerance by increasing antioxidant enzymes and molecules in stress-affected plants. They also have plant growth-regulating properties apart from disease protectants (Jaleel et al., 2007; Hassanpour et al., 2012; Desta and Amare, 2021). Triazole fungicide (penconazole) increased the shoot dry weight, root fresh weight and relative water content in pennyroyal under water deficit stress (Hassanpour et al., 2012).

Likewise, the application of pyraclostrobin + epoxiconazole, derived from the strobilurin and triazole family during induced drought conditions has shown increased stomatal conductance and photosynthesis intensity of ‘Ambrosini’ (stay-green) varieties of corn (*Zea mays* L.) (Sulewska et al., 2019). The use of such fungicides in corn during drought stress had a substantial impact on plant gas exchange, plant water usage efficiency, chlorophyll fluorescence, and fresh and dry plant biomass (Sulewska et al., 2019).

The same mixture of pyraclostrobin (12.5% w/w) + epoxiconazole (4.7% w/w) also called Opera, has positive physiological and morphological effects on soybeans (*Glycine max* L.) thriving in a water stress environment (Kanungo et al., 2021). Through the modification of biochemical and antioxidant properties, triazole such as hexaconazole and tebuconazole reduced the oxidative stress thereby mitigating the negative effects of drought stress in okra (*Abelmoschus esculentus*

L.). As a result, treatment of triazole has the potential to help overcome the challenges posed by drought stress (Rabert et al., 2013).

Objectives

A set of studies were carried out to assess the new at-plant fungicide, Xyway LFR^{@FMC} rates under varying environmental conditions and water regime scenarios to provide Tennessee corn producers with updated information on the Xyway LFR^{@FMC} fungicide and its interactions with the soil water availability. This information may help producers achieve greater yield stability and profitability under variable rainfall patterns and water regimes. This main objective is further broken down into three primary objectives:

- (1) to assess the potential of Xyway LFR^{@FMC}, at-plant fungicide to improve the corn water saving trait under water-deficit stress and well-watered conditions in controlled environments
- (2) to assess the Xyway LFR^{@FMC}, at-plant fungicide contribution in any plants physiological, growth, and yield responses to three water-regime scenarios in large plots' field trials.
- (3) by conducting an economic analysis, determine the effect of Xyway LFR^{@FMC}, at-plant fungicide application and three water regimes on economic net returns under field conditions.

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CHAPTER II
SAVING WATER UNDER WATER DEFICIT CONDITIONS BY APPLICATION OF
XYWAY LFR^{@FMC}: GREENHOUSE STUDIES

A version of this chapter was originally published by Isha Poudel and Avat Shekoofa:

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Author contribution

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Abstract

Triazole fungicides are often referred to as "stress protectants" due to their ability to enhance the abiotic stress tolerance of plants. Xyway LFR^{@FMC} (flutriafol) is a triazole and at-plant applied fungicide. The Xyway LFR^{@FMC} fungicide that has been introduced into corn production system starting 2020 has been observed to improve plant performance under drought stress conditions. In this study, we accessed the potential of Xyway LFR^{@FMC} product in altering the ability of corn (*Zea mays L.*) plants to control transpiration rates under water deficit-stressed (DS) conditions. Plants were grown under greenhouse conditions treated with Xyway LFR^{@FMC} at 0.56, 0.77, and 1.11 L ha⁻¹ in experiment 1 and 1.11 and 1.26 L ha⁻¹ rates in experiment 2. Plants treated with 1.11 L ha⁻¹ reduced the amount of water loss in response to DS and had the highest fraction of transpirable soil water (FTSW) thresholds. There was an increase in shoot hydraulic conductance (K_{shoot}) by 1.11 L ha⁻¹ in both experiments. Plants treated with 0.77 and 1.11 L ha⁻¹ had higher LWP rates compared to other treatments under DS conditions. In conclusion, the most likely chemical ingredient in Xyway LFR^{@FMC} fungicide triggering the transpiration control response was flutriafol. This is the first report that early stomatal closure under soil drying conditions can be induced by the application of Xyway LFR^{@FMC} fungicide. Application of at-plant fungicide, Xyway LFR^{@FMC} has potential to reduce the negative effect of water-deficit stress in corn along with improving plants growth and physiological performance.

Introduction

Corn (*Zea mays* L.) is one of the strategic crops in the world and is the third most important crop after wheat (*Triticum aestivum* L.) and rice (*Oryza sativa* L.) (Nuccio et al., 2015; Suganya, Saravanan and Manivannan, 2020; Abbas et al., 2021). It can play an essential role in ensuring food and nutrition security due to its high productivity and production potential. However, corn production is significantly impacted by environmental factors, with water deficit stress being identified as one of the most crucial factors that negatively affect it (Zhang et al., 2018). Drought stress in corn can affect anatomical, morphological, physiological, and biochemical processes, restricting corn growth (Cakir, 2004; Kapoor et al., 2020; Noein and Soleymani, 2022). Drought stress impacts corn yield and yield attributing features in addition to its effect on vegetative growth and development (Moser et al., 2006; Rivera-Hernandez et al., 2010).

Several agronomic strategies have been developed to minimize the effect of drought stress in corn. In case of limited water availability, applying available water in the crucial stages like knee high, flowering, and grain filling can help minimize the negative impact to some extent (Campos et al., 2004; Sah et al., 2020). Under conditions of limited water availability, the cultivation of drought-tolerant corn hybrids can assist in sustaining high yields (Mounce et al., 2016; Zhao et al., 2018; Schwartz et al., 2022; Messina et al., 2015; Shekoofa et al., 2015).

Similarly, drought stress can be mitigated by using bio-stimulators. Pre-treatment with melatonin (bio-stimulant) at a concentration of 100 μ M was found to mitigate the negative impact of drought stress in tomato plants (*Solanum lycopersicum* L.) (Altaf et al., 2022).

Additionally, plant health/protection products were found to improve the water saving potential of the crops and improve the crop performance and yield. Plant health product Daconil Action® was found to limit the transpiration under high vapor pressure deficit (VPD, kPa) in

creeping bent grass (*Agrostis stolonifera* L.) (Shekoofa et al., 2016). Seed treated with *Trichoderma asperellum* L., a plant growth-promoting fungus, improved leaf relative water content, water use efficiency and photosynthesis of corn under drought conditions (Estévez-Geffriaud et al., 2020). Some classes of fungicide, such as triazoles and strobilurins, not only alleviate fungal diseases but they also regulate various physiological and biochemical phenomena. As a result, they have been found to improve the growth and yield of plants under abiotic stresses (Venancio et al., 2003; Amaro et al., 2020; Ijaz et al., 2022).

Triazole fungicides are also called stress protectants because of their natural ability to induce abiotic stress tolerance by increasing antioxidant enzymes and molecules in stress-affected plants. They also have plant growth-regulating properties apart from disease protectants (Jaleel et al., 2007; Hassanpour et al., 2012; Desta and Amare, 2021). Triazole fungicide (penconazole) increased the shoot dry weight, root fresh weight, and relative water content in pennyroyal (*Mentha pulegium* L.) under water deficit stress (Hassanpour et al., 2012). Likewise, the application of pyraclostrobin + epoxiconazole, derived from the strobilurin and triazole family, during induced drought conditions has shown increased stomatal conductance and photosynthetic rate of ‘Ambrosini’ (stay-green) varieties of corn (Sulewska et al., 2019). The use of such fungicides in corn during drought stress had a substantial impact on plant gas exchange, plant water usage efficiency, chlorophyll fluorescence, and fresh and dry plant biomass (Sulewska et al., 2019). The same mixture of pyraclostrobin (12.5% w/w) + epoxiconazole (4.7% w/w) also called Opera, has positive physiological and morphological effects on soybean (*Glycine max* L.) thriving in a water stress environment (Kanungo et al., 2021). Through the modification of biochemical and antioxidant properties, triazole such as hexaconazole and tebuconazole reduced the oxidative stress thereby mitigating the negative effects of drought stress in okra (*Abelmoschus esculentus*

L.). As a result, treatment of triazole has the potential to help overcome the challenges posed by drought stress (Rabert et al., 2013)

A new triazole class of fungicide, Xyway LFR^{@FMC} is also called demethylation inhibitor (DMI) fungicide. It is a systemic fungicide and the active ingredient in Xyway brand fungicides is flutriafol. This fungicide was launched by FMC Technologies, Inc. in August 2020 with the aim of foliar disease protection from the inside out, from root to tassel, and from stalk to leaf. Our hypothesis was that, along with disease protection, Xyway LFR^{@FMC} fungicide can improve the corn plants water saving potential and protect them from the adverse impact of water deficit stress similar to the other triazole class of fungicides. Hence, our specific objectives were to (i) document possible differences between the Xyway LFR^{@FMC} fungicide treated and non-treated/check corn plants in the transpiration response curves to soil drying, and (ii) determine possible difference between the fungicide treated and non-treated/check corn plants in their soil water extraction and corn water saving trait. These objectives were pursued in experiments conducted in controlled and progressively soil drying systems in the greenhouse.

Materials and methods

Experiment 1

A greenhouse study was conducted at the West Tennessee Research and Education Center (WTREC), Jackson, Tennessee, USA in September 2021. The air temperature in the greenhouse was set to a minimum of 25 and a maximum of 35 °C and the photoperiod was set to 14 hours' light provided at 600–650 $\mu\text{mol m}^{-2} \text{s}^{-1}$. During the study period, the temperature and relative humidity were measured every five minutes using a universal serial bus (USB) data logger (MicroDAQ, Contoocook, NH, USA). Treatments used in the study include three recommended rates of Xyway LFR^{@FMC}: no fungicide (check/water), 0.56, 0.77, and 1.11 L ha⁻¹. There were 9

replications per treatment and all pots were completely randomized. Corn seeds DKC64-35 (DEKALB® Corn hybrid, DKC64-35RIB Brand Blend, DeKalb Genetics corporation, DeKalb, IL, USA) were sown in 3-liter pots (Nursery supplies Inc., Chambersburg, PA) filled with sand (50%) and silt loam (50%). Silt loam consisted of 264.5 kg ha⁻¹ of phosphorus and 365.4 kg ha⁻¹ of potassium with a pH of 6.4. Five seeds were sown per pot at a depth of 2.5 cm. All three fungicide rates were diluted with 20 mL of distilled water and a syringe was used for the precise application of fungicide rates on seeds at planting. Whereas for the no fungicide treatment (check), water using a syringe was applied to seeds at planting. Two weeks after sowing (WAS), the plants were thinned to one plant per pot. The plants were watered every other day and fertilized twice using Maxi-Grow (General Hydroponics) nutrients with 10-5-14 (N-P-K) until 3 WAS.

A dry-down experiment was initiated almost 4 WAS. In this experiment, the soil was dried but progressively, and water loss through transpiration was measured gravimetrically. The day before the initiation of the soil drying down experiment, all pots were over-watered until dripping and allowed to drain overnight. The following morning, each pot's mouth was sealed with a 7.6 cm thick Airtex high-density foam (Joann Inc., Hudson, OH, USA). Pots were then placed into two double-bagged 15-liter plastic bags (Wal-Mart Stores, Inc., Bentonville, AR, USA) (Figure 1). A plastic tube (13-mm diam. × 126-mm long) was inserted adjacent to the plant stem to make the daily watering easier (Figure 1, all tables and figures are located in the appendix after each chapter). The initial weight of each pot was measured immediately after bagging. Every other day, pots were weighed between 13:00 and 14:00 hours (Central U.S. Time) to estimate gravimetric water loss through transpiration. After calculating the daily transpiration rate (TR) of each individual plant for three days, plants were assigned to one of two treatments: water-deficit stressed (DS) or well-watered (WW). Within each treatment, six plants were assigned to the DS treatment

and three were assigned to be WW, which served as a reference for calculating the normalized transpiration rate (NTR). Normalized transpiration rate is a relative transpiration ratio of DS to WW plants normalized for plant size and environmental conditions (Shekoofa et al., 2013).

The TR data were subjected to two normalizations, first normalization was done to reduce the large variations in daily TR across days. The second normalization was done to reduce the variation in transpiration ratio among individual plants (Shekoofa et al., 2013; Rosas-Anderson et al., 2014). After weighing the plants, water was added to maintain the WW plants within 550 mL of pot capacity, based on the initial pot weight that was established at the beginning of the experiment. Soil water was allowed to gradually transpire at a rate of no greater than 450 mL day⁻¹ from the DS plants in order to simulate a prolonged development of water-deficit stress. Water was only added to the DS plants if daily water loss exceeded 450 mL day⁻¹ (Sheldon et al., 2021).

Data were collected for each pot until the plant's NTR was less than or equal to 0.10, which was considered the endpoint of transpirable soil water. The FTSW was calculated as the difference between daily weight and final weight, divided by the total transpirable water using the following equation (Ray and Sinclair, 1998; Shekoofa et al., 2013):

$$\text{FTSW} = (\text{daily weight} - \text{final weight}) / (\text{initial weight} - \text{final weight})$$

Plants transpiration rate data from each fungicide treatment under water regimes were combined by treatment and initially subjected to a two- segment linear regression analysis (GraphPad Prism version 8, GraphPad Software). The FTSW threshold was between the two segments where the NTR decrease was initiated. When all the DS plants reached NTR less than or equal to 0.1, plant shoot hydraulic conductance and leaf water potential (LWP) were measured for all treatments.

A hydraulic conductance flow meter (HCFM, Dynamax, Inc., Houston, TX, USA) was used to measure the plant shoot hydraulic conductance. HCFM records water flux/flow (F , kg s^{-1}) and pressure (P , kPa) (Tyree et al., 1995; Tsuda and Tyree, 2000; Judd et al., 2016; Wedegaertner et al., 2022). The measurement was initiated by cutting the plant's shoot 2 to 3 cm above the soil surface. Then, the cut shoot was submerged into the deionized water and again cut 1 cm above the original cut. The HCFM connection couple was immediately attached to the shoot. The shoot connected with a couple was taken out of the water and kept horizontally on a flat surface (Figure 2). Deionized water was then forced to flow through the shoot system under steadily increasing pressure. The measurement was done in "transient mode" (Tyree et al., 1995) in which pressure was increased to 500 kPa with a constant rate of $0.5\text{--}0.8 \text{ kPa s}^{-1}$ while measuring F and P every 3 s. Each measurement required 80-150 s. Shoot hydraulic conductance (K_{shoot}) was computed from the slope of linear regression between water flux/flow versus pressure (Tyree et al., 1995; Tsuda and Tyree, 2000; Judd et al., 2016).

Pressure chamber, model 1505D (PMS Instrument Company, Albany, OR, USA) was used to measure LWP. For the LWP measurement each time, two healthy and fully developed leaves were selected per plant. A section of the leaf, 10-20 cm from the tip of the leaf blade was cut and the cut leaf was placed in a plastic bag where the cut end of the leaf blade was positioned outside of the plastic bag. Then, the cut end of the leaf blade was placed in the pressure chamber while the cut end extending outside the chamber and exposed to atmospheric pressure. The pressure was increased around the leaf until xylem sap appeared at the cut end of the leaf and then, the pressure was recorded (Boyer, 1967; Ferry-Abee, 2016).

After the initiation of the dry-down experiment, at 7 WAS plant height, leaf number, and stem diameter data were collected. A vernier caliper (Penn tool co., Maplewood, NJ, USA) was

used for measuring plants stem diameter. All parameters were measured from 11:00 A.M until 3:00 P.M under controlled greenhouse condition. After collecting all the data, plants were cut above the soil surface and dried in an oven at 60 °C to record shoot dry weight. At the end, all the data were analyzed using JMP (version Pro 15, SAS Institute Inc., Cary, NC). ANOVA of all the physiological and yield components between treatment were calculated. Mean value of parameters with statistically significant difference ($p < 0.05$) were separated using Tukey's HSD test.

Experiment 2

The original experiment was repeated during January 2022 with the addition of a higher rate of Xyway LFR^{@FMC}. Therefore, the fungicide treatments included two recommended Xyway LFR^{@FMC} rates: no fungicide (check/water), 1.11 and 1.26 L ha⁻¹. There were 12 replications per treatment. Among the total plants per treatment, 3 plants were selected as DS and 9 plants were selected as WW. Growth parameters data were collected after initiation of dry down experiment at 7 WAS. All the other data were collected similar to experiment 1. The data were analyzed using JMP (version Pro 15, SAS Institute Inc., Cary, NC) and treatment means were separated using Tukey's HSD test ($p < 0.05$).

Results

Experiment 1

The FTSW thresholds were higher for all the Xyway LFR^{@FMC} fungicide treated plants compared to check. However, corn plants treated with 1.11 L ha⁻¹ fungicide rate had the lowest transpiration and highest water saving with the FTSW threshold of 0.62, R² value of 0.96 and confidence interval from 0.57 to 0.67 (Table 1). The amount of water loss was significantly lower for the plants treated with 1.11 L ha⁻¹ of fungicide rate at 1st week of drought compared to check/water (Figure 3a).

The K_{shoot} values for the water-deficit stressed (DS) plants treated with varying fungicide rates were greater than check/water and the highest was observed when 1.11 L ha^{-1} rate was applied (Table 2; Figure 2a). A similar pattern was observed for the K_{shoot} values among well-watered (WW) plants when treated with the higher fungicide rate (1.11 L ha^{-1}) (Table 2; Figure 4b).

When plants were treated with fungicide rates, 0.77 and 1.11 L ha^{-1} at planting their LWP improved by 17 and 20 (%), respectively compared to check/water under DS conditions (Table 2). We noticed a similar pattern for the LWP improvement when plants were under WW conditions but treated with fungicide rates (Table 2).

The analysis of variance (ANOVA) showed that under DS and WW conditions, there were not any significant differences among plant height and leaf number data when considering the fungicide treatments compared to the check/water (Table 2). Although, the number of leaves were numerically higher when plants were treated with 0.77 and 1.11 L ha^{-1} fungicide rates compared to check/water, under DS conditions (Table 2).

The fungicide treatments at 0.77 and 1.11 L ha^{-1} rates increased the plants stem diameter compared to check/water and the lowest fungicide rate (i.e., 0.56 L ha^{-1}) (Table 2). However, plants treated with the highest rate of fungicide (i.e., 1.11 L ha^{-1}) had the greatest stem diameter under DS conditions (Table 2). While the DS condition significantly reduced plants stem diameter when comparing with WW plants, the DS plants treated with 1.11 L ha^{-1} fungicide rate had the stem diameter as equal as possible to check/water treated WW plants (Table 2). Under WW conditions, all plants treated with fungicide rates had numerically higher stem diameter compared to check/water. Plants treated with 1.11 , 0.77 , and 0.56 L ha^{-1} had 24.1, 12.0, and 3.1(%) higher stem diameters, respectively compared to check/water (Table 2). Overall, the impact of fungicide treatments on plants shoot dry weight wasn't significant compared to check/water. But under WW

conditions plants treated with all fungicide rates had shoot dry weight data ranging from 48.67 to 49.00 g that were numerically higher than check/water (46.33 g) (Table 2).

Experiment 2

Similar to experiment 1, the FTSW threshold result for plants treated with 1.11 L ha⁻¹ fungicide rate was the highest in experiment 2 (Table 1). The FTSW threshold value for the initiation of stomata closure was 0.49 for plants treated with 1.11 L ha⁻¹ with the highest R² value, 0.95 and confidence interval ranged from 0.44 to 0.53 (Table 1). The amount of water loss was 18.2% lower for plants treated with 1.11 L ha⁻¹ of fungicide rate compared to check/water after one-week of drought development (Figure 3b).

Under the DS condition K_{shoot} value was the highest when plants were treated with 1.11 L ha⁻¹ fungicide rate compared to all other treatments (Table 3; Figure 4c). Under the WW condition, K_{shoot} values for plants treated with fungicide rates were higher than check/water (Table 3; Figure 4d). A similar pattern was observed in experiment 1 (Figure 3a and b).

The ANOVA revealed that under DS and WW conditions there were not any significant differences among LWP values for plants treated with the fungicide rates compared to check/water. But under the DS condition, plants treated with fungicide rates, 1.11 and 1.26 L ha⁻¹ at planting had 12 and 12.5 (%) higher LWP, respectively compared to check/water (Table 3).

Additionally, in experiment 2 under the DS condition, plants treated with the highest rate of fungicide, 1.26 L ha⁻¹ at planting were significantly taller than check/water (Table 3). Under DS and WW conditions, plants treated with fungicide rates had higher leaf numbers compared to check/water (Table 3).

Plants shoot dry weight were increased by both 1.11 L and 1.26 L ha⁻¹ fungicide rates. Under the DS condition, the highest fungicide rate, 1.26 L ha⁻¹ significantly increased plants shoot dry weight compared to check/water (Table 3).

Discussion

Fungicides protect plants against pathogens, but various active ingredients also offer plant health benefits and have been observed to improve plant performance under water-deficit conditions (Gilley and Fletcher, 1997; Gornik, Grzesik, and Romanowska-Duda, 2008; Rabert et al., 2013). In our study under DS conditions, most likely chemical ingredient in Xyway LFR^{@FMC} fungicide triggering the transpiration control response was flutriafol, a triazole class fungicide, demethylation inhibitor (DMI). Inhibition of demethylation increases the level of methylation in the plant (Li, Kumar, and Qian, 2018). DNA methylation is a heritable epigenetic modification that can regulate gene expression and genome stability. In plants, changes in DNA methylation patterns have been reported in response and adaptation to various abiotic stresses, including drought stress (Liang et al., 2014; Sun et al., 2022). Moreover, DNA methylation can also regulate the expression of genes involved in stress signaling and stress-responsive pathways, such as ABA (abscisic acid) signaling, antioxidant defense (Chang et al., 2020) regulating stomatal conductance and water use efficiency (Ding et al., 2022).

Our study revealed that application of Xyway LFR^{@FMC} fungicide at planting improved the corn plants water-saving potential by controlling transpiration rate and limiting stomatal conductance (Table1, Figure3). Xyway LFR^{@FMC} treatments at planting, specifically 1.11 L ha⁻¹ rate, increased the FTSW threshold compared to check/water (Table 1, Figure 3). The value of the FTSW threshold for the plants treated with 1.11 L ha⁻¹ was significantly higher than check/water (CI at 95%, $P < 0.05$) (Table 1). The early stomata closure during a progressive soil drying

condition has now been identified as a key genetic trait in the development of important drought-tolerant crops (Shekoofa, Balota, and Sinclair, 2014; Sinclair, 2017; Sheldon et al., 2021, Purdom et al., 2022; Wedegaertner et al., 2023).

In a study conducted by Sulewska et al. (2019), they found that the ‘Ambrosini’ (stay-green) variety of corn treated with pyraclostrobin + epoxiconazole fungicide exhibited defensive reactions to stress as early as 48 hours. They hypothesized that this may be due to an early “switching on” of the defense mechanisms of the plants and preparing them for future stress. Similarly, in a study by Fuller and Zajicek (1995) uniconazole-treated plants reduced the water usage by up to 35% in vinca (*Vinca major* L.) by lowering the stomatal conductance. This study supports our finding that fungicides application can regulate stomatal conductance and induce an early response to drought stress conditions.

Furthermore, triazole fungicide induces a number of biochemical responses in plants which also include transient increase in ABA under drought scenarios (Asare-Boamah et al., 1986; Zhu et al., 2004; Batlang, 2006; Gopi et al., 2007; Desta and Amare, 2021). One of the effects of ABA accumulation is the closure of stomata, which helps to reduce water loss by transpiration (Lim et al., 2015; Bharath, Gahir and Raghavendra, 2021). Triazole compound, triadimefon, and Paclobutrazol, partially closed the stomata by increasing ABA content and consequently reducing transpiration and water loss from plant leaves (Gopi et al., 2005; Petit et al., 2012; Soumya, Kumar, and Pal, 2017). Mohan et al. (2020) also observed influence in the stomata structure and function by paclobutrazol. Triazole treatment reduces the water requirement of plants compared to untreated plants, primarily due to a decrease in stomatal conductance (Fuller and Zajicek, 1995; Ijaz et al., 2022). Therefore, there may be a possibility that the application of Xyway LFR^{@FMC} fungicide also resulted in increasing ABA production with the onset of water deficit-stress in our

study and incorporated into early stomatal closure. Thus, further studies are needed to access the chemical signaling pathway regulating stomatal activities when using Xyway LFR^{@FMC} fungicides.

In our study there was an overall increase in the FTSW thresholds in experiment 1 compared to experiment 2 that can be due to an increase in the vapor pressure deficit (VPD, kPa) in controlled environment experiment 1. Figure 5 illustrates that in experiment 1, the daytime VPD after initiation of dry down increased from 1.98 in day 8 to 3.58 kPa in day 9 and remained high from that point of the dry down experiment to the end (Figure 5 a). Plants may have experienced more stress due to this sudden and abrupt increase in VPD compared to the VPD rates at the initial days of dry down. Additionally, from day 9 to 13 of dry down, the night-time VPD was higher in experiment 1 compared to experiment 2 (Figure 5b). Hence, higher VPD rates during critical period of water-deficit stress may have increased the FTSW threshold in experiment 1. Thus, a substantial change in the atmospheric VPD affected the FTSW threshold. According to the studies carried out by Manandhar et al (2017) and Devi and Reddy (2020) the FTSW threshold increases with an increase in VPD.

We noticed our corn plants treated with fungicide rates had higher shoot hydraulic conductance rates under DS conditions. The application of Xyway LFR^{@FMC} impacted, and lowered, the water loss during early water deficit stress (i.e., week one of drought) (Figure 3) and conserved water. Thus, it could have helped maintaining the water flow rate under extreme water limited conditions at the end of drying cycle when flow rates were measured (Figure 4). Triazole fungicide inhibits sterol synthesis which is an important component of cell membranes (Stenzel and Vors, 2019; Sun et al., 2021). Plant sterols, like other types of sterols, are essential constituents of cellular membranes. They play a critical role in regulating the permeability and fluidity of the

membrane (Schaller, 2003; Dufourc, 2008; Valitova, Sulkarnayeva, and Minibayeva, 2016). Inhibition of sterol biosynthesis by triazole fungicide disturbs the membrane function and permeability. It's possible that the inhibition of sterol biosynthesis by Xyway LFR@^{FMC} fungicide has changed the membrane permeability and increased the shoot hydraulic conductance.

Our observation that the application of Xyway LFR@^{FMC} induced the plants early stomatal closure and conserved the water under extreme water-deficit stressed conditions, can also be explained by the potential impact of Xyway LFR@^{FMC} in reducing the xylem cavitation/embolism caused by severe water-deficit stressed condition. Thus, treated plants with varying fungicide rates maintained the high shoot hydraulic conductance under DS conditions. A study by Li, Sperry, and Shao (2009) reported that corn hybrid 'Pioneer 3902' had greater resistance to cavitation and hence maintained higher conductivity on both a stem area and leaf area. Water-deficit stress conditions can cause significant tension, which may result in a considerable reduction in hydraulic conductivity due to embolism (Sperry and Tyree, 1990; Yuksel, 2023).

Our study revealed that plants treated with 0.77 and 1.11 L ha⁻¹ had higher LWP rates compared to other treatments under DS conditions. In a study by Zhu et al. (2004), they reported that the leaf water potential of the apple cultivar Red Elstar/M9 (*Malus domestica* L.), decreased significantly when subjected to drought conditions. However, when treated with paclobutrazol, the reduction in leaf water potential was noticeably less under drought. Hassanpour et al (2012) found that penconazole increased the relative water content in pennyroyal (*Mentha pulegium* L.) under water stress condition. The increase in relative water content generally leads to an increase in LWP. In a study by Premachandra, Chaney and Holt (1997), the impact of flurprimidol on plant water relations was studied in one-year-old white ash (*Fraxinus americana* L.) seedlings exposed to soil water deficits. Under non-irrigated conditions ash seedlings treated with flurprimidol had higher

leaf water potential, turgor, and leaf relative water content than non-irrigated ash seedlings without flurprimidol. These findings confirm that triazole fungicides can improve plants' LWP, especially under water-deficit conditions.

Our study demonstrated that plants treated with 1.11 and 1.26 L ha⁻¹ fungicide rates had greater plant height, leaf number, stem diameter and shoot dry weight compared to check plants. Under DS conditions, plants treated with 1.11 L ha⁻¹ rate and untreated/check had 46.0 and 62.5 (%) shoot dry weight reduction compared to treated/check plants under well-watered conditions. That confirms 16.5 (%) less shoot dry weight (i.e., biomass) reduction for treated plants with 1.11 L ha⁻¹ rate under DS conditions.

Triazole fungicides, contrary to their growth retarding effects, have been found to promote plant growth in certain cases (Yang et al., 2014). Triadimefon treatment increased dry weight of tomato under drought stressed conditions (Mohamadi and Rajaei, 2013). In a study by Sulewska et al. (2019), they reported that the application of pyraclostrobin + epoxiconazole fungicide during induced drought conditions in corn had a positive effect on fresh and dry plant biomass. Severe drought conditions led to the reduction in the survival rate of wheat seedlings, but treatment with triazoles (paclobutrazol, propiconazole and tetraconazole) resulted in the highest percentage of survival, and the greatest regrowth of shoots upon rewatering (Gilley and Fletcher, 1997; Shell, 2013). These studies support our current research results and confirm that Xyway LFR[®]_{FMC} fungicide has the potential to improve plant growth and biomass and increase water saving, a beneficial impact during drought stress with inducing early stomatal closure under water-deficit conditions.

Conclusion

Corn treated with 1.11 L ha⁻¹ Xyway LFR^{@FMC} had significantly higher FTSW thresholds and less water loss compared to check/water under DS conditions. Plants shoot hydraulic conductance and LWP were higher at the rates of 1.11 and 1.26 L ha⁻¹ compared to check under DS conditions. Plants had higher leaf number and stem diameter under DS conditions when treated with 1.11 L ha⁻¹ fungicide rate in experiment 1. Similarly, plant height and shoot dry weight were significantly increased by 1.26 L ha⁻¹ under DS conditions, in experiment 2. These results indicated the potential benefits of Xyway LFR^{@FMC} application at planting for corn plant health management with improving plant growth and water-saving potential under DS conditions. Further studies are needed to assess the effect of Xyway LFR^{@FMC} application at planting on plant growth, physiology, and yield under field conditions.

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Appendix

Table 1. The table contains days to reach endpoint of dry down, fraction of transpirable soil water (FTSW) threshold, confidence interval, and their R^2 for transpiration response of corn plants treated with four different rates of Xyway LFR^{@FMC} fungicide: 0.56, 0.77, 1.11, and 1.26 L ha⁻¹, and no fungicide (check/water) in both sets of progressive soil drying experiments.

Fungicide Treatment	Days to endpoint of dry down	FTSW threshold	Confidence interval (CI) at 95% ($P < 0.05$)	R^2
Experiment 1				
Check/water	13.0	0.51	0.46 to 0.56	0.94
0.56 L ha ⁻¹	12.3	0.57	0.54 to 0.61	0.98
0.77 L ha ⁻¹	13.3	0.57	0.53 to 0.61	0.97
1.11 L ha ⁻¹	13.5	0.62	0.57 to 0.67	0.96
Experiment 2				
Check/water	14.4	0.36	0.28 to 0.44	0.79
1.11 L ha ⁻¹	13.8	0.49	0.44 to 0.53	0.95
1.26 L ha ⁻¹	14.4	0.38	0.33 to 0.43	0.91

Table 2. The table contains shoot hydraulic conductance (K_{shoot}), leaf water potential (LWP), height, leaf number, stem diameter and shoot dry weight of corn plants under water-deficit stressed condition and well-watered conditions treated with three different rates of Xyway LFR^{@FMC} fungicide: 0.56, 0.77, 1.11 L ha⁻¹, and no fungicide (check/water) (Experiment 1).

Fungicide treatment	K_{shoot} (kg s ⁻¹ mPa ⁻¹)	LWP (mPa)	Height (cm)	Leaf number	Stem diameter (cm)	Shoot dry weight (g)
Water-deficit stressed						
Check/water	5.55×10^{-8}	-2.60 ^{ns}	118.54 ^{ns}	11.33 ^{ns}	1.88 ab	17.67 ^{ns}
0.56 L ha ⁻¹	1.92×10^{-7}	-3.29	119.38	11.00	1.75 b	15.80
0.77 L ha ⁻¹	1.43×10^{-7}	-2.15	118.95	11.50	1.88 ab	16.00
1.11 L ha ⁻¹	2.75×10^{-7}	-2.09	110.06	11.83	2.02 a	17.00
Well-watered						
Check/water	9.95×10^{-8}	-1.38 ^{ns}	138.86 ^{ns}	14.00 ^{ns}	2.08 ^{ns}	46.33 ^{ns}
0.56 L ha ⁻¹	1.18×10^{-7}	-0.58	132.08	14.00	2.15	48.67
0.77 L ha ⁻¹	8.51×10^{-8}	-0.64	131.24	13.67	2.34	48.67
1.11 L ha ⁻¹	1.93×10^{-7}	-0.95	127.84	14.00	2.59	49.00

Means followed by different letters within columns indicate significant difference at $p < 0.05$ Tukey HSD test for pair wise comparison.

^{ns}: not significant

Table 3. The table contains shoot hydraulic conductance (K_{shoot}), leaf water potential (LWP), height, leaf number, stem diameter, and shoot dry weight of corn plants under water-deficit stressed condition and well-watered conditions treated with two different rates of Xyway LFR^{@FMC} fungicide: 1.11, 1.26 L ha⁻¹, and no fungicide (check/water) (Experiment 2).

Fungicide treatment	K_{shoot} (kg s ⁻¹ mPa ⁻¹)	LWP (mPa)	Height (cm)	Leaf number	Stem diameter (cm)	Shoot dry weight (g)
Water-deficit stressed						
Check/water	5.80×10^{-7}	-3.02 ^{ns}	82.12 b	8.89 ^{ns}	1.46 ^{ns}	16.10 b
1.11 L ha ⁻¹	8.10×10^{-7}	-2.66	84.38 ab	9.00	1.47	17.67 b
1.26 L ha ⁻¹	1.25×10^{-7}	-2.64	99.62 a	9.56	1.44	23.33 a
Well-watered						
Check/water	1×10^{-7}	-0.62 ^{ns}	88.06 ^{ns}	11.67 b	2.34 ^{ns}	43.20 ^{ns}
1.11 L ha ⁻¹	7.5×10^{-8}	-0.97	104.14	13.00 a	2.32	46.97
1.26 L ha ⁻¹	6.5×10^{-7}	-0.75	106.68	13.00 a	2.02	45.47

Means followed by different letters within columns indicate significant differences at $p < 0.05$ Tukey HSD test pairwise comparison.

^{ns}: not significant

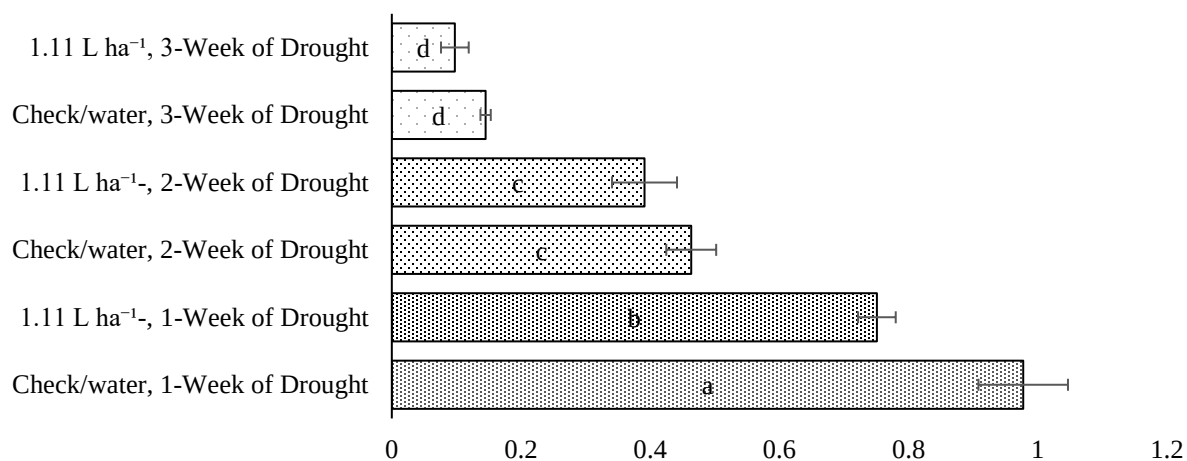


Figure 1. A greenhouse setup where each pot's mouth was sealed with 7.6 cm thick foam and placed into doubled-bagged 15 L plastic bags to allow water loss only through transpiration during the soil dry-down study



Figure 2. Measurement of shoot hydraulic conductance (K_{shoot}) using a hydraulic conductance flow meter (HCFM)

(a)



(b)

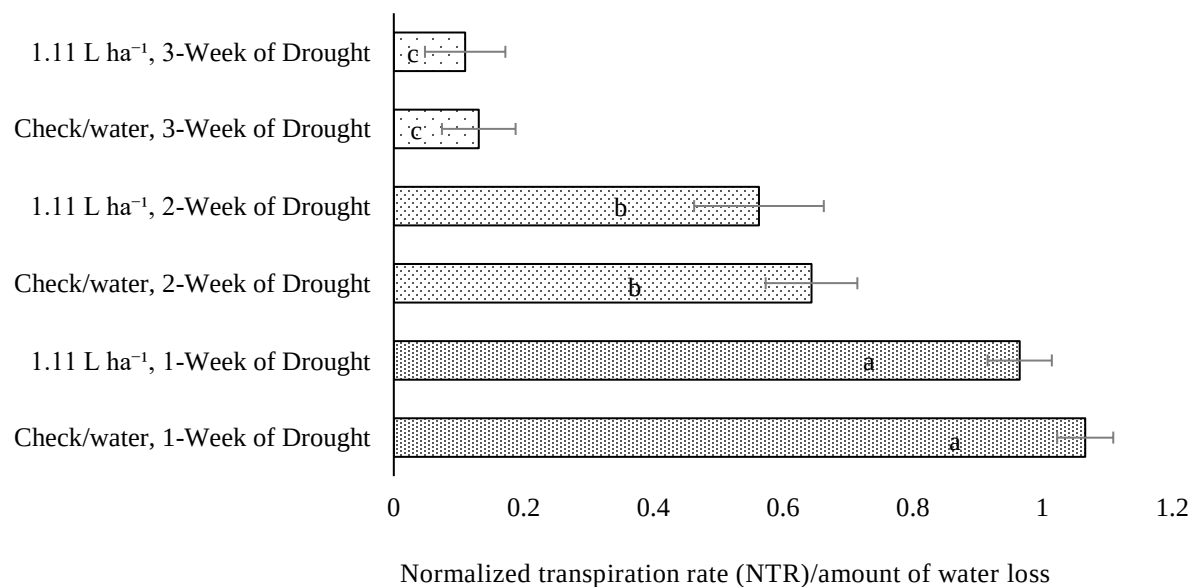


Figure 3. Normalized transpiration rate (NTR)/amount of water loss by plants treated with 1.11 L ha⁻¹ compared to untreated (check/water) plants in (a) experiment 1 and (b) experiment 2. Bars accompanied by the same letter are not significantly different (Tukey's HSD, $p < 0.05$)

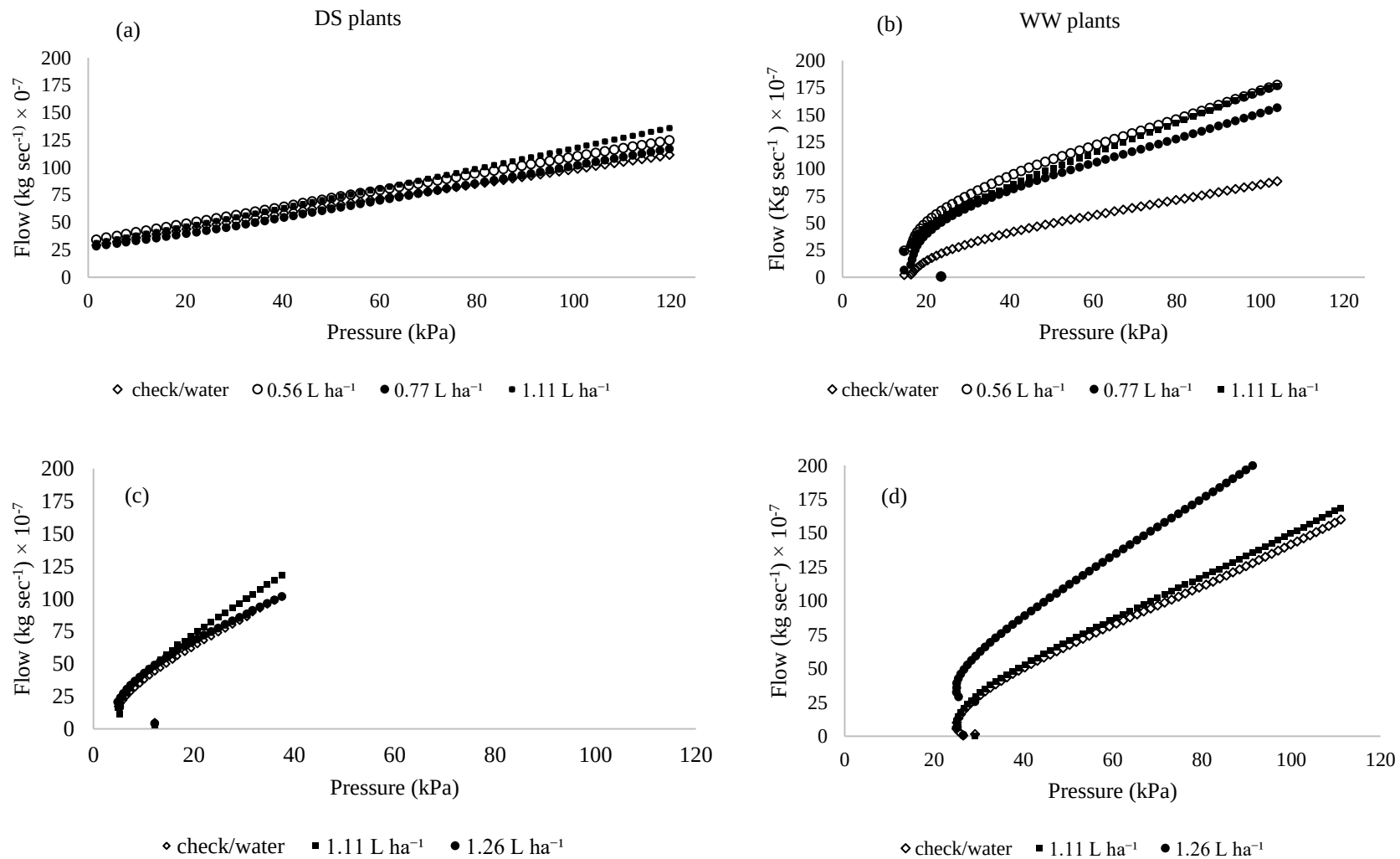


Figure 4. Shoot hydraulic conductance of water-deficit stressed (DS) and well-watered (WW) plants in experiment 1 (a, b) and experiment 2 (c, d) treated with varying rates of Xyway LFR[®]FMC fungicide: 0.56, 0.77, 1.11, and 1.26 L ha $^{-1}$ compared to no fungicide (check/water)

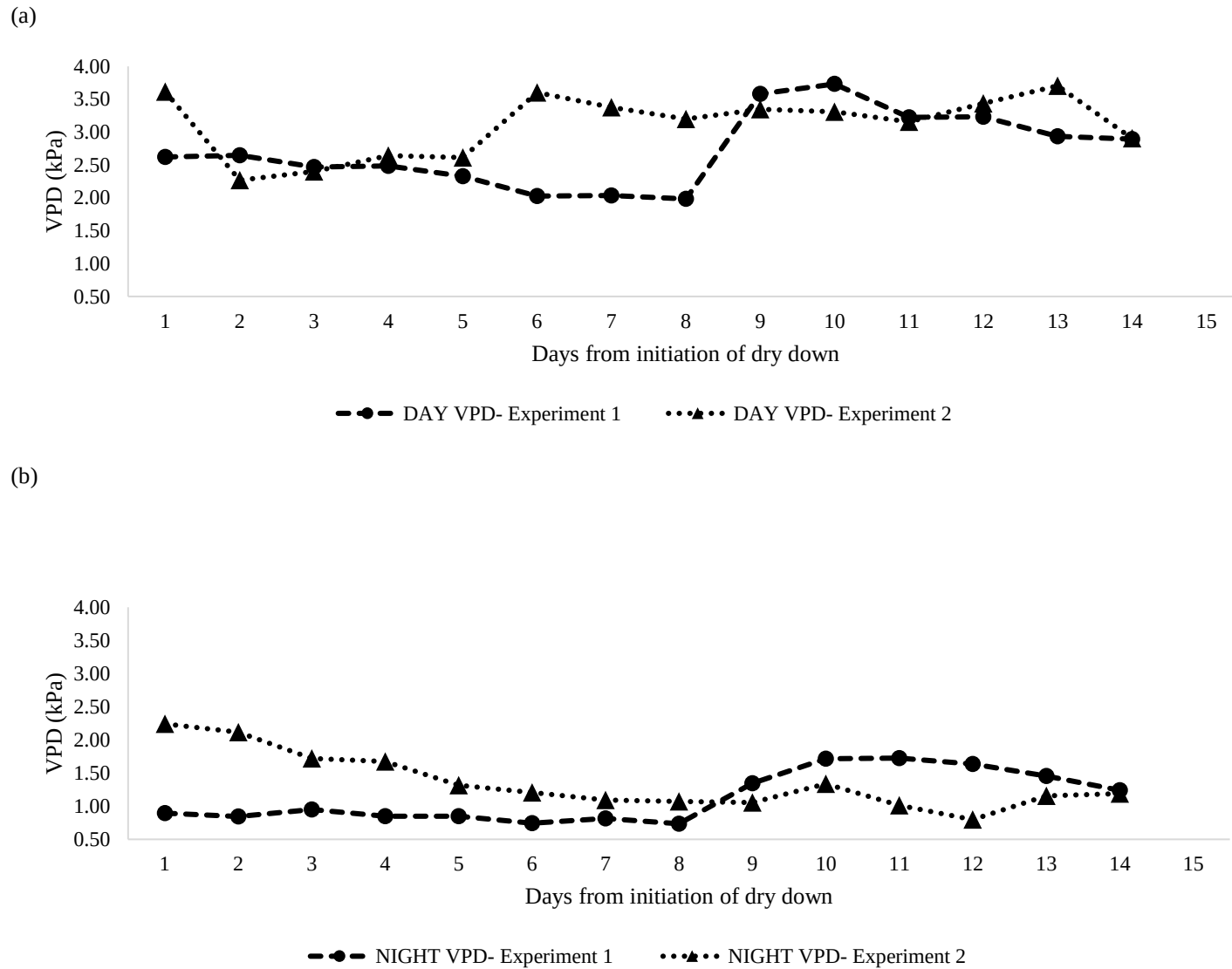


Figure 5. Day (a) and night (b) vapor pressure deficit (VPD) inside the greenhouse after initiation of the soil-dry down study in experiments 1 and

CHAPTER III
CAN CORN (*ZEAMAYS* L.) PRODUCTIVITY AND WATER USE BENEFIT FROM
THE APPLICATION OF XYWAY FUNGICIDE?

A version of this chapter is submitted for publication by Isha Poudel and Avat Shekoofa:

“Can corn (*Zea Mays* L.) productivity and water use benefit from the application of Xyway fungicide?” *Agrosystems, Geosciences & Environment*.

Abstract

A fungicide's ingredients can play a physiological role in crops water management decisions. In our study in 2021, greenhouse-grown plants treated with Xyway LFR^{@FMC} fungicide had a significant improvement in crop water-saving potential. In 2022 and 2023, a field study was initiated to assess the Xyway LFR^{@FMC} contribution to plant growth and yield under three different water regimes. The 1.11 L ha⁻¹ of Xyway LFR^{@FMC} and no- fungicide/check were the main plot effect. Three water regimes, high (HI), low (LO) number of irrigation events, and rainfed (RF) were the subplot effect. Physiological parameters were documented during the season. At harvest, yield and yield-components were determined. Plants treated with Xyway LFR^{@FMC} had significantly higher plant height, stem diameter, leaf water potential (LWP), and yield compared to check under all water regimes in 2022. And compared to check, they had 11.9, 13.4, and 18.3 (%) higher yield under RF, LO, and HI, respectively. In 2023, there were no significant differences observed for the yield components and growth parameters when fungicide treatments and water regimes interaction was considered. However, plants treated with the at-plant fungicide had higher number of rows per ear, kernel number per row, and cob diameter compared to check plants. There was no significant separation for yield among the water regimes in 2023. But the crop yield was overall higher for fungicide treated plots compared to check. Our results indicate that Xyway LFR^{@FMC}, at-plant fungicide has the potential to improve plant growth and protect yield when limited water is applied.

Introduction

Managing water for crop production is becoming more important as declining groundwater and frequent drought scenarios, due to climate change, are becoming common challenges (Bodner et al., 2015; Cotterman et al., 2018). Additionally, yield loss due to limitation in water availability is very common on many corn producing countries in the world including United States (Ao et al., 2020).

The question is how producers can reduce the potential for seasonal drought-related damages to their crops? Obviously, they have limited choices to make when it comes to water management practices. According to Waldlander et al. (2017), they can modify crop rotations to include less water-intensive crops (such as wheat), employ more water-conserving techniques (like conservation tillage), adopt more effective irrigation equipment, improve irrigation applications, or add supplemental irrigation.

But irrigation is either not available in some parts of the Corn Belt (McFadden et al., 2019), or would require investing in expensive irrigation equipment (Boyer et al., 2014). Producers in varying regions from semi-arid to sub-humid with access to limited rainfall from June to August often have to choose among options such as: only properly irrigating a portion of the field area, deficit-irrigating a larger crop area, switching to crops that require less water, or investing in more efficient irrigation technologies (Schaible & Aillery, 2012; Sheldon et al., 2023).

Research has shown that irrigation can increase crop yield (Boyer et al., 2014); however, scheduling the irrigation in sub-humid areas has proven difficult due to the high probability of seasonal rainfall. Since both excessive and insufficient water application can significantly reduce the potential for profitability, irrigation scheduling is necessary to control irrigation for maximum performance (Nafziger, 2016; Sheldon et al., 2023). Through site-specific variable rate irrigation

(VRI) management of crops, precision agriculture offers the ability to improve irrigation efficiency and can address inefficient irrigation scheduling (West & Kovacs, 2017). Soil water sensors can be used as a supplement to VRI systems to enhance irrigation scheduling (Bondesan et al., 2019).

According to West and Kovacs (2017), networks of remote soil water sensors efficiently provide information to VRI equipment and improve irrigation efficiency. In order to forecast when water is truly required during critical crop growth stages, soil water sensors can more accurately measure soil water availability in the soil profile (Bondesan et al., 2019; Shekoofa et al., 2020). Tassel emergence to the start of grain filling are the most crucial growth periods for corn; if water requirements are not satisfied during these phases, yield would drastically suffer (Cakir, 2004; Rudnick et al., 2017).

Furthermore, previous research results have identified that some classes of fungicide such as triazoles and strobilurins not only alleviate fungal diseases, but they also regulate various physiological and biochemical phenomena. They have been found to mediate the water-deficit stress and promote plant growth and yield (Amaro et al., 2020; Ijaz et al., 2022; Poudel & Shekoofa, 2024).

Triazole compounds are systemic fungicides that have plant growth-regulating properties and are called plant multi-protectants because of their natural ability to induce abiotic stress tolerance by increasing antioxidant enzymes and molecules in stress-affected plants (Jaleel et al., 2007; Fletcher et al., 2000). Triazoles modify the isoprenoid pathway and alter the level of certain hormones by suppressing gibberellin synthesis, decrease ethylene evolution, and increase cytokinin levels (Craven et al., 2017; Jaleel et al., 2008).

Triazole treatment modified biochemical content and antioxidant enzyme activity in okra (*Abelmoschus esculentus* L.) and resulted in a partial recovery of the damaging effect of drought stress by its influence on antioxidant system (Rabert et al., 2013). The mixture of strobilurin and triazole family, pyraclostrobin (12.5% w/w) + epoxiconazole (4.7% w/w) also called Opera, has positive physiological and morphological effects on soybean (*Glycine max* L.) under water stress environment (Kanungo et al., 2021).

A product called Xyway LFR^{@FMC}, a novel triazole class of fungicide, is also known as a demethylation inhibitor (DMI) fungicide. Flutriafol is the active ingredient in Xyway brand fungicides, which are systemic in nature. In August 2020, FMC Technologies, Inc. introduced this fungicide with the goal of protecting against foliar diseases from the root to the tassel and from the stalk to the leaf. Poudel and Shekoofa (2024) reported that in a set of greenhouse studies, the application of 1.11 L ha⁻¹ of Xyway LFR^{@FMC} fungicide at planting improved the corn plants water-saving potential by controlling transpiration rate and limiting stomatal conductance (Poudel & Shekoofa, 2024).

Therefore, a study was initiated to determine the effectiveness of an application of 1.11 L ha⁻¹ Xyway LFR^{@FMC}, at-plant fungicide under field conditions. The objective of this study was to assess the Xyway LFR^{@FMC}, at-plant fungicide contribution in any plants physiological, growth, and yield responses to three water-regime scenarios in large plots field trials.

Material and methods

Field description and experimental design

Field research was done in Milan Research and Education center (MREC), Milan, TN in 2022 and 2023 under center pivot irrigation system equipped with variable rate irrigation (VRI) technology. Corn hybrid, DKC64-35 (DKC64-35RIB Brand Blend, DeKalb Genetics corporation, DeKalb, IL,

USA) was sown, and fungicide was applied at-plant. Planting was initiated on May 10th in 2022 and April 26th in 2023 with a planting rate of 88,955 seeds ha⁻¹ for both years.

For both years, the soil type for the study site was providence silt loam (fine-silty, mixed, active thermic Oxyaquic Fragiudalfs) (Table 4). On May 7, 2022, and April 20, 2023, composite soil samples were collected from the experimental site locations at a depth of 0 to 15 cm. Ten soil probes of 2.5-cm diameter were randomly collected for each sample. Soil samples were sent to the University of Tennessee Soil, Plant, and Pest Center for analysis. In accordance with the most recent guidelines from the University of Tennessee Soil, Plant, and Pest Center, lime, fertilizer, and pesticide were applied.

Each year, the treatments were arranged in a split plot with completely randomized design. Fungicide treatments were the main plot effect and water regimes were the subplot effect. The subplots sizes were approximately 34 × 31 meter. Fungicide treatments include (1) without fungicide/check (2) 1.11 L ha⁻¹ of Xyway LFR^{@FMC} and three water regimes including high (HI), low (LO) number of irrigation events, and rainfed (RF)/check (Table 5). Each water regime was replicated 3 times within fungicide and without fungicide/check plots. Four weeks after plating, five loggers (ZL6-Meter logger, METER Group, Inc. Pullman, WA) equipped with soil water content, matric potential sensors and digital rain gauges were installed in each fungicide and check plots, one in each irrigation treatment (except for RF in check plots). The sensors were installed at the depth of 20 and 66 cm to monitor the soil water content and rainfall and thereby schedule irrigation.

Sensor based scheduling

The irrigation scheduling was designed based on the depth and reading of soil matric potential sensors, as well as the percentage of the crop rooting zone (Roach & Gholson, 2016; Sheldon et

al., 2023). To determine the actual soil water availability for the corn plants' rooting zone, the sensor reading at 20 cm depth, which represents the top 50% of the rooting zone, was multiplied by 0.5. The same process was applied to the 66 cm depth, representing another 50% of the rooting zone and the actual value of available water was calculated, following the procedure explained by Sheldon et al. 2023.

Irrigation was initiated when the actual value, measured by a ZL6-Meter logger (METER Group, Inc. Pullman, WA) using soil matric potential sensors at depths of 20 and 66 cm, falls within the range of -65 to -75 kPa (Sheldon et al., 2023). At the end of the growing season, each water regime including HI, LO, and RF were irrigated 14, 9, and 0 times respectively in 2022 and 6, 4, and 0 times respectively in 2023 (Table 5). In each irrigation event, 12.7 mm of water was applied in 2022. Whereas in 2023, 10.41 mm of water was applied in each irrigation event except for two times where 7.62 mm and 15.24 mm of water was applied, due to some technical issue within the irrigation system. The rainfall amount (Fig. 6) was also incorporated when irrigation decision was made each time.

Data collection

During growing seasons

In the 2022 growing season, in each plot, five plants were randomly selected within a radius of 9-meters from the center of the plot and plant height, leaf number, and stem diameter were monitored and recorded weekly. We also measured leaf water potential (LWP) at 5, 7, 9, and 11 weeks after sowing (WAS), relative water content (RWC) at 13 and 15 WAS, and ear height at 13, 15, and 17 WAS. In 2023, data were collected similar to 2022. But plant height and stem diameter data measurements were done at 4, 6, and 12 WAS, ear height, LWP, and RWC at 8 and 12 WAS in 2023.

For the RWC, two leaves were randomly selected within a 3 m radius from the center of each plot. According to sampling method explained by Mullan and Pietragalla (2012), the top-most fully expanded leaf receiving sunlight was selected. As a sample, circular leaf portion of 15 cm diameter from middle part of the leaf was collected using a paper punch (Bira craft, Amazon, USA). The samples were placed in a sealed plastic bag after harvest. To maintain the turgidity of samples, they were immediately kept in a cooler. Samples were taken to the lab to measure the fresh weight (g). After measuring fresh weight, samples were placed in a tub of deionized water. The tub with samples were then exposed to 4°C in a walk-in cooler. After 6-8 h samples' turgid weight (g) were recorded.

Then to document the samples' dry weight, all samples were placed in individual paper bags (model no. S-7798, Uline.com) and moved to an oven at 80°C for 12 h. Leaf dry weight (g) was collected soon after samples were out of the oven. After all measurements were taken, following equation was used to calculate RWC,

$$RWC = \frac{\text{Fresh weight} - \text{Dry weight}}{\text{Saturated weight} - \text{Dry weight}} \times 100$$

Pressure chamber, model 1505D (PMS Instrument Company, Albany, OR, USA) was used to measure LWP. For the LWP measurement each time, two healthy and fully developed leaves were selected per plot. A section of the leaf, 10-20 cm from the tip of the leaf blade was cut and the cut leaf was placed in a plastic bag where the cut end of the leaf blade was positioned outside of the plastic bag. Then, the cut end of the leaf blade was placed in the pressure chamber while the cut end extended outside the chamber and exposed to atmospheric pressure. The pressure was increased around the leaf until xylem sap appeared at the cut end of the leaf and then, the pressure was recorded (Boyer, 1967; Ferry-Abee, 2016).

At harvest

Each plot within a 9.1 m radius from the center of the plot was harvested mechanically on September 22nd, 2022, and 2023. Before mechanically harvesting the plot, 10 ears were collected within a 3 m radius from the center of the plot then the cob length, cob diameter, ear length, number of rows per ear, and kernel per row data were documented. Additionally, kernel oil, protein, and starch were recorded using a near infrared reflectance diode array feed analyzer (Perten, Springfield, IL).

Statistical analysis

All the growth, physiological parameters, yield components, and yield data were analyzed using JMP (version Pro 17, SAS Institute Inc., Cary, NC). ANOVA of all the physiological, yield components and yield between treatment were calculated. Mean value of parameters with statistically significant difference ($p < 0.05$) were separated using student's t-test.

Results and discussions

The fungicide treatment, water regimes, and their interaction effect were statistically significant in the year 2022. However, the interaction effect was not significant in the year 2023 due to high rainfall events throughout the season.

The effect of interaction between water regimes and fungicide treatments on plants height was significant and varied by year (Table 6). In 2022, the corn plants treated with 1.11 L ha⁻¹ of Xyway LFR^{@FMC} fungicide, under all water regimes consistently resulted in taller plants (Table 3). Corn plants treated with the at-plant fungicide, under RF were as tall as the untreated (i.e., without fungicide treatment) plants under the LO water regime (Table 6).

Sankar et al. (2016) reported that when peanut (*Arachis hypogaea* L.) plants were treated with the paclobutrazol (a triazole) fungicide under drought stressed. Peanut (*Arachis hypogaea* L.) plants treated with a recommended rate of paclobutrazol (10 mg L⁻¹) had longer stem compared to drought-stressed plants without paclobutrazol treatment (Sankar et al., 2016).

When plants were treated with fungicide under HI, LO, and RF water regimes their stem diameters were higher than plants without fungicide/check (Table 6). The at-plant fungicide treatment resulted in a significant increase by 4.2 to 5.4 (%) when comparing HI and LO with LO under no fungicide application (Table 6). The RF plants treated with the fungicide had 2.4 (%) larger stem diameter compared to the similar water regime under no fungicide application (Table 6).

Triazole fungicides have been found to improve plant growth contrary to their growth retarding effects in some cases (Yang et al., 2014). A study by Ijaz et al., (2015) reported that triazole and strobilurin fungicides increased the plant height and had positive effects on growth parameters of winter rapeseed (*Brassica napus* L.).

However, in our study, in 2023 the plants height and stem diameter were not affected by either fungicide treatments or water regimes (Table 6). This could be caused by a shift in rainfall seasonality. In 2022, there were only three rainfall events from 19 to 60 days after planting (Fig. 6) that is a critical period for plant growth and development (de Araujo Rufino et al., 2018; Shaw, 2019). Thus, the change in rainfall patterns may have created the separation between the treatments. Additionally, Pandey et al. (2000) reported that the deficit water availability at the beginning of plants vegetative growth phase can affect leaf area index, plant height, and plant growth rate. Whereas, in 2023 season there was an even distribution of rainfall within this critical period.

In 2022, water regimes and fungicide treatments significantly impacted the plants ear height (Table 6). The analysis of variance (ANOVA) showed that plants treated with the fungicide had 13, 14, and 9 (%) higher ear height under HI, LO, and RF regimes, respectively compared to plants without any fungicide treatment (Table 36) under the exact same water regimes.

There was no significant difference in plants RWC (%) for either fungicide treatments or water regimes in both years (Table 6). But overall, plants treated with the fungicide had higher RWC (%) than plants without any fungicide treatment in 2023 (Table 6). In contrast to our finding, the application of paclobutrazol at (1498.2 mg L^{-1}), a triazole compound kept the plants RWC (%) higher than the non-treated plants when subjected to water-deficit stress (Jungklang & Saengnil, 2012; Jungklang et al., 2017). In their study Poudel and Shekoofa (2024) indicated that corn treated with 1.11 L ha^{-1} Xyway LFR^{@FMC} had significantly less water loss compared to check/no fungicide treatment under water-deficit conditions in the greenhouse. Plants shoot hydraulic conductance and LWP were higher at fungicide application rates of 1.11 and 1.26 L ha^{-1} compared to check under water-deficit conditions (Poudel & Shekoofa, 2024).

In 2022, the fungicide treated plants had improved the LWP by 18 and 16 (%) compared to plants without fungicide treatment under LO and RF, respectively (Fig. 8). Unlike 2022, LWP values were significantly more negative for fungicide treated plants compared to plants without any fungicide treatment under all water regime scenarios, in 2023 (Fig. 8). In 2023 growing season, our soil analysis results confirmed that there was a significantly less amount of potassium (K^+) in the fungicide treated plots area compared to plots without any fungicide treatment (Table 4). Clearly, there is an important role for K^+ when discussing plants cell membrane stability and osmotic adjustment ability (Wang et al., 2013). Hence, the low level of K^+ in the experimental soil may have influenced the plants' LWP result in 2023.

In 2022, there was a positive effect of fungicide treatment on plants cob length under all water regime scenarios compared to plants without any fungicide treatment/check. The plants cob length amounts were increased by 10, 9, and 4 (%) by the fungicide treatment under HI, LO, and RF, respectively (Table 7).

Plants treated with the fungicide under LO and RF water regimes had 3 to 5 (%) longer ear length, respectively in 2022 compared to plants without any fungicide treatment/check (Table 7). Furthermore, fungicide treated plants under HI and LO water regimes resulted in significant increase in cob diameter rates by 3 to 5 (%), respectively compared to plants without any fungicide treatment/check in 2022 (Table 7).

A significant difference in number of rows per ear was observed among fungicide treated plants compared to those without any fungicide/check under HI and LO water regimes (Table 7). In 2022, the fungicide treatment increased the number of rows per ear by 17, 10, and 7 (%) under HI, LO, and RF, respectively compared to the no fungicide treatment/check (Table 7). In 2023 overall, the fungicide treated plants had higher number of rows per ear compared to the no fungicide treatment/check (Table 7).

A possible reason behind the yield component improvements observed in our study might be that the increase in plants growth and canopy area provided plants with a better condition for light interception and photosynthesis. Zhang et al. (2010) reported that azoxystrobin (a strobilurin) and tebuconazole (a triazole) application delayed senescence and hence enhanced the grain yield of winter wheat.

In another study by Berdugo et al. (2013) green leaf area duration was extended by bixafen, fluoxastrobin, and prothioconazole fungicides application compared with the untreated control. They reported that fungicide treatments numerically increased the number of ears per pot, ear

weight, and number of kernels per ear (Berdugo et al., 2013). Delayed senescence/extended green leaf area in plants helps in prolonging the stage of kernel growth and expansion and as a result productivity is amplified (Berdugo et al., 2013).

In 2022, the effect of interaction between fungicide treatments and water regimes on corn grain yield was significant and varied by year ($p < 0.05$) (Fig. 4). Fungicide treatment increased the yield ranging from 8.5 to 13.3 t ha⁻¹ compared to the no fungicide treatment/check under all water regime scenarios (Fig. 9). The application of 1.11 L ha⁻¹ of Xyway LFR^{@FMC}, at-plant fungicide increased the yield by 11.9, 13.4, and 18.3 (%) under RF, LO, and HI water regimes, respectively (Fig. 9).

A substantial number of studies have shown that triazole, in combination with strobilurin, had led to the highest seed yield over other treatments for winter rapeseed (*Brassica napus* L.) (Ijaz & Honermeier, 2012; Ijaz et al., 2015). In a multivariate random-effects meta-analyses conducted on 12 years of data from 14 U.S. states to determine the mean yield and test-weight responses of wheat (*Triticum aestivum* L.) to treatment with propiconazole, prothioconazole, tebuconazole, metconazole, and prothioconazole + tebuconazole, all the fungicides led to a significant increase in mean yield and test weight relative to the check (Paul et al., 2010).

No significant difference was observed for kernel protein, oil, and starch in both years (Table 7). In the Ijaz and Honermeier (2015) report, the application of various combinations of nine triazole and strobilurin fungicides had no prominent effect on oil quality of winter rapeseed (Ijaz & Honermeier, 2015).

In 2023 growing season, there was no significant differences observed in the cob length, ear length, cob diameter, kernel number per row, and number of rows per ear when interaction

between fungicide treatments and water regimes were considered (Table 7). But overall, the plants treated with the at-plant fungicide had numerically higher number of rows per ear, kernel number per row, and cob diameter compared to those without any fungicide treatment (Table 7). The crop yield was overall higher for fungicide treated plots compared to no fungicide application/check (Table 8). There was no significant separation for yield among the water regimes in 2023 (Table 8).

The lack of consistency for these observations between 2022 and 2023 growing seasons data could be explained by sufficient rainfall during early vegetative, pollination, and grain filling stages (Fig. 6). Additionally, the rainfall was more evenly distributed in 2023 versus 2022 (Fig. 6) and in contrast with the 2022 season, the medium vapor pressure deficit (VPD) (i.e., 1.0 to 1.5 kPa) was recorded throughout the growing season in 2023 (Fig. 7). Favorable weather conditions might be another reason we could not see differences in most growth and physiological parameters and yield components for the interaction between fungicide treatments and water regimes in 2023.

The other confounding factors that could lead to variable yield responses between the two years in our study are the presence (and possibly intensity) of plant diseases. Kelly (2023) reported that there was little to no disease observed in 2023 during corn vegetative to early reproductive stages in Tennessee (Kelly, 2023). Thus, less disease incidences in 2023 may have reduced the separation of interactions between fungicide treatments and water regimes.

In a study by Swoboda and Pedersen (2009), the application of strobilurin and a triazole (Pyraclostrobin rate of 113 g a.i. ha⁻¹ and tebuconazole rate of 95 g a.i. ha⁻¹) alone or in combination in soybean did not produce nonfungicidal physiological effect or associated yield improvement in the absence of foliar disease (Swoboda & Pedersen, 2009). In another study, the application of three different commercial triazole, strobilurin, or carboxamide-based fungicides

during pre-bloom and bloom stage on soybean disease-free plants in the greenhouse, did not affect the physiological traits and crop yield (Junqueira et al., 2021).

According to Paul et al. (2010), variable yield responses to triazole based fungicide treatments are the presence (and intensity) of foliar diseases, the physiological effects of fungicide on crop yield in the absence of any disease, and environmental conditions. Hence, the difference in diseases occurrence and severity as well as environmental conditions including rainfall and evaporative demand (i.e., VPD) may have created the variation in our results in 2022 and 2023.

Conclusion

The Xyway LFR^{@FMC}, at-plant fungicide application in 2022 improved the corn plants height, stem diameter, LWP, and most yield components under all water regime scenarios compared to our no fungicide treatment/check. Moreover, the fungicide treatment increased the corn grain yield by 11.9, 13.4, and 18.3 (%) under RF, LO, and HI, respectively in 2022. Due to favorable growing condition i.e., less disease pressure, frequent rainfall, and VPD range of 1.0 to 1.5 kPa there was no significant difference observed for the interactions between fungicide treatment and water regimes in 2023. Hence, our results conclude that the application of Xyway LFR^{@FMC} at-plant fungicide applied at the rate of 1.11 L ha⁻¹ can improve morphology, physiology, and yield response of the corn under different water regime scenarios. But varying environmental conditions and assessment of disease levels should be used as a guide to determine the benefit from the fungicide application.

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Appendix

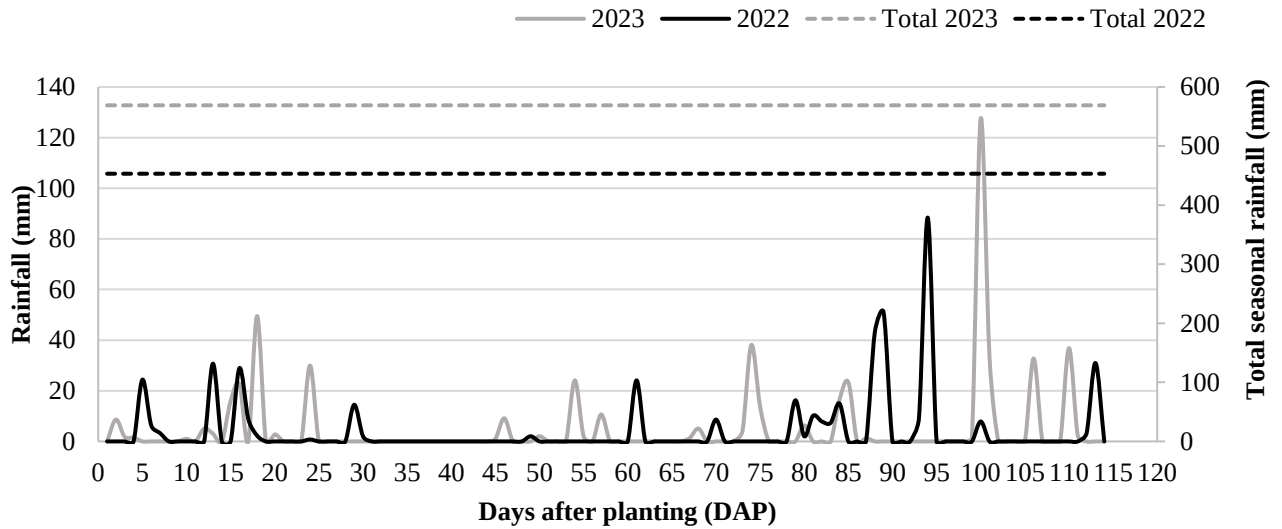


Figure 6. Rainfall (mm) on days after plating and total seasonal rainfall in 2022 and 2023.

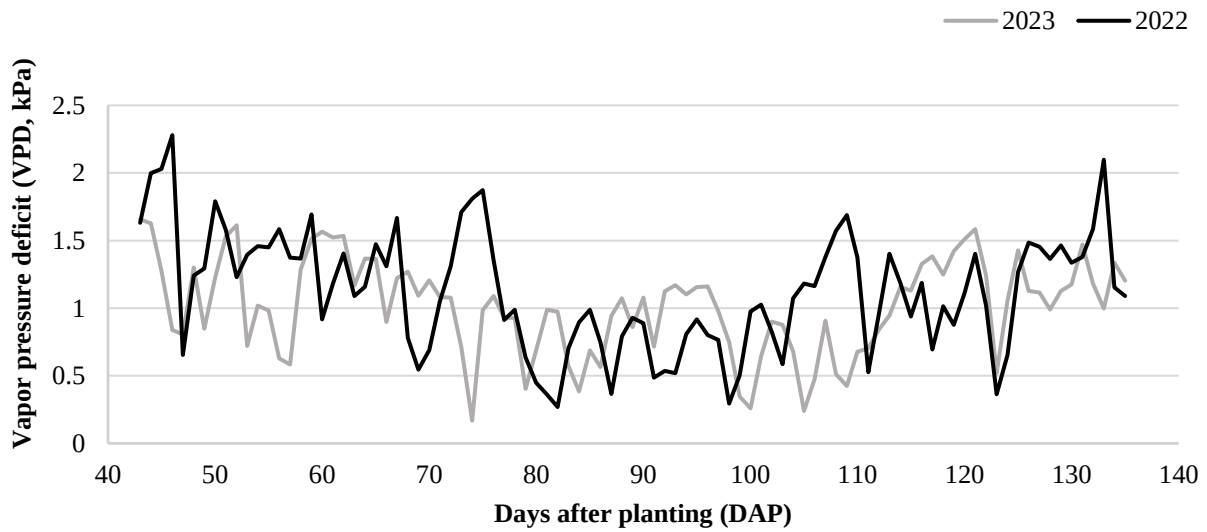


Figure 7. Vapor pressure deficit (VPD, kPa) during days after planting in 2022 and 2023.

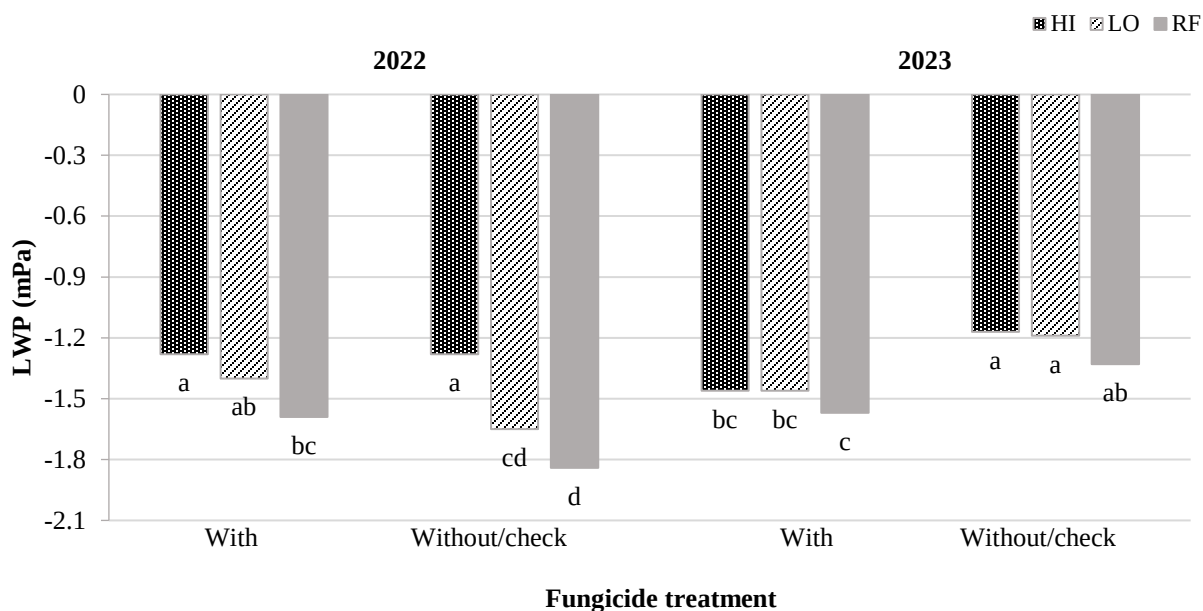


Figure 8. Plants leaf water potential (LWP) (mPa) under two fungicide treatments: without fungicide/check and with 1.11 L ha⁻¹ of Xyway LFR^{®FMC} and three water regimes: high (HI), low (LO) number of irrigation events, and rainfed (RF) in 2022 and 2023. Means with different letters are significantly different from one another according to student's t-test ($p < 0.05$).

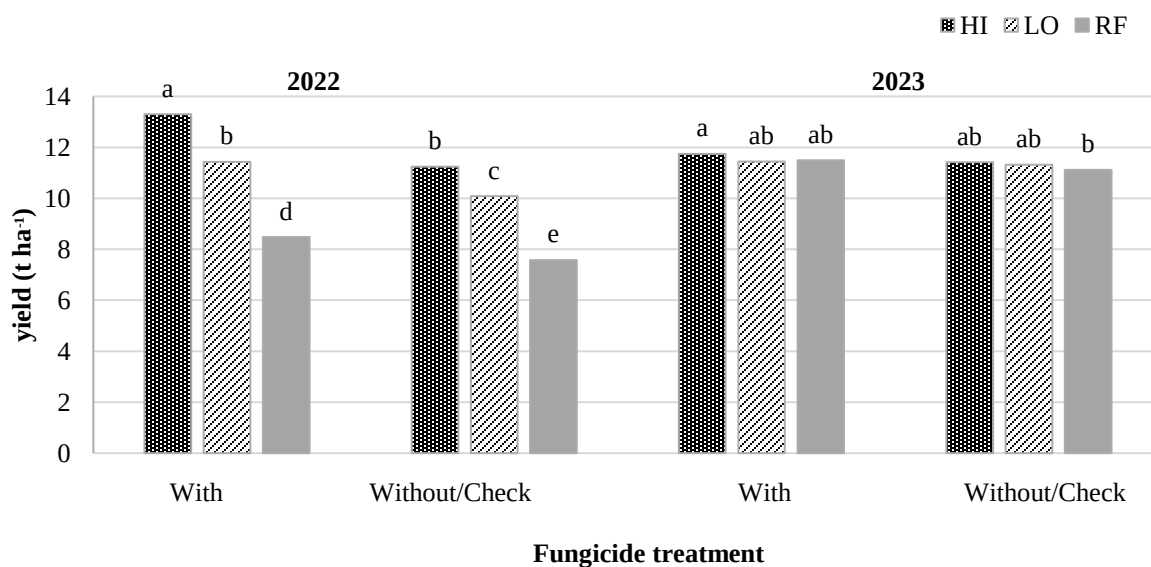


Figure 9. Final grain yield (t ha⁻¹) under two fungicide treatments: without fungicide/check and with 1.11 L ha⁻¹ of Xyway LFR^{®FMC} and three water regimes: high (HI), low (LO) number of irrigation events, and rainfed (RF) in 2022 and 2023. Means with different letters are significantly different from one another according to student's t-test ($p < 0.05$).

Table 4. Soil properties of Milan research and education center (MREC) for 2022 and 2023.

Fungicide treatment	pH	Phosphorus (kg ha ⁻¹)	Potassium (kg ha ⁻¹)	Calcium (kg ha ⁻¹)	Magnesium (kg ha ⁻¹)	Soil type
2022						
Without/check	6.3	53.7	217.2	4686.0	161.2	Providence silt loam (fine-silty, mixed, active thermic Oxyaquic Fragiudalfs)
With	6.2	56.0	215.0	4426.2	203.8	Providence silt loam (fine-silty, mixed, active thermic Oxyaquic Fragiudalfs)
2023						
Without/check	6.6	38.0	165.7	3053.1	154.5	Providence silt loam (fine-silty, mixed, active thermic Oxyaquic Fragiudalfs)
With	6.8	53.7	132.1	3012.8	159.0	Providence silt loam (fine-silty, mixed, active thermic Oxyaquic Fragiudalfs)

Table 5. Irrigation scheduling during 2022 and 2023 field experiment.

Week	Growth stage	High (HI) number of irrigation events	Low (LO) number of irrigation events	Rainfed (RF)
2022				
5-7	V7-tassling	6 ×*	4 ×	0
8-9	Ear size potential/silking to blister	4 ×	2 ×	0
10-11	Grain filling/soft dough	4 ×	3 ×	0
Total irrigation applied (mm)		177.8	114.3	0.0
2023				
9-10	Silking to blister	3 ×	3 ×	0
13	Soft dough	2 ×	1 ×	0
17	Dent	1 ×	0	0
Total irrigation applied (mm)		64.5	43.68	0.0

* Number of irrigation events

Note: Total rainfall for (2022: 453.14 mm) and (2023: 568.96 mm) May to September

Table 6. Plants height, stem dimeter, relative water content (RWC), and ear height under two fungicide treatments: without fungicide/check and with 1.11 L ha⁻¹ of Xyway LFR^{@FMC} and three water regimes: high (HI), low (LO) number of irrigation events, and rainfed (RF) in 2022 and 2023.

Fungicide treatment	Water regime	Height (cm)	Stem diameter (cm)	RWC (%)	Ear height (cm)
2022					
With					
	HI	247.14 a	2.36 a	91.71 ^{ns}	123.62 a
	LO	227.08 b	2.39 a	89.24	114.30 b
	RF	201.42 c	2.18 bc	91.41	107.37 c
Without/check					
	HI	219.56 b	2.34 a	90.89	108.20 bc
	LO	205.66 c	2.26 b	91.12	99.24 d
	RF	192.76 c	2.13 c	90.14	98.22 d
2023					
With					
	HI	102.44 ^{ns}	1.91 ^{ns}	81.20 a	87.96 abc
	LO	89.22	1.78	78.89 ab	84.46 c
	RF	99.92	1.80	66.84 ab	85.17 bc
Without/check					
	HI	100.15	1.93	77.05 ab	93.47 a
	LO	80.62	1.85	73.48 ab	91.62 ab
	RF	99.85	1.91	65.15 b	87.31 abc

Means followed by different letters within columns indicate significant difference at $p < 0.05$ student's t-test for pair wise comparison.
ns: not significant

Table 7. Plants yield components measurement under two fungicide treatments: without fungicide/check and with 1.11 L ha⁻¹ of Xyway LFR^{@FMC} and three water regimes: high (HI), low (LO) number of irrigation events, and rainfed (RF) at harvest in 2022 and 2023.

Fungicide treatment	Water regime	Cob length (cm)	Ear length (cm)	Cob diameter (cm)	Kernel number per row	Number of rows per ear	Protein (%)	Oil (%)	Starch (%)
2022									
With									
	HI	18.57 a	22.94 ab	2.44 a	17.19 ^{ns}	32.82 a	9.36 ^{ns}	4.11 ab	71.07 ^{ns}
	LO	18.56 a	23.60 a	2.47 a	17.32	31.62 a	10.32	4.79 a	71.75
	RF	16.30 bc	22.52 b	2.36 b	16.74	28.70 b	9.69	4.08 ab	71.88
Without /check									
	HI	16.83 b	23.28 ab	2.36 b	17.00	28.11 b	8.72	4.27 ab	67.12
	LO	16.98 b	22.82 ab	2.36 b	16.59	28.84 b	9.22	4.24 ab	68.84
	RF	15.64 c	21.43 c	2.35 b	16.44	26.76 b	8.62	3.86 b	67.87
2023									
With									
	HI	17.53 a	23.35 a	24.37 a	33.45 a	16.14 ab	9.40 ^{ns}	3.25 ^{ns}	61.65 ^{ns}
	LO	16.55 b	22.37 b	24.25 ab	29.59 cd	16.20 ab	9.63	3.30	61.33
	RF	17.42 a	22.88 ab	23.96 ab	31.76 abc	15.93 abc	9.45	3.35	61.60
Without/check									
	HI	17.44 a	22.68 ab	23.98 ab	32.32 ab	15.19 d	9.13	3.13	61.53
	LO	16.47 b	22.14 b	23.91 ab	28.63 d	15.47 bcd	9.33	3.17	61.60
	RF	17.33 a	22.67 ab	23.72 b	30.83 bcd	15.32 cd	9.50	3.27	61.53

Means followed by different letters within columns indicate significant difference at $p < 0.05$ student's t-test for pair wise comparison.

^{ns}: not significant

Table 8. Crop yield under two fungicide treatments: without fungicide/check and with 1.11 L ha⁻¹ of Xyway LFR^{@FMC} and three water regimes: high (HI), low (LO) number of irrigation events, and rainfed (RF) in 2022 and 2023.

Treatment	Yield (t ha ⁻¹)	
	2022	2023
Fungicide		
1.11 L ha ⁻¹	11.07 a	11.56 a
0	9.63 b	11.28 b
Water regime		
HI	12.27 a	11.58 ^{ns}
LO	10.76 b	11.38
RF	8.03 c	11.30

Means followed by different letters within columns indicate significant difference at $p < 0.05$ student's t-test for pair wise comparison.

^{ns}: not significant

CHAPTER IV
PARTIAL NET RETURNS ANALYSIS OF XYWAY LFR^{@FMC} FUNGICIDE
APPLICATION WITHIN THREE WATER REGIMES UNDER FIELD CONDITIONS

A version of this chapter is getting ready to be submitted to the *Agricultural Economics* for publication by Isha Poudel, Avat Shekoofa, and Aaron Smith

Abstract

It is crucial to assess the economic impact, while optimizing irrigation schedules and implementing fungicide treatments for enhancing the crop performance and yield. The specific objective of this chapter was to evaluate the partial net returns of a triazole, at-plant fungicide (i.e., Xyway LFR^{@FMC}) under varying water scenarios in Tennessee. A partial net return analysis in 2022 confirmed that the rainfed (RF) and water regimes with low (LO) number of irrigation events had the highest net returns compared to the same water regimes without fungicide/check treatment. Additionally, in 2022, all water regimes and fungicide treatments had positive average partial net returns compared to RF with no fungicide treatment. However, in 2023 due to beneficial rainfall during the growing season and beneficial environmental factors, low yield differences between treatments resulted in negative partial net returns for all treatments compared to RF with no fungicide treatment. The annualized capital recovery cost of the irrigation equipment was one of the reasons for the negative partial net returns across treatments and water regimes for 2023. The Xyway LFR^{@FMC} fungicide application can be profitable for corn production. However, different environmental factors will determine yield and net return differences each year.

Introduction

Corn (*Zea mays* L.) is one of the most significant food crops in the world after rice (*Oryza sativa* L.) and wheat (*Triticum aestivum* L.) (Abd El-Wahed et al., 2013; Albahri et al., 2023). In the United States corn production was 58 million metric tons with a total export value of \$18.57 billion in 2022 (U.S. Department of Agriculture, National Agricultural Statistics Service, June 30, 2023). The U.S. Department of Agriculture's National Agricultural Statistics Service (NASS) estimated 38.1 million hectares of corn planted in the United States for 2023, up 6% from 2022. Corn is the second largest row crop, by acreage in Tennessee, behind soybeans. The majority of corn production in Tennessee occurs in west Tennessee.

Extreme weather events like drought can have catastrophic effects on agricultural output on a regional and worldwide level (Zipper et al., 2016). Although there has been genetic advancement and improvements in production during drought scenarios (Gaffney et al., 2015; Shekoofa et al., 2016), corn is still susceptible to water-limiting conditions (Campos et al., 2006). A single moderate drought event (with the drought indicator SPEI (Standardized Precipitation Evapotranspiration Index) ranging from -0.8 to -1.2) would lead to a 64.3% chance of yield loss (i.e. yield lower than expected value) for the country as a whole. Under an exceptional drought (i.e. SPEI ranging < -2.0), US corn yield would have a 78.1% probability of loss risk (Leng, 2021).

Drought and corn prices are correlated at the local and national level. Instances of high corn prices in the United States, such as 2012, are often the result of wide scale drought. Smaller regional droughts, such as 2007 in Tennessee, do not produce as strong of a price response nationally and globally, but can dramatically impact local basis, thus affecting local cash prices.

Irrigation has reduced corn yield loss risk by 10, 17, 22, and 27 (%) under moderate, extreme, severe, and exceptional droughts in western US, respectively (Leng, 2021). However, in the view of reduction of water availability in the future, it is imperative to implement water management strategies that prioritize water conservation while ensuring adequate production levels. Improving productivity through irrigation scheduling is undoubtedly one of these strategies (Da Cunha Leme Filho et al., 2020; Sheldon et al., 2023).

Irrigation costs can be divided into two broad cost categories. Fixed costs are the costs associated with installing irrigation, including establishment of a well and purchase of a center pivot system. Fixed irrigation costs are onetime expenses that can be used for multiple growing seasons. Fixed cost can be annualized to account for the capital recovery over time. Variable costs are expenses that are contingent upon utilization of the irrigation equipment. Variable costs include the cost of water (if applicable), energy cost for pumping water, labor, and repair and maintained of the irrigation system. Fixed and variable costs should be included in partial net returns analysis.

In addition to the irrigation management strategies, in the recent years, many studies have been carried out to investigate how to improve the crop performance under water stress or drought condition using the complementary properties of certain agrochemicals normally used for plant protection such as triazole (Arivalagan & Somasundaram, 2015; Rajasekar, Rabert and Manivannan, 2016).

In our greenhouse and field study we determined the positive effect of Xyway LFR[®]FMC, a triazole at-plant fungicide, on improving water saving potential, morphological and physiological parameters, and increasing yield under water-deficit conditions (Shekoofa and Poudel, 2024a; Shekoofa and Poudel, 2024b). To model costs for using agrochemicals both the cost of the product

and any application costs need to be accounted for. Depending on the delivery method of the agrochemical there could be fixed costs due to the need for specialized equipment.

When optimizing irrigation scheduling and implementing fungicide treatments for improved crop performance and yield it is crucial to assess their attendant costs and revenues. Additionally, it is important to consider the long-term return on investment of any capital investment, such as irrigation equipment, under different weather scenarios, crop prices, and production practices. Varying economic returns have been investigated for deficit/limited irrigation management and irrigation scheduling (Da Cunha Leme Filho et al., 2020; Sheldon et al., 2023). However, very limited studies have investigated the economic implications of integrated management of irrigation scenarios and Xyway LFR^{@FMC} a triazole, at-plant fungicide. Given the uncertainty regarding future irrigation water availability, regulations on fungicide management, and corn prices, the net returns of Xyway LFR^{@FMC} under different water regime scenarios needs to be investigated. Therefore, the specific objective of this study was to determine the effect of Xyway LFR^{@FMC}, at-plant fungicide application and three water regimes on net returns under field conditions in Tennessee.

Materials and Methods

Field research was conducted at Milan Research and Education center (MREC), Milan, TN in 2022 and 2023 under a center pivot irrigation system equipped with variable rate irrigation (VRI) technology. Corn hybrid, DKC64-35 (DKC64-35RIB Brand Blend, DeKalb Genetics corporation, DeKalb, IL, USA) was sown, and fungicide was applied at-plant. Planting was initiated on May 10th in 2022 and April 26th in 2023 with a planting rate of 88,955 seeds ha⁻¹ for both years.

Each year, the treatments were arranged in a split plot with completely randomized design. Fungicide treatments were the main plot effect and water regimes were the subplot effect. The

subplots sizes were approximately 34×31 meter. Fungicide treatments include (1) without fungicide/check (2) 1.11 L ha^{-1} of Xyway LFR^{@FMC} and three water regimes including high (HI), low (LO) number of irrigation events, and rainfed (RF)/check. Each water regime was replicated 3 times within fungicide and without fungicide/check plots. Four weeks after plating, five loggers (ZL6-Meter logger, METER Group, Inc. Pullman, WA) equipped with soil water content, matric potential sensors and digital rain gauges were installed in each fungicide and check plots, one in each irrigation treatment (except for RF in check plots). The sensors were installed at the depth of 20 and 66 cm to monitor the soil water content and rainfall and thereby schedule irrigation.

At harvest, each plot within a 9.1 m radius from the center of the plot was harvested mechanically on September 22nd, 2022, and 2023. The yields for each trial were used to estimate partial net returns for each fungicide and water regime. Three water regimes were analyzed, high (HI) number of irrigation events (7.0 inches; 14 applications $\times$ 0.5 inches per application), and low (LO) number of irrigation events (4.5 inches; 9 applications $\times$ 0.5 inches per application) and rainfed (RF) in 2022 (Table 10).

Similarly, in 2023 high (HI) number of irrigation events [2.54 inches; 6 applications $\times$ (0.41 inches per four applications, 0.3 and 0.6 inch per one application each)], and low (LO) number of irrigation events [1.72 inches; 4 applications $\times$ (0.41 inches per two applications, 0.3 and 0.6 inch per one application each)] and rainfed (RF) (Table 10). Each water regime was considered with the application of Xyway LFR^{@FMC} fungicide at 1.11 L ha^{-1} rate and no fungicide/check. Partial net returns analysis includes only the costs and revenues that change as a result of the treatments being analyzed. All other costs and revenues are assumed to remain the same across treatments.

In addition to yield, water regimes, fungicide application, and weather data, the price data, irrigation costs, fungicide price, and application cost data were collected and considered in our

analysis. Daily corn price data for Tennessee was collected from elevators and barge points in west Tennessee reported by USDA Agricultural Marketing Service (AMS). Daily average prices were reported from the start of the corn marketing year (September 1). From 2022 to 2023 average Tennessee corn prices declined substantially due to regional, national, and global market dynamics.

The irrigation costs were estimated using University of Tennessee Crop Budgets and University of Arkansas irrigation cost estimates. Fungicide costs were obtained from local chemical providers. Application costs were estimated based on prevailing application rates in west Tennessee. Annualized fixed cost for irrigation was assumed to be \$ 247.11 ha⁻¹.

The fungicide and irrigation applications, irrigation costs, corn price, and yield were used to calculate the partial net return for each irrigation treatment based on the following equation:

$$(1) \text{ Partial Net Return}_{ij} = (\text{Price} \times \text{Yield}_{ij}) - (\text{Irrigation amount}_{ij} \times \text{Irrigation cost}_{ij}) - (\text{Fungicide cost}_{ij} + \text{Application cost}_{ij}) - \text{Annualized fixed Irrigation cost}_{ij}$$

Where, Partial Net Returns were estimated for:

Water regimes/irrigation treatment (i); and

Fungicide application (j)

Price was the average daily corn closing price reported by USDA AMS for Tennessee elevators and barge points in dollars per metric ton (prices ranged from a low of \$159.84 to a high of \$288.57 in 2022 and \$137.79 to \$198.81 in 2023); Yield was the average yield in ton per hectare reported by the field trials for each combination of fungicide and water regime; Irrigation amount was the amount of irrigation applied to each treatment in inches per hectare; Irrigation cost was the cost of irrigation in dollars per irrigation event; Fungicide cost was the estimated cost per hectare of Xyway LFR^{@FMC} (\$46.28 L⁻¹ x 1.11 L ha⁻¹); Application cost was the estimated cost to

apply fungicide in dollars per hectare; and fixed irrigation cost was the estimated annualized capital recovery cost of the irrigation system measured in dollars per hectare.

Results and discussion

2022 crop year

For the 2022 crop year, significant variation in yield (Table 9) was realized across water regimes and fungicide treatments, which was a key driver in differences in partial net returns. The HI irrigation water regime with fungicide treatment had the highest average net returns compared to the RF water regime with no fungicide application (Fig.10). Average partial net returns were positive for all water regimes and fungicide treatments compared to the RF water regime with no fungicide treatment. RF plants with fungicide treatment had average net returns of \$122.56 ha⁻¹ compared to RF plants without fungicide/check in 2022 (Fig. 10). LO water regimes plants with fungicide treatment increased partial net return ranging from \$503.75 to \$41.09 ha⁻¹ compared to net return for same water regimes without fungicide/check (i.e. \$224.77 to -75.02 ha⁻¹) (Fig. 10).

Likewise, HI water regimes fungicide treatment had the highest average partial net returns of \$689.84 ha⁻¹ and the greatest variability in net returns (\$208.63 ha⁻¹ to \$895.76 ha⁻¹) compared to without fungicide/check (Fig. 10). Yield differences were the primary driver of positive partial net returns compared to RF with no fungicide treatment. Variability in partial net returns across treatments was largely driven by the price range for the 2022 crop. The 2022 partial net returns results confirmed that growers can get a higher rate of return if Xyway LFR^{@FMC} is applied under RF or deficit irrigation (i.e., LO water regime) scenarios when rainfall increases the likelihood of drought stress. Positive partial net returns indicate that all variable (irrigation and fungicide) costs and fixed costs (annualized capital recovery of irrigation equipment) were less than the change in revenue for the water regime and fungicide treatment.

2023 crop year

High rainfall and favorable weather conditions along with less diseases pressure, resulted in a less pronounced yield difference by fungicide treatment under all water regime scenarios compared to RF without fungicide/check. This resulted in negative partial net returns for all the fungicide and water regimes scenarios compared to the RF no fungicide treatment (Fig. 11). Negative partial net returns indicate that compared to the RF with no fungicide treatment, other water regimes and fungicide treatments did not produce revenues that exceeded the variable and fixed costs. Wise and Mueller (2011) provide an overview of the findings from multiple field experiments that looked at fungicide applications on corn. Wise and Mueller (2011) reported that in order to justify the use of fungicides in corn production in 2009 and 2010, a yield increase of roughly 6 bushels per acre was required.

Furthermore, the corn price range in 2022 was substantially higher compared to 2023 (\$159.84 to \$288.57 in 2022 and \$137.79 to \$198.81 in 2023) which significantly affected the variability in partial net returns in 2023 (Fig. 10 and 11). According to Wiik and Rosenqvist (2010), after doubling and tripling the grain price of winter wheat there was greatest effect on the net return from the fungicide application.

Conclusion

In conclusion, our research has demonstrated that there are potential yield and economic benefits of the application of Xyway LFR^{@FMC} fungicide at 1.11 L ha⁻¹ rate for corn plants under field conditions. However, profitability of the fungicide application is reliant on a number of variables, including weather conditions, the level of disease intensity, the cost and rate of fungicide application, fixed and variable irrigation costs, and the corn price. The fungicide application may result in lower partial net returns in years with low disease intensity and favorable growing

conditions. Additionally, the differences in yield for the fungicide versus no fungicide will be influenced by water availability (rainfed or irrigation). Additional research on long-term returns and return on investment under different weather patterns and price scenarios is required.

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Appendix

Table 9. Crop yield under two fungicide treatments: without fungicide/check and with 1.11 L ha⁻¹ of Xyway LFR^{@FMC} and three water regimes: high (HI), low (LO) number of irrigation events, and rainfed (RF) in 2022 and 2023.

Treatment	Yield (t ha ⁻¹)	
	2022	2023
Fungicide		
1.11 L ha ⁻¹	11.07 a	11.56 a
0	9.63 b	11.28 b
Water regime		
HI	12.27 a	11.58 ^{ns}
LO	10.76 b	11.38
RF	8.03 c	11.30

Means followed by different letters within columns indicate significant difference at $p < 0.05$ student's t-test for pair wise comparison.

^{ns}: not significant

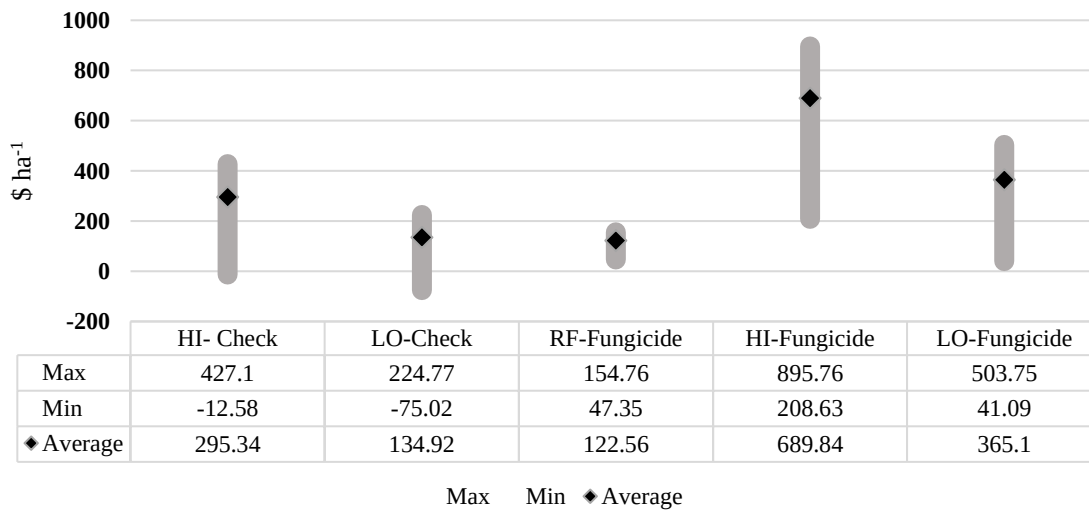


Figure 10. Partial net return analysis under two fungicide treatments: without fungicide/check and with 1.11 L ha⁻¹ of Xyway LFR^{@FMC} and three water regimes: high (HI), low (LO) number of irrigation events, and rainfed (RF) compared to without fungicide/check and rainfed condition in 2022.

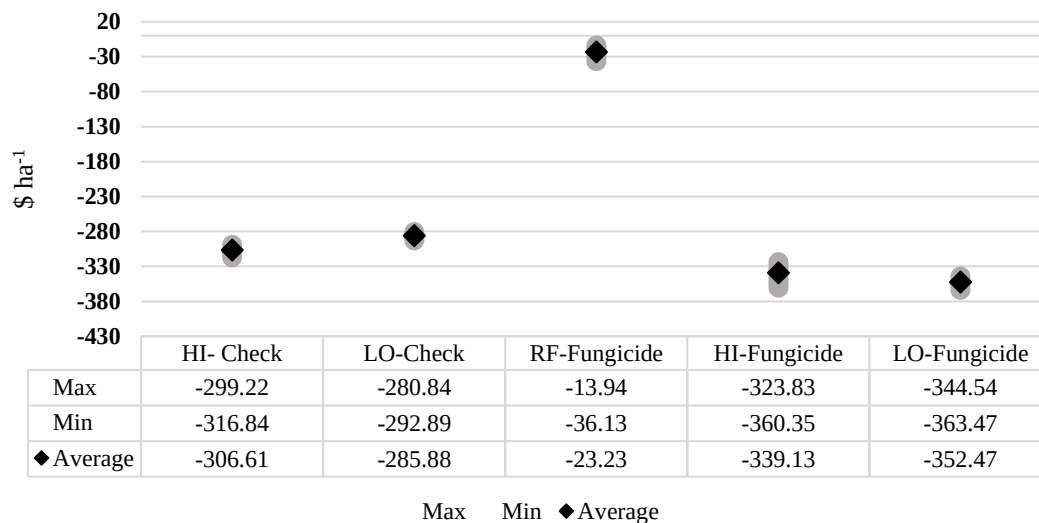


Figure 11. Partial Net Return analysis under two fungicide treatments: without fungicide/check and with 1.11 L ha⁻¹ of Xyway LFR[®]FMC and three water regimes: high (HI), low (LO) number of irrigation events, and rainfed (RF) compared to without fungicide/check and rainfed condition in 2023.

Table 10. Irrigation scheduling during 2022 and 2023 field experiment.

Week	Growth stage	High (HI) number of irrigation events	Low (LO) number of irrigation events	Rainfed (RF)
2022				
5-7	V7-tassling	6 ×*	4 ×	0
8-9	Ear size potential/silking to blister	4 ×	2 ×	0
10-11	Grain filling/soft dough	4 ×	3 ×	0
Total irrigation applied (mm)		177.8	114.3	0.0
2023				
9-10	Silking to blister	3 ×	3 ×	0
13	Soft dough	2 ×	1 ×	0
17	Dent	1 ×	0	0
Total irrigation applied (mm)		64.5	43.68	0.0

* Number of irrigation events

Note: Total rainfall for (2022: 453.14 mm) and (2023: 568.96 mm) May to September

CHAPTER V

CONCLUSION

Corn (*Zea mays* L.) ranks among the top three most widely grown crops worldwide (Abd El-Wahed et al., 2013; Albahri et al., 2023). In the United States, corn production was about 58 million metric tons with total export value of \$18.57 billion in 2022 (U.S. Department of Agriculture, National Agricultural Statistics Service, June 30, 2023). But this productivity is impacted by water limitation conditions. The plant's morphology, biochemistry, and physiological processes are all altered by water-deficit stress in dryland corn production systems, which has a detrimental effect on corn productivity (Sah et al., 2017; Wijewardana, Henry, and Reddy, 2017).

Irrigation is required to prevent crop cultivation failure or reduction in production. However, given the rising demand for water and the anticipated future decline in water availability, it is imperative to implement water management strategies that save water while preserving adequate production levels (Costa, Ortuño, and Chaves, 2007).

Therefore, in addition to the irrigation management strategies, in the recent years, many studies have been carried out to investigate how to improve the crop performance under water stress or drought conditions using the complementary properties of certain agrochemicals normally used for plant protection such as triazole (Arivalagan and Somasundaram, 2015; Rajasekar, Rabert, and Manivannan, 2016). The triazole treatment has been found to mitigate the adverse effects of drought stress by increasing the biochemical potentials and pave the way to overcome drought stress in corn (Rajasekar, Rabert, and Manivannan, 2016).

The Xyway LFR^{@FMC}, a triazole fungicide has been introduced into corn production system starting 2020 have been observed to improve plant performance under drought stress conditions. This research sought to assess the potential of Xyway LFR^{@FMC}, at-plant fungicide to improve the corn water saving trait under water-deficit stress conditions in controlled environments. Furthermore, a field study was conducted in two years to assess the Xyway LFR^{@FMC} contribution

to improve crop growth, development, and yield under irrigation and rainfed environments. Lastly, an economic analysis was conducted to determine the effect of Xyway LFR^{@FMC}, at-plant fungicide application and three water regimes on net returns under field conditions.

In the greenhouse study discussed in chapter 2, plants were treated with Xyway LFR^{@FMC} at 0.56, 0.77, and 1.11 L ha⁻¹ in experiment 1 and 1.11 and 1.26 L ha⁻¹ rates in experiment 2 to evaluate the transpiration rate (TR) response to water-deficit stresses (DS) and well-watered (WW) conditions compared with plants without fungicide (check/water). The most significant finding from this study was that plants treated with 1.11 L ha⁻¹ reduced the amount of water loss in response to DS and had the highest fraction of transpirable soil water (FTSW) thresholds. There was an increase in shoot hydraulic conductance (K_{shoot}) by 1.11 L ha⁻¹ in both experiments.

Plants treated with 0.77 and 1.11 L ha⁻¹ had higher LWP compared to other treatments under DS conditions. This result indicates that the most likely chemical ingredient in Xyway LFR^{@FMC} fungicide triggering the transpiration control response was flutriafol. This study confirms that early stomatal closure under soil drying conditions can be induced by the application of Xyway LFR^{@FMC} fungicide. Hence, we can conclude that application of at-plant fungicide, Xyway LFR^{@FMC} has potential to reduce the negative effect of water-deficit stress in corn along with improving plants growth and physiological performance.

In chapter 3, field study was carried out in two years (2022 and 2023) to assess the Xyway LFR^{@FMC} at-plant fungicide contribution in any plants physiological, growth, and yield responses to three water-regime scenarios in large plots' field trials. Our data indicated showed that the plants treated with Xyway LFR^{@FMC} at 1.11 L ha⁻¹ rate had significantly higher plant height, stem diameter, leaf water potential (LWP), and yield compared to no fungicide application/check under all three water regimes in 2022.

Similarly, plants treated with Xyway LFR^{@FMC} had 11.9, 13.4, and 18.3 (%) yield improvements under RF, LO, and HI, respectively in 2022 compared to no fungicide/check. Due to favorable growing condition in 2023 (i.e., less disease pressure, frequent rainfall, and low VPD rates) there was no significant separation for yield among the three water regimes. But the crop yield was overall higher for fungicide treated plots compared to no fungicide application/check. Our results indicate that Xyway LFR^{@FMC}, an at-plant fungicide has the potential to improve plant growth and protect yield when limited water is applied. But environmental conditions and assessment of disease levels should be used as a guide to determine the benefit from the fungicide application.

A partial net return analysis in chapter 4, indicated that RF plants with fungicide treatment had an average net returns of \$122.56 per hectare compared to RF plants without fungicide application/check in 2022. In 2022, the plants under the LO water regime had a higher net return of \$365.10 per hectare when treated with Xyway LFR^{@FMC} at 1.11 L ha⁻¹ rate, at planting compared to plants under LO water regime without fungicide/check (i.e. \$134.92 per hectare). For 2022, the data indicated that growers could get higher net returns if Xyway LFR^{@FMC} was applied under RF or deficit irrigation (i.e., LO water regime).

However, due to high rainfall and favorable weather conditions along with less diseases pressure rates, there was less pronounced yield difference between the no fungicide application/check and fungicide treatment in 2023. These conditions resulted in a negative partial net return in 2023. Our 2022 and 2023 data indicate the need for additional research to determine the partial net returns under long term weather variability.

Overall, these results provide evidence that Xyway LFR^{@FMC}, a triazole fungicide can improve crop water saving potential, crop performance, and yield under water-deficit conditions.

Although, the positive effect of Xyway LFR^{@FMC} application was limited in the absence of diseases and under the high rainfall condition, still some positive impacts on crop yield were observed. And from the economic perspective, the use of Xyway LFR^{@FMC}, at-plant fungicide, was found to be a profitable option for corn growers under RF conditions with average net returns of \$122.56 per hectare compared to RF plants without fungicide application/check in 2022. The application of Xyway LFR^{@FMC} at planting is one possible way to protect the corn yield under reduced irrigation strategy (i.e, LO) and water-deficit stress (i.e., dryland) conditions along with diseases protection. On the other hand, growers can expect a net return on their investment with the application of Xyway LFR^{@FMC} under reduced irrigation and rainfed conditions compared to no Xyway LFR^{@FMC} application at planting.

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VITA

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