IMPACT OF GROUNDWATER TABLE ON YIELD, WATER USE, ROOT DISTRIBUTION, AND SEED QUALITY OF HARD RED SPRING WHEAT (*TRITICUM AESTIVUM* L.)

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Impact of Groundwater Table on Water Use, Yield, Root Distribution, and
Seed Quality of Hard Red Spring Wheat (*Triticum aestivum* L.)

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ABSTRACT

The impact of groundwater table depth on hard red spring wheat (*Triticum aestivum* L.) yield, water use, root distribution, and grain quality were investigated in a greenhouse utilizing the lysimeter technique. Three different groundwater table depths (WTD) of 30, 60, and 90 cm, along with irrigation application (control treatment) were tested. Results showed that crop water use reduced as WTD increased from 30 to 90 cm, while yield and water use efficiency (WUE) increased as WTD increased. Similarly, 90 cm WTD resulted in the greatest yield, aboveground biomass, harvest index, and the greatest values for average kernel length, width, weight, and pasting properties compared to other WTD treatments. Consequently, the results suggested that for the WTD tested in this study, 90 cm was found to be the optimal WTD for the best hard red spring wheat yield and groundwater management.

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DEDICATION

This thesis is dedicated to

my ever loving and supportive wife, **Krista Lee Odili**,

and to

my dear mother, **Elizabeth Eluagwuni Odili**.

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LIST OF ABBREVIATIONS

ANOVA	Analysis of Variance
BD	Bulk Density
ET_0	Reference Crop Evapotranspiration
ETc	Groundwater Use
ET_i	Irrigation Water Use
FC	Field Capacity
GWD	Groundwater Depth
IWUE	Irrigation Water Use Efficiency
LSD	Least Significant Difference
RAW	Readily Availably Water
SMC	Soil Moisture Content
SMP	Soil Metric Potential
SMPS	Soil Moisture Potential Sensor
SPSS	Statistical Package for the Social Sciences
PWP	Permanent Wilting Point
WTD	Water Table Depth

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1. INTRODUCTION

For several decades, water supply has been an issue globally, as many areas of the world are currently being affected by water scarcity. Water conservation is crucial in modern agriculture as managing water outflow helps to optimize water use and avoid drought stress. In addition, there are environmental concerns about nutrient losses via drainage water, especially in regards to nitrogen and phosphorus pollution and the related eutrophication processes (Alcamo et al., 1997; Mancosu et al., 2015; Dodds and Smith, 2016). Competition for water use between rural, urban, industrial, environmental, and agricultural interests continues to intensify with continuous population growth (Ayars et al., 2006; Xue et al., 2014; Zhang et al., 2018). Recent studies project an increase in the world population from a current estimate of approximately 8 billion people to 10 billion people by 2050 (UN 2019). This projection suggests higher water demands for domestic, industrial, and agricultural utilization (Mancosu et al., 2015). Moreover, due to the increased water scarcity and drought as a result of climate change, extensive water use for irrigation is expected to occur in relation to increasing competition between agriculture and other sectors of the economy (Ayars et al., 2006; Jiménez Cisneros et al., 2014).

Managing and optimizing the efficiency of water use in the agricultural sector has been shown to be an effective way of addressing future projections of global water shortages (Ripoll et al., 2014). Water use efficiency (WUE) in agriculture refers to crop yield or total crop biomass per unit of water use. It usually involves consuming less water to reach a specific production goal or increasing the production from a given water supply (Sinclair et al., 1984). The overall goal of improving WUE in agriculture is increasing food production, enhancing financial gains, and assuring the sustainable supply of ecosystem services at a reduced social and environmental cost per water unit used (Xue et al., 2014).

Groundwater is an important water source for crop irrigation in most parts of the world, due to its application through surface irrigation. Groundwater table level varies seasonally through various processes, including recharge, drainage, and usage of water resources (Stromberg, 2001; Bai et al., 2020). Seasonal variation in groundwater table influences the amount of water available for crops and leads to changes in crop productivity. When the groundwater table level was maintained through controlled drainage systems at an optimum water table depth (WTD), crop yield and water use efficiency was increased (Wesstrom and Messing, 2007).

A shallow water table increased the availability of water for plants. A shallow water table serves as an efficient water source for sub-irrigation practices by utilizing proper irrigation schedules to balance water demand and supply in agriculture (Kahlown et al., 2005; Gowing et al., 2009; Kadioglu et al., 2019). Several studies have reported significant contributions of shallow water tables to improved crop production by enabling crops to satisfy their water requirement and enhancing crop water uptake (Ayars et al., 2006; Gowing et al., 2009; Ghamarnia and Farmanifard, 2014). However, if the water table is too shallow, crop yield could decrease due to waterlogging and root anoxia (Nosetto et al., 2009; Bansal and Srivastava, 2015; Ghobadi et al., 2017).

When groundwater recharges due to high rainfall or precipitation and moves toward the soil surface through capillary action, it may carry excessive salts into the soil profile. As the water approaches the soil surface, evaporation leaves the salts behind in the root zone when appropriate leaching is not practiced (Xu et al., 2013; Abliz et al., 2016). Salinity affects almost all aspects of plant development, including germination, vegetative growth, and reproductive development. Soil salinity imposes ion toxicity, osmotic stress, nutrient (N, Ca, K, P, Fe, and Zn) deficiency, and oxidative stress on plants, and thus limits water uptake from soil (Bano and Fatima, 2009; Ghobadi et al. 2017).

Groundwater utilization for crop production depends on several factors such as groundwater availability, WTD, water quality, crop species, the plant rooting system, weather conditions, and soil types (Ghamarnia et al., 2012). Bai et al. (2020) noted that the quantity and quality of groundwater are also affected by irrigation methods and management practices, as an excessive amount of irrigation increases groundwater utilization. Water table management for improved agricultural production has progressed from the concept of drainage alone to that of surface and subsurface drainage, controlled drainage, controlled drainage subirrigation (combined drainage and subirrigation). Controlled drainage-subirrigation maintains shallow water table depths in the field during certain periods of the growing season (Ghamarnia and Farmanifard 2014; Bai et al. 2020). Water table management with controlled drainage or controlled drainage-subirrigation prevents indiscriminate drainage of wetlands and provides water quality benefits by promoting the growth of denitrifying bacteria (Shirmohammadi et al., 1992; Noshadi and Karimi 2021).

Compared with conventional drainage systems, water table management can provide better flood control, improved water conservation, optimized water conditions for crop growth, and improved water quality (Noshadi and Karimi, 2021). Water table management is especially suited to areas where high water tables persist for long periods and have the potential to increase net farm returns by improving crop yield and reducing chemical use (Ghamarnia et al., 2012; Ghamarnia and Farmanifard 2014). Water table management maintains adequate soil moisture and soil air in the crop root zone and creates favorable plant growth conditions. The quantity of soil moisture and soil air in the root zone, however, depends on the depth at which the water table is maintained. The crop's physiological growth differs significantly depending on soil moisture and soil air in the root zone. Transpiration rates, photosynthesis rates, stomatal conductance, chlorophyll content, and canopy temperatures may vary (Ghamarnia et al., 2012; Xue et al., 2014; Zhang et al., 2018).

Due to the difficulty in estimating groundwater contributions and the numerous variables involved, controlling the parameters surrounding groundwater use for crop production under field conditions is almost impossible. Hence, lysimeter systems are often used to conduct an experiment that simulates only a single parameter at a time (Luo and Sophocleous, 2010). Lysimeters in greenhouse conditions allow for more complex field studies to be conducted in a controlled environment. Lysimeter studies have been carried out to estimate groundwater depth and contribution and determine the effects of different water table levels on crop grain yields. Lysimeters can also be used to predict the quantity of crop water use from the groundwater table (Mejia et al., 2000; Ayars et al., 2006; Putz et al., 2018; Kadioglu et al., 2019).

1.1. Statement of Objectives

The primary goal of this study is to investigate the optimum WTD for the best hard red spring wheat production and groundwater management practice. The specific objectives are as follows:

i. To assess the impact of different groundwater table depths (30, 60, and 90 cm) on hard red spring wheat yield and water use efficiency.

ii. To determine the effect of groundwater table depths on the hard red spring wheat root distribution.

iii. To evaluate the impact of groundwater table depths on the hard red spring wheat seed quality.

2. LITERATURE REVIEW

2.1. Background of the Study

The management of soil water in agricultural cropland in humid and semi-humid areas of the US is complicated by the unpredictable spatial and temporal occurrence of rainfall. In many humid areas, such as the mid-western regions of the US, periods of surplus and deficit soil water conditions occur within the same cropping season. This issue sometimes leads to production losses (Stromberg, 2001; Luo et al., 2010). Therefore, proper soil and water management have become one of the most important challenges in these and the other humid areas of the US to reduce soil productivity losses. The primary purposes of water table control are to minimize the time of surplus or deficit soil-water conditions in the root zone and to maximize the use of natural rainfall, thus minimizing the amount of subirrigation water required from external sources (Luo et al., 2010; Javai et al., 2018). Water table management which includes both irrigation and drainage, can improve productivity in humid and semi-humid climates, where weather extremes can result in crop losses and in arid areas where salinity control is necessary for sustained agricultural production (Nosetto et al., 2009; Bansal and Srivastava, 2015; Ghobadi et al., 2017).

The objective of water table management is to provide a root environment that results in optimum crop yields (Ghamarnia et al., 2012; Ghamarnia and Farmanifard 2014). In the past, the direct aim of water table management systems in humid regions was to lower the moisture content of upper layers of the soil so that air could penetrate the soil more easily and become available to the roots of the plants. At the same time, carbon dioxide produced by roots, by microorganisms, or by chemical reactions in the soil was able to diffuse through the air-filled pores to the surface (Xue et al., 2014; Noshadi and Karimi, 2021). The water table should not be lowered so deep that a severe water deficiency will cause death or reduced plant production. Therefore, water table management systems have been used to maintain the required WTDs in the field during certain periods of the growing season. These systems are known by various names such as drainage, controlled drainage, drainage subirrigation, controlled drainage subirrigation, and controlled and reversible drainage (Shirmohammadi et al., 1992; Xue et al., 2014; Noshadi and Karimi, 2021).

2.2. Water Table Depth and Crop Production

Bhuiyan and Alagcan (1990) investigated the growth response of corn (*Zea mays* L.) to changes in the shallow water table in fields near irrigation canals or rice areas. They found that lowering the water table a small amount produced a strong negative response in both plant height and yield. The investigators indicated that during the vegetative growth stage of corn, yields above 7.3 tonnes/hectares could be achieved by controlling the average WTD at 15 cm.

Kalita and Kanwar (1992) studied the response of corn to WTDs of 20, 30, 60, 90, and 110 cm below the soil surface in Iowa. They found that corn yields increased with increasing WTDs. For 20 and 30 cm WTDs, corn yield decreased significantly compared with yields from plots with deeper WTDs. Dry and wet seasons significantly affected grain yield. Plant water use efficiency and grain yield were significantly related. Ahmed et al. (1992) investigated the effects of soil surface submergence and WTD on corn vegetative growth. They observed that plant growth was significantly affected by excessive water stress due to soil submergence compared to under 15 cm depth.

In a silt loam soil, Fisher et al. (1999) compared yield and nitrogen uptake of corn and soybean (*Glycine max* (L.) Merr.) in the controlled drainage (controlled groundwater depth in 40 cm) with conventional drainage. The mean yield of corn and soybean in controlled drainage was

19% and 64%, respectively, higher than that obtained in conventional drainage. The nitrogen uptake in controlled drainage for corn and soybean was 13% and 62% higher than conventional drainage, respectively.

Mejia et al. (2000) conducted a two-year field experiment to determine the effect of two different WTDs (50 and 75 cm) on corn and soybean grain yields. A free drainage system was installed 100 cm below the soil surface for both treatments. In the first year, corn yields were 13.8% and 25% greater for 50 and 75 cm WTDs, respectively, compared to the free drainage system, while soybean yields were 8.5% and 12.9% greater for 50 and 75 cm WTDs, respectively, compared to the free drainage system. In the second year, corn yields were 6.6 and 6.9% greater and soybean yields 37.3 and 32.2% greater in the 50 and 75 cm WTD plots than in the free drainage plots, respectively. The authors concluded that the 75 cm WTD was the most efficient WTD for corn and soybean.

Kahlown and Ashraf (2005) investigated the effect of shallow water tables on wheat, sugarcane (*Saccharum officinarum* L.), corn, sorghum (*Sorghum bicolor* (L.) Moench), berseem (*Trifolium alexandrinum* L.), and sunflower (*Helianthus annuus* L.) using lysimeters. They reported that the contribution of groundwater in meeting the crop water requirements varied with the WTD. With the WTD at 0.5 m, wheat met its entire water requirement from the groundwater and sunflower absorbed more than 80% of its required water from groundwater. Corn and sorghum were found to be waterlogging sensitive crops whose yields were reduced with a shallower WTD. However, maximum sugarcane yield was obtained with the WTD at 2.0 m or less. Overall, the WTD of 1.5–2.0 m was found to be optimum for all the crops studied.

Nosetto et al. (2009) quantified influences of WTD in flat sedimentary landscapes of the Inland Pampas occupied by wheat, soybean, and corn during two growing seasons. An optimum groundwater depth (GWD) range, where crop yields were greatest, was determined for all three crops analyzed (1.40–2.45 m for corn, 1.20–2.20 m for soybean, and 0.70–1.65 m for wheat). The areas within these optimum GWD bands had yields that were 3.7, 3.0, and 1.8 times greater than those where the water table was deeper than 4.0 m for wheat, maize, and soybean, respectively. As groundwater levels become shallower than the optimum GWD bands, crop yields declined sharply, suggesting negative effects of waterlogging, root anoxia and/or salinity. Groundwater levels greater than these optimum GWD bands were associated with gradually declining yields, likely driven by poorer groundwater supply.

Kang et al. (2012) evaluated the effects of different water levels on cotton (*Gossypium arboretum* L.) yield and water use in an arid region of Northwest China. The experiment included five water treatments in which the soil matric potential (SMP) at a depth of 20 cm was controlled higher than −10 (S1), −20 (S2), −30 (S3), −40 (S4), and −50 kPa (S5) after cotton was established. The results revealed that the highest cotton evapotranspiration (ET_C) was achieved under S1 (−10 kPa) treatment. Similarly, deep percolation and the ratio of deep percolation with irrigation water all increased with increasing SMP threshold. After three years of experiment, no salt accumulation was found in the soil surface layer under irrigation schedule. The highest cotton yield was obtained when the SMP threshold was controlled above −30 kPa in 2008, and −20 kPa in 2009 and 2010. Moreover, the highest yield obtained after three years was 42% higher than the average yield achieved by local farmers in the area. Additionally, the water use value (WUE and IWUE) increased as the SMP threshold decreased in 2009 and 2010. Considering the cotton yield and the impact of irrigation on the underground water table, the study suggested that an SMP higher than −20 kPa at 20 cm can be used as an indicator for cotton drip irrigation scheduling and agronomic practices in the area to help alleviate the dangerous increase in the water table while increasing the cotton seed yield.

Kadioglu et al. (2019) conducted lysimeter experiments to investigate canola (*Brassica napus* L.) water use, growth, and yield parameters for three different WTDs of 30, 60, and 90 cm. Additionally, control experiments were conducted, and only irrigation was applied to these lysimeters without water table limitations. The canola plant's tolerance level to shallow groundwater was determined. Results showed that groundwater contributions to the canola plant for the treatments at 30, 60, and 90 cm WTDs were 97, 71, and 68%, respectively, while the average grain yields of canola were 4.5, 5.3, and 6.3 grams, respectively. These results demonstrate that a 90 cm WTD is the optimum depth for canola plants to produce a high yield with the least amount of water utilization.

2.3. Wheat

Wheat is a crop with wide adaptability, good storability, and high nutritional value (Wrigley, 2009). It is the main ingredient in a variety of foods, including noodles, pastries, crackers, and bread. Based on acreage, wheat is the most important food crop in the world (FAO, 2017a). In 2017, more than 771 million tons were produced worldwide, of which the US contributed over 47 million tons (FAO, 2017b). The intrinsic properties of wheat make it unique among cereals. Only wheat doughs exhibit viscoelastic properties essential for the production of leavened bread and other food products (Gianibelli et al., 2001; Wrigley, 2009).

2.4. Origin of Wheat

Wheat was first domesticated about 10,000 years ago, which makes it one of the oldest cultivated crops (Shewry, 2009; Weiss and Zohary, 2011; Faris, 2014). It is widely accepted that it originated in the 'Fertile Crescent', a region in the Middle East (Faris, 2014). As we know it today, wheat is the result of thousands of years of crop evolution and human selection. The first cultivated wheat species are believed to have been Einkorn (*Triticum monococcum* L.) and Emmer (*T. turgidum ssp. dicoccum* L.) (Atwell and Finnie, 2016; Shewry, 2009). Both species served as an important food source in ancient civilizations (Figure 1) (Faris, 2014; Shewry, 2009). Hybridization events between diploid species led to the formation of tetraploid wheat. The hybridization between *T. urartu* (2n = 2x = 14, AA) and *Aegilops speltoides* (2n=2x=14, SS) resulted in the formation of emmer (*T. dicoccum*; 2n=4x=28, AABB) (Faris, 2014; Gooding, 2009) and durum wheat (*T. durum*; 2n=4x=28, AABB) (Gustafson et al., 2009). *T. spelta* (2n=6x=42, AABBDD) is believed to have arisen through a natural hybridization event between *T. turgidum* and *Ae. tauschii* (Faris, 2014; Matsuoka, 2011). The resulting hybrid was hulled because of the tenacious glume gene Tg1 from *Ae. tauschii*. Selection and evolution resulted in free-threshing *T. aestivum* (2n=6x=42, AABBDD) (Faris, 2014). *T. aestivum* makes up about 95% of today's wheat production (Almansouri et al., 2001).

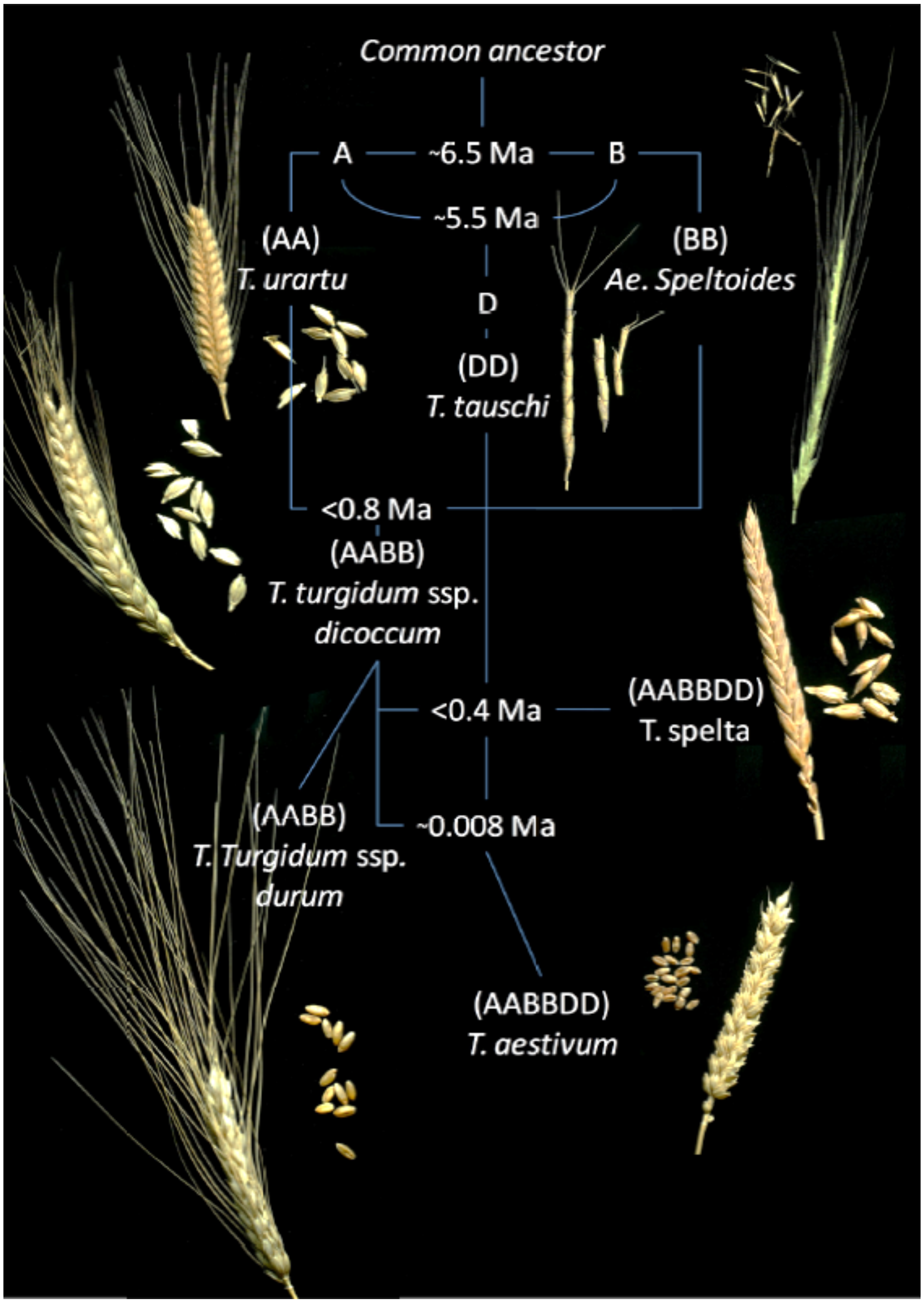

Figure 1. Phylogenic history of wheat, with the approximate dates for divergence and hybridization events (Shewry, 2009).

2.5. Wheat Classification and Economic Importance

In the US, wheat is divided into six market classes which are designated by kernel hardness, seed color, and growth habit. The six market classes are hard red winter (HRW), hard red spring (HRS), soft red winter (SRW), soft white (SW), hard white (HW), and durum wheat

(U.S. Wheat Associates, n.d.). HW, SW, and durum wheats have both spring and winter types. HRW is the most grown market class, followed by HRS, SRW, white wheat, and durum wheat (AgMRC, 2019).

Wheat is used to produce a variety of foods. Each class has different functional properties and is used for different end-products. Hard wheats are mostly used for bread and breadlike products, whereas soft wheat is better suited for batter-based products (Atwell and Finnie, 2016). HRW is mostly grown in the Great Plains and California (Wheat Marketing Center, 2008). It is characterized by high protein content and water absorption (Atwell and Finnie, 2016) and is generally used for pan bread, flat bread, and Asian noodles (Wheat Marketing Center, 2008). SRW is predominately grown in the eastern part of the US It is low in protein and has weak gluten. End-uses include pastries, cookies, cakes, and crackers. HRS is primarily grown in North Central states. It is characterized by high protein content, strong gluten, and high-water absorption. It is used for bread, bread related products, and blending. Most of the SW wheat is grown in the Pacific Northwest. Flour made from SW generally has low protein and weak gluten. It is used in the production of cakes, pastries, crackers, and Asian noodles. HW is the newest wheat class in the US. Its production is not focused on a specific region. It is high in protein and used for whole wheat products, bread products, and Asian noodles. Durum wheat is the hardest of all wheat classes. It has high protein and is commonly used for Italian pasta and couscous production (Wheat Marketing Center, 2008).

2.6. Water Table Effect on Wheat Yield and Water Use

Wheat is an extensively grown crop in the United States and around the world. Several studies have been conducted to investigate the effect of different water tables on wheat production and water use to understand the optimal water table depth for the best wheat production.

Luo and Sophocleous (2010) combined both lysimeter system and numerical models to investigate seasonal groundwater contribution to crop water use and yield of winter wheat. Groundwater evaporation experiments were conducted through a weighing lysimeter at an agricultural experiment station located within an irrigation district in the lower Yellow River Basin for two winter wheat growing seasons. An HYDRUS-1D model was calibrated and validated with weighing lysimeter data and then was employed to perform scenario simulations of groundwater evaporation under different depths to water table (DTW) as well as water input (rainfall plus irrigation) driven by long term meteorological data. The scenario simulations revealed that the seasonally averaged groundwater evaporation amount was linearly correlated to water input for different values of DTW. The linear regression could explain more than 70% of the variability. The seasonally averaged ratio of the groundwater contribution to crop-water use varied with the seasonal water input and DTW. The ratio reached as high as 75% in the case of DTW = 1.0 m and no irrigation and as low as 3% in the case of DTW = 3.0 m and three irrigation applications. The results also revealed that the ratio of seasonal groundwater evaporation to potential evapotranspiration could be fitted to an exponential function of the DTW that may be applied to estimate seasonal groundwater evaporation.

Huo et al. (2011) evaluated the effect of groundwater level and irrigation amount on water fluxes at the groundwater table and water use of wheat. Three irrigation water regimes (90.0, 67.5, and 45.0 mm) and five groundwater table depths (1.5, 2.0, 2.5, 3.0, and 3.5 m) were considered in the lysimeter experiment. The results showed that deep percolation (irrigation of 16–23%) occurred to a considerable extent in the present irrigation level at a shallow groundwater table of 1.5–2.0 m. Capillary rise comprised 29% of the water use of wheat, within the period from regreening to harvest, at 1.5 m groundwater table depth and was reduced with an increase in table depth. Irrigation conditions, the water productivity (WP_b) of wheat was enhanced from 3.59kgm^{-3} at a shallower groundwater level depth of 1.5 m to 4.58 kg m^{-3} at a deeper groundwater level depth of 3.5 m. WP_b can be higher if deficit irrigation is enforced and can reach 3.93–6.03kgm^{-3}.

Karimov et al. (2014) analyzed the effect of shallow water table on water use of winter wheat using HYDRUS-1D. Numerical simulations show that the contribution of the groundwater to evapotranspiration increases with a rising water table and decreases with increasing irrigation applications. Under irrigation conditions, an increase in evapotranspiration resulted in a buildup of salinity in the crop root zone. After harvest, 45%–47% of the groundwater was lost due to evapotranspiration, thus increasing soil salinity and affecting ecosystem health. Consequently, maintaining a water table is suggested to achieve effective groundwater management.

Ghamarnia and Farmanifard (2014) conducted a two-year lysimeter experiment to determine the effect of different shallow water table levels (without any supplementary irrigation) on water requirements, yield, and water use efficiencies of three wheat cultivars. Nine treatments were applied to each experiment by maintaining groundwater electrical conductivity (EC) of 5 dSm^{-1}, with different water table levels of 0.6, 0.80, and 1.10 m, respectively. The results showed the highest and lowest groundwater uses by wheat were water table levels of 0.6 and 1.10 m, respectively. For all wheat cultivars, the average groundwater contributions were found to be 70.90% (5 mm day^{-1}), 67.85% (4.3 mm day^{-1}), and 63.4% (3.6 mm day^{-1}) for water table levels of 0.60, 0.80, and 1.10 m, respectively. Finally, the results showed the highest yield production and groundwater-use efficiency were observed in 0.80 m water table level for all the three wheat cultivars.

Noshadi and Karimi (2021) investigated the effect of controlled groundwater depths (CD) and nitrogen levels on wheat yield, sub-irrigation, and water productivity. The treatments were three nitrogen fertilizer levels, including 27, 227, and 327 kgN/ha, and three groundwater depths, including 60, 90, and 120 cm. The results showed that the wheat yield was highest at 90 cm and lowest at 60 cm groundwater depths. Water productivity and sub-irrigation increased from 60 to 90 cm, and reduced from 90 to 120 cm. Also, by increasing the nitrogen fertilizer level to 227 kgN/ha, the wheat yield and water productivity also increased. In general, the optimum groundwater depth was 90 cm at N fertilizer level of 227 kgN/ha. The groundwater depth higher than or less than 90 cm decreased the yield and water productivity and increased drainage water and nitrate leaching. The study suggested that the yield reduction in groundwater depth lower than 90 cm was due to a lack of soil aeration (water logging) in the root zone. Additionally, the reduction in yield in groundwater depth higher than 90 cm was due to lower groundwater contribution for supplying the wheat crop water requirement.

3. IMPACT OF GROUNDWATER TABLES ON HARD RED SPRING WHEAT YIELD, WATER USE, ROOT DISTRIBUTION, AND SEED QUALITY

3.1. Introduction

The world population is growing radically, and water scarcity is becoming a challenge throughout the world that nearly 40% of the population experiences water shortage. On the other hand, the rate of water utilization increases at twice the rate in the world as compared to the increases in the human population. Population growth, urbanization, industrialization, and environmental pollution cause water shortages to the extent that water can no longer be considered as an infinite source (Hamdy et al., 2003; Steduto et al., 2017).

The Food and Agricultural Organization (2016) reported that water utilization in agriculture is 69% of the total water consumption, while it is 19 and 12% in industrial and municipal utilization in the world, respectively. It was projected that increases in world population cause an intensification of industrial development, and water utilization in this sector could be increased accordingly. This water demand could affect the amount of water utilization in agricultural sectors since more water could be used in an industrial area (Hamdy et al., 2003; Ayars et al., 2006). To deal with this potential water crisis, new water management approaches and strategies are required for all sectors, especially in the agricultural sector.

Projected restrictions on the availability of water for food production could be overcome by improving WUE, which is a strong indication of improved agricultural water management. Improved WUE is possible through innovations in irrigation, technological development in drainage systems, improved crop tolerance, and productive land use (precision agriculture). Deficit irrigation applications combined with water use from shallow groundwater could be an approach to increase WUE in arid and semi-arid areas where water supply is limited (Franzen, 2013). Maintaining optimal water table levels through controlled drainage provides the best crop water use and aeration within the plant root zones, as well as limits the accumulation of salts near the soil surface, which leads to improved plant root distribution and crop yield (Zhang et al., 2018; Fidantemiz et al., 2019; Kadioglu et al., 2019). When the water table depth is maintained at an optimum level for a crop, the water table becomes an accessible water source to support the crop water requirement. Consequently, the crop yield increases while the amount and frequency of surface irrigation decreases (Fidantemiz et al., 2019).

The study of groundwater under open field conditions is challenging and unreliable as many causative factors are not under control and accurate observations are very difficult. Therefore, a lysimeter is an ideal system used to simulate and evaluate a single parameter at a time (Luo and Sophocleous, 2010). Several studies have been conducted utilizing lysimeter to investigate the effects of shallow groundwater table levels on water use and yield of various crops, including soybeans (Mejia et al., 2000; Fidantemiz et al., 2019), corn (Bhuiyan and Alagcan, 1990; Kalita and Kanwar, 1992; Kahlown and Ashraf, 2005; Nosetto et al., 2009), canola (Kadioglu et al., 2019), wheat (Luo and Sophocleous, 2010; Liu and Luo, 2011; Karimov et al., 2014; Noshadi and Karimi, 2021), and cotton (Kang et al., 2012). In the present study, the impact of groundwater table levels on spring wheat production was evaluated under controlled conditions using a lysimeter system to determine the optimum WTD to achieve the best spring wheat yield and seed quality. The objectives of the current study were (i) to assess the impact of different WTD (30, 60, and 90 cm) on spring wheat growth, yield, and water use, (ii) to investigate spring wheat root distribution at different WTDs, and (iii) to determine the impact of different WTDs on spring wheat seed quality.

3.2. Materials and Methods

3.2.1. Experimental Setup, Planting, and Harvesting

For the lysimeter construction, Schedule-40 PVC pipes with a diameter of 12.58 cm (6 inches), a wall thickness of 0.5 cm (0.2 inches), and a height of 127 cm (50 inches) were used. The bottom part of the lysimeters was closed with caps to hold the water in the lysimeter. An opening was created at the bottom end of each lysimeter to allow for a tubing connection to the Mariotte bottles. The Mariotte bottles were constructed using 4-liter amber glass bottles with 5.7 cm (2.25 inches) holes placed on the cap for air outlet and tube connection to the lysimeter (Fidantemiz et al., 2019; Kadioglu et al., 2019). The Mariotte bottles were placed on adjustable shelves, and their heights were adjusted to the target WTDs. The Mariotte bottles were connected to the lysimeters from the bottom, and they continuously supplied water to the lysimeters at a constant flow rate. The water volume in the Mariotte bottles was measured continuously during the experiments to determine the water consumption of the plant (spring wheat). Water reduction in the Mariotte bottles was monitored, and the volume difference was considered as the plant water consumption from the groundwater table. Graduated cylinders were used to replenish the water in the Mariotte bottles. Tap water was used in this study for both irrigation (controls) and WTD treatments.

Bulk field loam topsoil was collected from an agricultural field near Fargo, ND. The soil samples were air-dried for a week and mixed by adding 300 g of sand to each 1 kg of field soil to prevent soil compaction in the lysimeters (Kadioglu et al., 2019). The soil's physical properties were measured at the NDSU Soil Testing Laboratory (Table 1).

A total of thirty-two lysimeter columns and twenty-four Mariotte bottles were used for the study. The study comprised of four treatments include; three different WTDs (T30 = 30 cm, T60 = 60 cm, and T90 = 90 cm) and one surface irrigation treatments (Tcontrol = control treatment, no water table). Each treatment consists of eight replicates (R1 to R8), resulting in 24 lysimeters for the WTD treatments and eight lysimeters for the control treatments. The 32 lysimeters were packed with gravel at the bottom (8 cm), and sand directly above the gravel (8 cm), and then filled with the sandy loam soil (100 cm) through the top of the lysimeters (Figure 2). The lysimeters were distributed using a randomized complete block design method with eight blocks for the eight replications.

A total of 15 soil moisture potential sensors (SMPSs) (TEROS-21, METER Group, Inc., Pullman, WA, USA) were used to monitor the soil moisture content of the control and WTD treatments as well as to determine the irrigation amount and timing for the control treatments. Three SMPSs were placed in control treatment lysimeters at the depths of 15, 45, and 75 cm. One SMPS was placed in T30 WTD treatment lysimeters at the depth of 15 cm from the top of the soil. Two SMPSs were placed in T60 WTD treatment lysimeters at the depths of 15 and 45 cm, while three SMPSs were placed in T90 WTD treatment lysimeters at the depths of 15, 45, and 75 cm. A VP-4 sensor (METER Groups, Inc., Pullman, WA, USA) which is used to measure humidity and air temperature was positioned at the middle of the greenhouse. The installed SMPSs and Vp-4 were connected to three multichannel data loggers (ZL6, METER Group, Inc., Pullman, WA, USA). An atmometer (ETgage-model E, C&M Meteorological Supply, Colorado Springs, CO, USA) that was used for measuring reference crop evapotranspiration (ET_0), was placed in the greenhouse and connected to HOBO pendant event data loggers (Onset Computer, Bourne, MA, USA) to monitor the daily evapotranspiration in the greenhouse. Similarly, the packed soil field capacity, readily available water (RAW), permanent wilting point, and bulk density were determined using HYPROP-FIT data evaluation software (METER Group, Inc., Pullman, WA, USA) and WP4 method (Roy et al., 2018).

Table 1. Textural properties, field capacity (FC), readily available water (RAW), permanent wilting point (PWP), and bulk density (BD) of study soil.

Soil fraction			Soil physical properties				
Sand (%)	Silt (%)	Clay (%)	Soil texture	FC (cm^3/cm^3)	RAW (50%) (cm^3/cm^3)	PWP (cm^3/cm^3)	BD (g/cm^3)
43	35	22	Loam	0.32	0.26	0.21	1.43

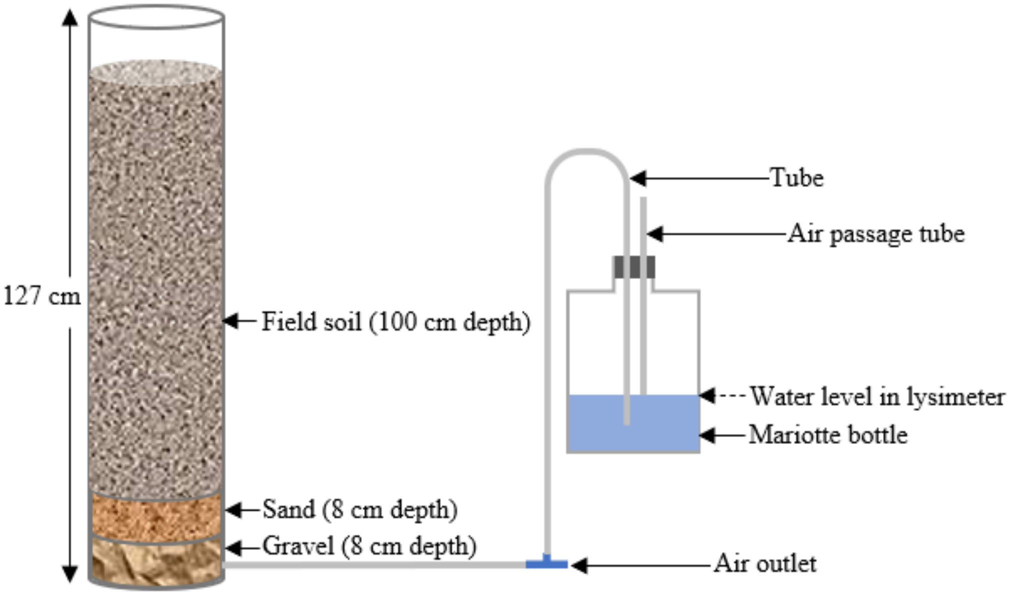

Figure 2. Schematic diagram of lysimeter and Mariotte bottle system.

After soil packing (before planting), all the lysimeters were completely filled with water to the top to provide uniform water curve conditions across the treatments. The water was drained out of the lysimeters by opening the valves at the bottom over 36 hours to allow for sufficient drainage. Afterward, the Mariotte bottles were filled with water, connected to the lysimeter columns, and placed on the adjustable shelves according to targeted WTDs. As a wheat cultivar, North Dakota VitPro Hard Red Spring Wheat was used. Eight hard red spring wheat kernels were planted in each of the thirty-two lysimeter columns. The germination and growth stages were monitored and recorded. Over the growing period (September to December 2020), irrigation was applied to only the control treatments by checking the readings from the soil moisture sensors, which were placed inside the lysimeters. The plants had a 12-hour photoperiod for the first four weeks after germination in the greenhouse, then the light exposure time increased to 14 and 16 hours after two and six weeks of germination, respectively, until the time of harvest. The greenhouse temperature was adjusted to 21ºC daytime and 15ºC nighttime, and the light intensity (artificial lights, Sunblaze T5 4'x8 with Spectralux 6500K lamps) was around 775 µM $m^{-2}s^{-1}$. Harvest was carried out after the wheat plants had reached a physiological mature condition (the point where the peduncle meets the first spike was brown upward to the top of the spike).

3.2.2. Spring Wheat Growth Characteristics, Yield, and Root Distribution Assessment

Following the harvest, plant yield parameters, aboveground biomass, and root biomass were measured. The aboveground biomass was determined by cutting stems just above the soil surface and weighing to determine the fresh weight. After weighing, the plants were dried at 80ºC and weighed again to determine the dry weight. The number of seeds was counted after threshing the spikelets manually. The yield was determined as the total weight of the seeds per plant (after removing the seeds from the enclosing capsules). Following aboveground biomass determination, three columns were selected from each treatment for the root distribution assessment. The soil cores from each of the selected columns were carefully extracted at three depths (0 – 40 cm, 40 – 70 cm, and 70 – 100 cm) to determine the root distribution in each column and to identify how the WTD impacted the root development and distribution. The extracted soil cores were placed over a screen then rinsed to separate coarse roots from the soil. After rinsing, the roots were oven-dried and weighed to determine the below-ground biomass.

3.2.3. Spring Wheat Seed Quality Assessment

Wheat kernels were analyzed in the Wheat Quality Laboratory at NDSU to determine the quality of the harvested wheat grains. The length and width of the wheat kernels were measured using a Mitutoyo caliper. Furthermore, the harvested kernels were analyzed to determine the starch and gluten protein properties. The starch granule morphology was determined using scanning electron microscopy (SEM) at the NDSU Electron Microscopy Center, Fargo, ND. Samples were mounted on aluminum mounts with silver paint. After attachment to the mounts, the samples were coated with gold-palladium using Balzars SCD030 sputter coater. The samples were photographed using a JEOL JSM-6300 scanning electron microscope. Rapid Visco Analyzer (RVA) model 4SA (Newport Scientific) was used to determine the starch pasting properties of the kernels following the AACC International Method (Method 76-21-02). The RVA equipment was interfaced with a computer equipped with Thermocline and Thermoview software (Newport Scientific). Starch (3.5 g, based on 14% moisture basis) was added to deionized distilled water (25 ml, based on 14% moisture basis) in an RVA canister. The rate of heating and cooling was 12°C/min, and the idle temperature was 50°C. The total run time for each sample was 13 min.

Proteins were extracted from kernel sample flour following published protocols with minor modifications (Gupta et al., 1993; Ohm et al., 2009). The 10 mg (12% moisture basis) powder was suspended in 1 mL of 0.5% sodium dodecyl sulfate (SDS) and 0.05 M sodium phosphate buffer (pH 6.9) followed by stirring for 5 min (at 2,000 rpm) using a mixer (Eppendorf Thermomixer C) to obtain SDS extractable proteins. The supernatant was separated after centrifuging the mixture for 15 min at 17,000 g (Eppendorf Centrifuge 5424). The residue was sonicated in the 1 mL of extraction buffer for 30 sec at 10 W output to solubilize SDS unextractable proteins using a Sonic Dismembrator 100 (Fisher Scientific) and the sonicated mixture was also centrifuged as described for the extractable fraction. The supernatants from extractable and unextractable fractions were individually filtered by a membrane (0.45 mm PVDF) and then heated in a water bath at 80°C for 2 min (Larroque et al., 2000) to remove any enzyme activity.

The Size Exclusion-High Performance Liquid Chromatography (SE-HPLC) was performed on a narrow-bore size exclusion column (Yarra 3μm SEC S4000, 300 x 4.6mm, Phenomenex, Torrance, CA) with a guard cartridge (BioSep SEC S4000) using an Agilent1100 Series chromatograph (Agilent Technologies, Santa Clara, CA) (Larroque and Bekes, 2000; Ohm et al., 2009). The SE-HPLC settings were as follows: injection volume, 10 μL; eluting solution, 50% acetonitrile in aqueous 0.1% trifluoroacetic acid solution; flow rate of 0.5 mL/min; and detection, UV 214 nm absorbance (Photodiode array detector, 1200, Agilent Technologies).

3.2.4. Calculation of Crop Water Use from Groundwater and Applied Irrigation

After the harvest, three randomly selected lysimeters from each of the treatments were cut vertically to determine the spring wheat plant water use. The water use of the plants in the selected lysimeters was determined following the soil water balance equation (Eq. 1) (Hillel, 2004):

$$(\Delta \mathrm{S}) = (\mathrm{P} + \mathrm{I} + \mathrm{Cr}) - (\mathrm{R} + \mathrm{Dp} + \mathrm{ET}) \tag{1}$$

where ΔS is the change in storage in the soil profile (mm), P is precipitation (mm), I is irrigation (mm), Cr is the capillary rise (mm), R is runoff (mm), Dp is deep percolation (mm), and ET is evapotranspiration (mm). The experiment was performed in a controlled environment; hence, precipitation, irrigation, runoff, and deep percolation did not occur in the lysimeters. Considering the controlled environment, the soil water balance equation is simplified, as shown in Eq. (2).

$$\mathrm{ET} = \mathrm{Cr} + \mathrm{S1} - \mathrm{S2} \tag{2}$$

where S1 and S2 are water storages in the soil profile. At the beginning of the study, the initial moisture conditions of the lysimeters were determined by using soil water potential sensors and soil moisture release curve. The amount of water stored in the lysimeters at the beginning of the experiments (the initial condition) was approximately 360 and 168 mm for different WTD treatments and control treatment, respectively. Based on the developed soil water release curve, 50% of the total available water was considered as the threshold for the RAM in the soil profile for irrigation to the control treatments. The depth (d, cm) of the required irrigation was determined using the Eq. (3) (Majumdar, 2013):

$$d = \sum_{i=1}^{n} \frac{F_{ci} - M_{bi}}{100} x A_{si} x D_i \quad (3)$$

where F_{ci} denotes field capacity of the layer in percent by weight, M_{bi} is the current water content of the layer in percent by weight, A_{si} denotes apparent specific gravity (bulk density, mg/cm^3), D_i denotes the depth of each layer (cm), and n is the number of layers.

3.2.5. Water Use Efficiency (WUE)

WUE (g cm^{-1}) was calculated for the WTD and control treatments using Eq. (4) described by Bai et al., 2020. The WUE for the WTD treatment was calculated as grain yield (Y, g plant^{-1}) divided by water consumed by the spring wheat plants in the WTD treatment columns (ETc) to produce the yield:

$$\mathrm{WUE} = \frac{\mathrm{Y}}{\mathrm{ETc}} \quad (4)$$

The WUE for the control (irrigation) treatment was calculated as grain yield (Y, g plant^{-1}) divided by the amount of irrigation applied to the spring wheat plants in the control treatment columns (ETi) to produce the yield (Eq. 5).

$$\mathrm{WUE} = \frac{\mathrm{Y}}{\mathrm{ETi}} \quad (5)$$

3.3. Statistical Analysis

The significance of differences among the treatment means was tested by one-way analysis of variance (ANOVA) at 95% confidence level ($P \leq 0.05$ significance level) using Statistical Package for the Social Sciences (SPSS) version 27.0. Fisher's protected least significant difference (LSD) test at $P \leq 0.05$ level of significance was used to separate treatment means where appropriate. Pearson partial correlation (two-tailed) and multiple regression were used to analyze the relationship among WTD with spring wheat yield, aboveground and below-ground biomass, and crop water use at $P \leq 0.05$ probability level, where appropriate.

3.4. Results and Discussions

3.4.1. Greenhouse Temperature and Reference Crop Evapotranspiration

To monitor the temperature and reference crop evapotranspiration (ET_0) in the greenhouse during the spring wheat growing period, daily air temperature and ET_0 readings were collected between September 24 (planting) and December 24 (harvest), 2020 (Figure 3). The daily air temperature readings were determined between 16.9 ± 3.7 and 19.8 ± 4.3ºC. The highest average air temperature was observed during the harvest stage, while the lowest average air temperature was observed in the middle of the growing period (in November). The daily ET_0 reading from the atmometer during the growing period was between 3.9 and 7.6 mm, with the lowest and highest ET_0 readings observed during germination and after anthesis (when the wheat plant started flowering), respectively. Cumulative ET_0 was calculated as 591.53 mm during the entire period of the experiment (92 days). Due to the controlled temperature conditions of the greenhouse, there was no noticeable effect of air temperature on the ET_0 as the temperature was mostly uniform throughout the experiment.

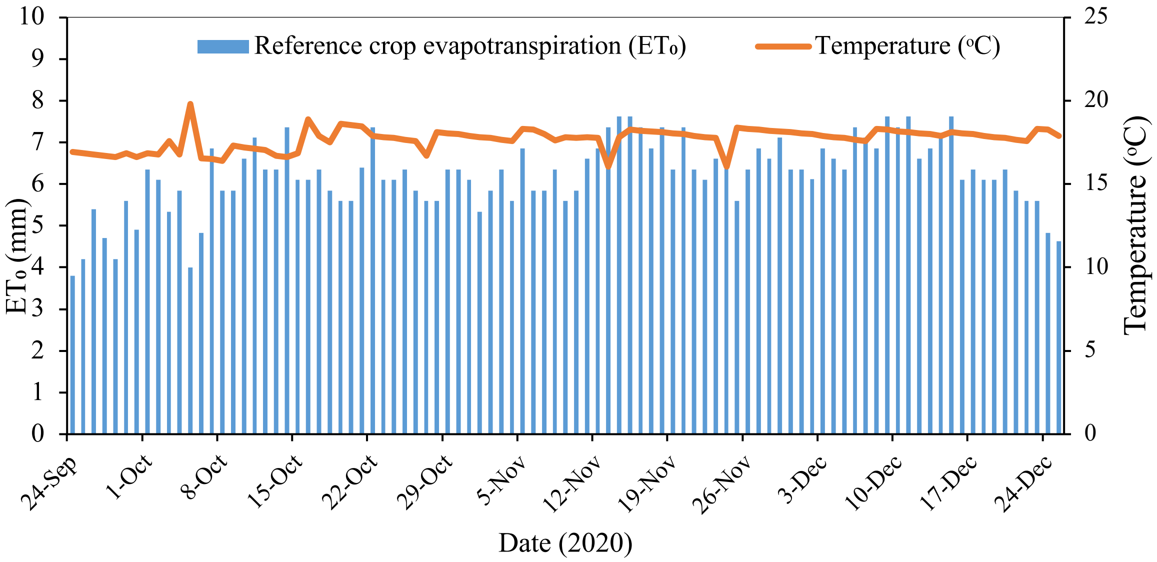

Figure 3. Daily greenhouse air temperature (°C) and reference crop evapotranspiration (ET_0, mm) over the growing period (September – December 2020). The air temperature and ET_0 readings were obtained from a VP-4 sensor and an atmometer (ETgage), respectively.

3.4.2. Soil Moisture Content and Irrigation Regime of Control Treatment

The daily soil moisture content and irrigation regime for the control treatment varied throughout the growing period (Figure 4). The soil moisture content was maintained between field capacity and readily available water (RAW) to prevent plant exposure to water stress as a result of either excess or insufficient irrigation. To ensure the control treatment received the required amount of irrigation during the growing period, plant root depths were assumed at different growth stages for calculating the crop water requirements of the respective growth stage. Based on described spring wheat root development (Thorup-Kristensen, 2009), the plant root depths were projected to be at: 30 cm depth between September 24 and October 24; 60 cm depth between October 24 and November 26 and; 90 cm depth after November 24 to harvest. Irrigation was applied up to the specified root depths following the calculated crop water requirements.

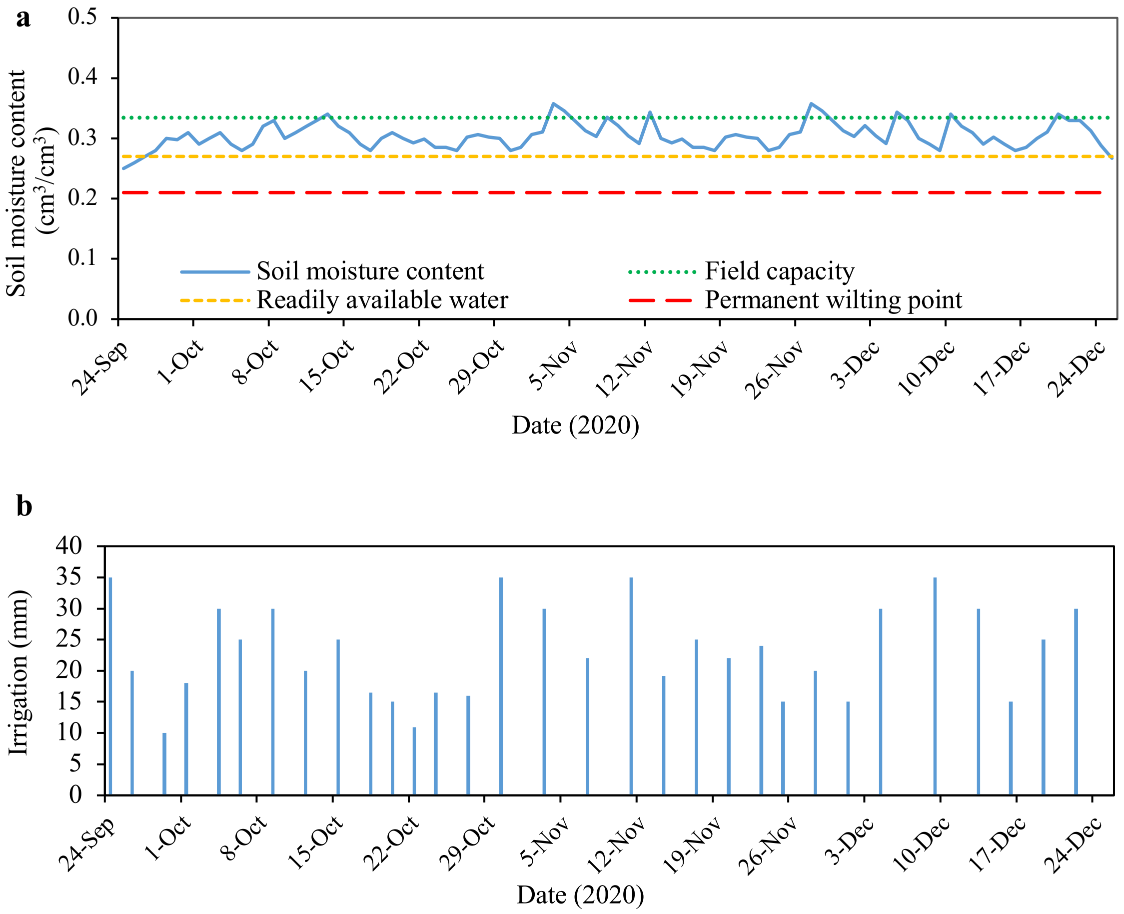

Figure 4. Control treatment (a) soil moisture content and (b) irrigation regime throughout the growing period (September 24 to December 24).

3.4.3. Growth Characteristics and Grain Yield

Treatment differences were significant ($P \leq 0.05$) for plant height, aboveground biomass, number of kernels, grain yield, 1000- kernel weight, and average weight per kernel. The results showed that the growth parameters were affected by WTD. Plants in T30 had the lowest values for aboveground biomass, number of kernels, and grain yield (Table 2). Plants in Tcontrol had the lowest 1000-kernel weight and average weight per kernel, but weights were only less than those for plants in the T90 WTD. Plants in T90 WTD treatment had the greatest values for plant height, aboveground biomass, 1000-kernel weight, and average weight per kernel. Similar to the growth parameter results, the grain yield increased with increasing WTD from 60 to 90 cm.

These findings were similar to those obtained by Noshadi and Karimi (2021). Crop growth and yield have been linked to soil moisture in the root zone (Bai et al., 2020; Zhang et al., 2000). When the groundwater table was lower than 70 cm, soil aeration was reduced in the root zones, which decreased root penetration through the soil profile, thus leading to reduced grain yield (Wesstrom et al., 2001).

Table 2. Influence of water table depth on wheat growth and yield components.

Treatment	Plant height	Aboveground biomass	Number of kernels	Grain yield	1000-kernel weight	Average weight/kernel
	(cm)	(g plant^{-1})	(kernels plant^{-1})	(g plant^{-1})	(g)	(mg kernel^{-1})
T30	56.2 ± 7.7a	3.1 ± 0.1a	32.5 ± 0.11a	0.98 ± 0.1a	29.6 ± 0.9a	3.0 ± 0.08a
T60	65.0 ± 3.3ab	4.9 ± 0.8b	47.8 ± 12.4ab	2.9 ± 0.8b	32.1 ± 0.4ab	3.2 ± 0.04ab
T90	67.5 ± 3.1b	5.6 ± 0.9b	54.8 ± 12.9b	3.4 ± 0.7c	34.1 ± 4.2b	3.4 ± 0.42b
Tcontrol	64.9 ± 5.7b	4.9 ± 1.3b	63.3 ± 9.5b	3.4 ± 0.4c	27.3 ± 0.5a	2.7 ± 0.05a

Note: Mean ± standard deviation; The same letter(s) in a column are not significantly different according to Fisher's Protected Least Significant Difference (LSD) $P \leq 0.05$ probability level. Treatments T30, T60, and T90 represent groundwater table depth treatments of 30, 60, and 90 cm depths from the soil surface in the lysimeter, respectively, with no applied irrigation, while Tcontrol represents control treatment with applied irrigation.

3.4.4. Root Biomass Distribution

The average root biomass of all the plants in the WTD and control treatments was the highest at the upper level of the soil (0-40 cm) (Table 4). The root biomass of plants in T30, T60, and Tcontrol treatments decreased as the soil depth increased, while the root biomass of the plants in T90 slightly decreased across the soil depths, with no substantial reduction at 40-70 cm and 70-100 cm soil depths (Figure 4). The plants in T30 had the lowest total average root biomass while the plants in T90 had the highest total average root biomass in the WTD treatments (Table 4). There was no significant difference ($P \leq 0.05$) between the average root biomass of the plants in T90 and Tcontrol treatments, even though T90 had the highest total average root biomass values among all the treatments. Similar to the grain yield, plant height, total biomass, and kernel weight results, plants in the WTD T90 treatment had the greatest total root biomass value. These results were similar to those reported by Fidantemiz et al. (2019) and Kadioglu et al. (2019) where root biomass was lowest at T30 and highest at T90. According to Kahlown and Azam (2002), waterlogging under shallow water table depth deteriorates the physiological and environmental conditions in the root zone and is not conducive for crop growth and ultimately for yields. This further explains why the root biomass and grain yield were lowest in T30 WTD, and highest in T90 WTD.

Table 3. Influence of water table depth on root biomass distributions.

Treatment	Root biomass (g) per soil depth			Total root biomass (g)
	0 – 40 cm	40 – 70 cm	70 – 100 cm	
T30	3.7 ± 0.33	1.7 ± 0.39	0.95 ± 0.29	6.35 ± 1.23
T60	5.1 ± 0.30	3.4 ± 0.34	1.7 ± 0.72	10.2 ± 1.47
T90	5.2 ± 0.39	3.8 ± 0.68	3.6 ± 0.60	12.6 ± 1.00
Tcontrol	5.1 ± 0.39	3.8 ± 0.13	2.9 ± 0.26	11.7 ± 1.61

Note: The soil profilces divided into three sections as 0 – 40, 40 – 70, and 70 – 100 cm from top to bottom of the lysimeters. Treatments T30, T60, and T90 represent groundwater table depth treatments of 30, 60, and 90 cm depths from the soil surface in the lysimeter, respectively, with no applied irrigation, while Tcontrol represents control treatment with applied irrigation.

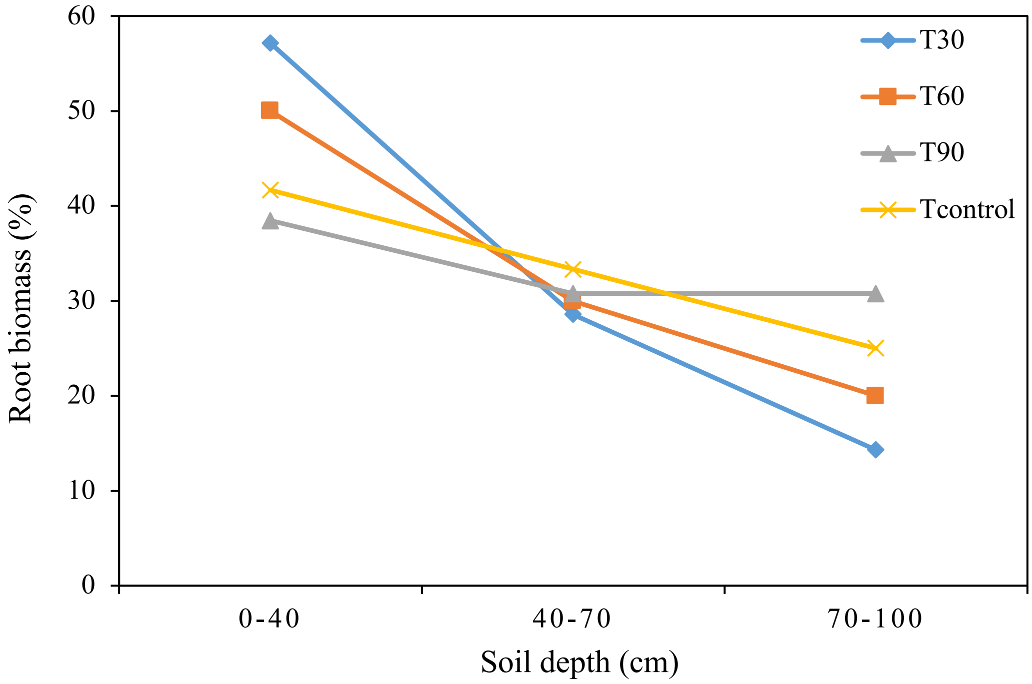

Figure 5. Root biomass distribution (%) of the plants in the water table depth (WTD) and control treatments. Treatments T30, T60, and T90 represent groundwater table depth treatments of 30, 60, and 90 cm depths from the soil surface in the lysimeter, respectively, with no applied irrigation, while Tcontrol represents control treatment with applied irrigation.

3.4.5. Water Use and Water Use Efficiency (WUE)

Prior to commencing the experiment, the soil moisture content was placed at field capacity (-33 kPa) by adding an equal amount of water (360 mm) across all the treatments. The ETc values of the WTD treatments decreased with increasing WTDs from 30 to 90 cm (Table 4). The plants in T30 WTD had the highest ETc values, while the plants in T90 WTD had the lowest ETc values. Hence, plants in T30 WTD used the most groundwater, while plants in T90 WTD utilized the lowest amount of groundwater. The control treatment, which was irrigated throughout the experiment had the highest water use with ETi values of 721 ± 2.16 mm. The WUE results showed that for plants in the WTD treatments; T30 had the lowest WUE while T90 had the highest WUE (Figure 5). The control treatment recorded the lowest WUE compared to all the WTD treatments (Figure 6). Significant differences ($P \leq 0.05$) in water use by the plants were observed among the treatments. However, there was no significant difference ($P \leq 0.05$) in crop water use between T30 and Tcontrol. The results suggested that for wheat production without any supplementary irrigation, groundwater can meet the necessary water requirements to produce a high yielding crop when the optimum water table is maintained (Ghamarnia and Farmanifard 2014). Similar to these results, Kahlown and Ashraf (2005) reported that groundwater contribution was the highest under the shallowest water table, which gradually reduced with increasing WTD. Noshadi and Karimi (2021) also reported that groundwater use and WUE were best at 90 cm WTD.

Table 4. Influence of water table depth and control treatments on groundwater use (ETc) and irrigation water use (ETi), respectively by the spring wheat plants.

Treatment	Initial soil moisture content	Cumulative groundwater/irrigation used	Final soil moisture content	ET_c/ET_i
	mm	mm	mm	mm
T30	360 ± 0.00	603 ± 6.86a	278 ± 11.36a	706 ± 13.91a
T60	360 ± 0.00	428 ± 6.68b	242 ± 7.85b	546 ± 3.77b
T90	360 ± 0.00	330 ± 7.50c	229 ± 5.00b	487 ± 9.22c
Tcontrol	168 ± 0.00	736 ± 0.00d	183 ± 2.16c	721 ± 2.16a

Note: Mean ± standard deviation; The same letter(s) in columns are not significantly different at the $P \leq 0.05$ probability level. Treatments T30, T60, and T90 represent groundwater table depth treatments of 30, 60, and 90 cm depths from the soil surface in the lysimeter, respectively, with no applied irrigation, while Tcontrol represents control treatment with applied irrigation.

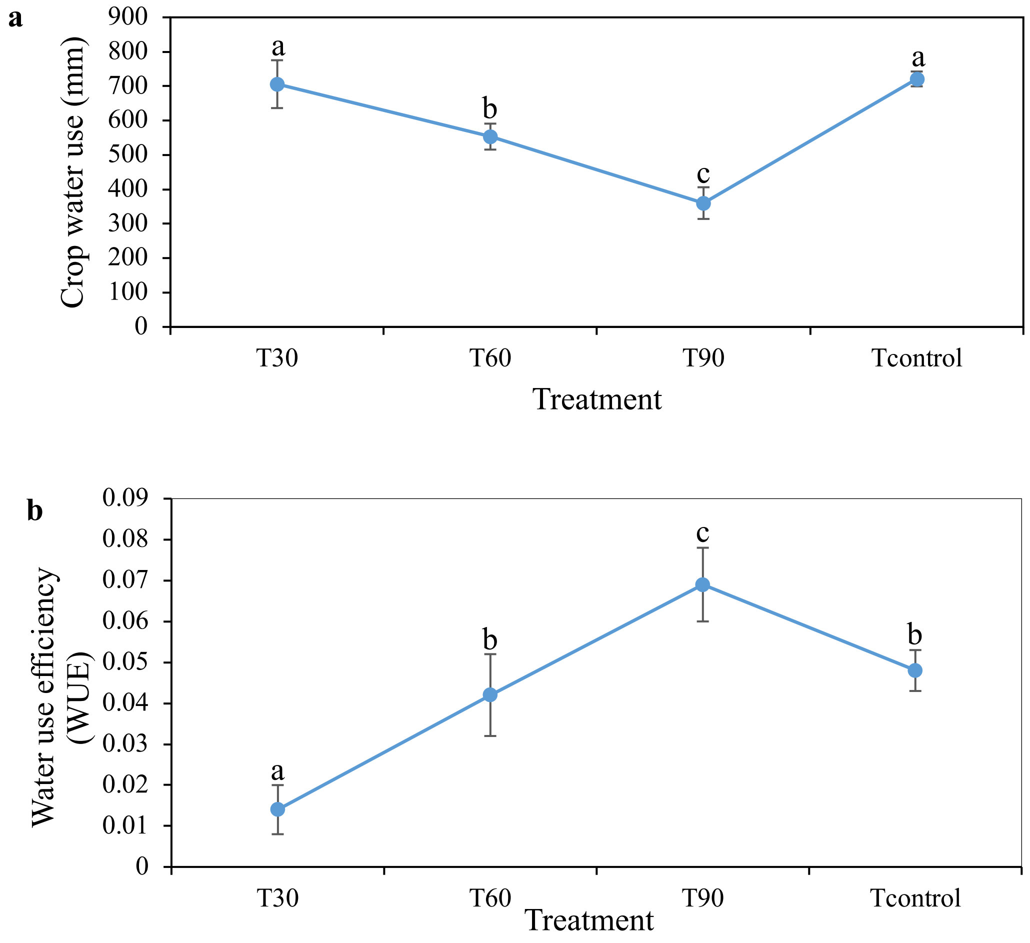

Figure 6. (a)Water use and (b) water use efficiency of the WTDs and control treatments. Values represent the mean ± standard deviation of each treatment. Error bars with the same letter(s) are not significantly different at the $P \leq 0.05$ probability level. Treatments T30, T60, and T90 represent groundwater table depth treatments of 30, 60, and 90 cm depths from the soil surface in the lysimeter, respectively, with no applied irrigation, while Tcontrol represents control treatment with applied irrigation.

3.4.6. Spring Wheat Seed Quality

The scanning electron microscopy (SEM) images of the wheat kernels from the WTD and control treatments showed that the extractable starch had distinctive large (A-granules) and small (B-granules) starch granules (Figure 7). The A-granules are identified by the characteristic disk-like shape, whereas the B granules tend to be spherical (Singh et al., 2003), both exhibiting a smooth surface (Magallanes Lopez et a., 2019). The SEM images of the wheat kernels across the treatments showed no noticeable difference, although some damaged starch granules were detected across the treatments. However, none of the observed damage was attributed to the differences in WTD. Water stress during germination and fungal infections are some of the main factors that may affect starch composition (Jackowiak et al., 2005; Gou et al., 2017). In this study, the wheat plant was not exposed to either water stress or diseases. This may help explain why there were no noticeable differences in the starch content across treatments based on the SEM images.

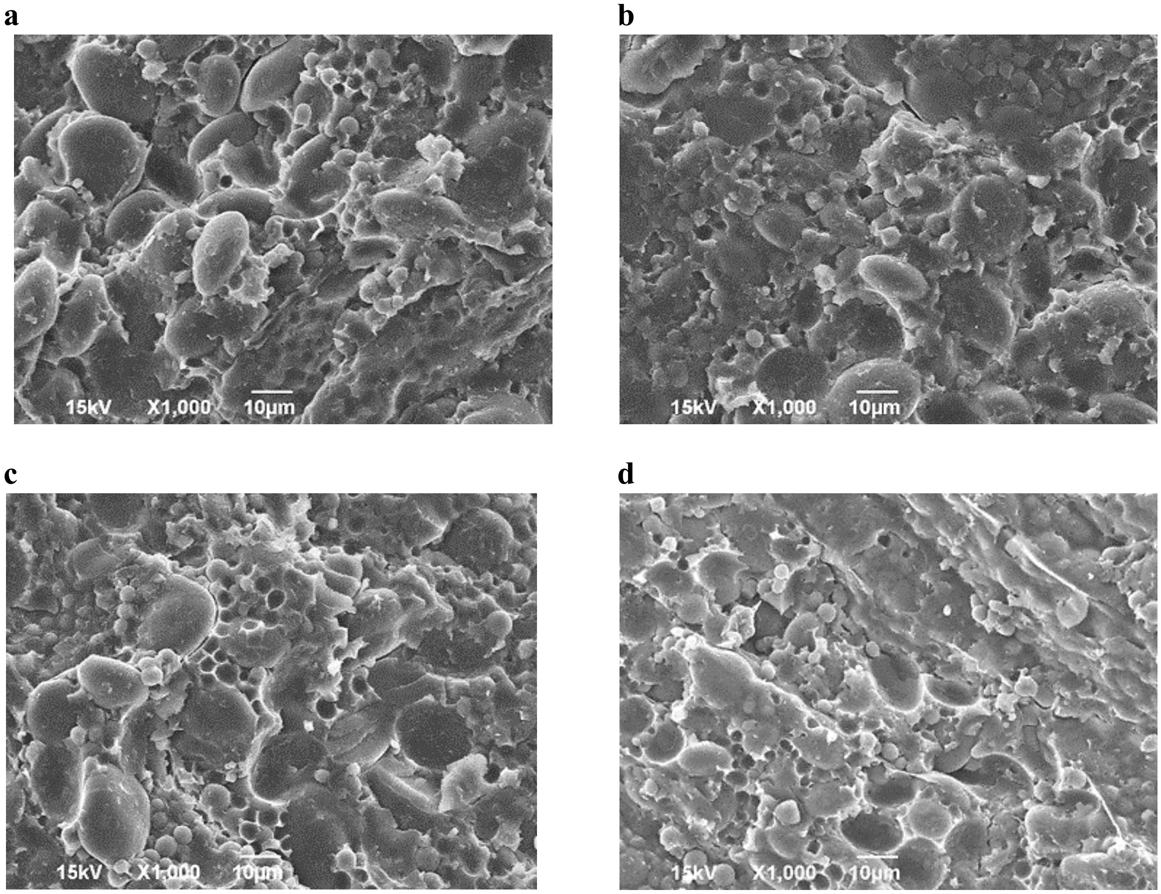

Figure 7. Scanning Electron Microscopy (SEM) images of extracted starch from spring wheat seeds harvested from plants grown in different treatments. (a) T30 (b) T60 (c) T90, and (d) Tcontrol treatments. T30, T60, and T90 represent groundwater table depth treatments of 30, 60, and 90 cm depths from the soil surface, respectively, with no applied irrigation, while Tcontrol represents control treatment with applied irrigation.

Significant associations appeared between protein molecular weight distribution (MWD) parameters and breadmaking quality characteristics (Ohm et al. 2010). Specifically, Ohm et al.

(2010) reported that SDS-unextractable fraction 1(F1) had positive correlations with breadmaking parameters, and SDS-extractable F1 had negative correlations among hard spring wheat genotypes. The absorbance area (AA) represents the quantity of protein fraction based on flour weight and the area % represents the percent of the protein fraction based on total protein. Similar to the starch component results, the gluten protein fractions analyses did not show any significant differences across the treatments (Figure 8).

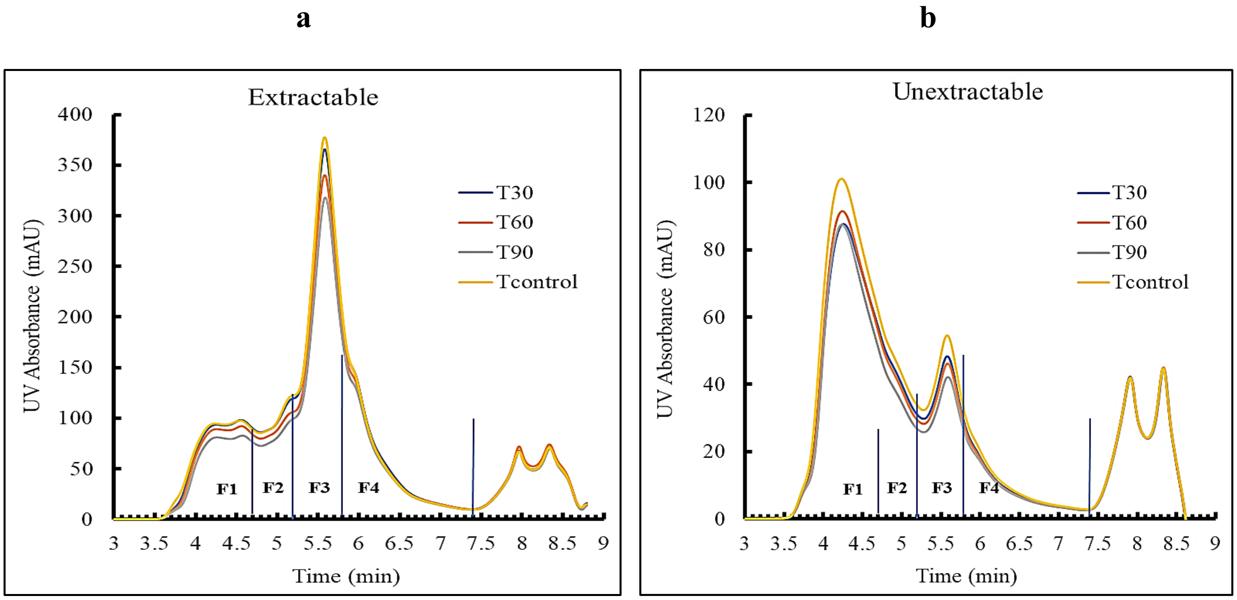

Figure 8. Size-exclusion HPLC separation of (a) extractable and (b) unextractable protein fractions of spring wheat seeds harvested from plants grown in different treatments. The chromatograms are divided into four fractions as follows: F1- high molecular weight (MW) polymeric proteins (3.5-4.7 min), F2- low MW polymeric proteins (4.7-5.2 min), F3- gliadin (5.2-5.8 min), and F4- albumin and globulins (5.8-7.4 min). Treatments T30, T60, and T90 represent groundwater table depth treatments of 30, 60, and 90 cm depths from the soil surface in the lysimeter, respectively, with no applied irrigation, while Tcontrol represents control treatment with applied irrigation.

4. CONCLUSIONS AND FUTURE WORK RECOMMENDATIONS

4.1. Conclusions

This present study evaluated the impact of groundwater table depths on the yield, water use, root distribution, and seed quality of hard red spring wheat under controlled conditions in a greenhouse using the lysimeter technique. Results indicated that the growth and yield of the hard red spring wheat plants were affected by WTD. Yield and growth characteristics, including the plant height, aboveground biomass, number of kernels, 1000-kernel weight, and average weight per kernel, increased as WTD increased from 30 cm to 90 cm. Similarly, crop water use reduced with increasing WTD, while WUE increased as WTD increased with plants grown at the 90 cm WTD having the lowest crop water use and highest WUE. The crop water use between T30 and Tcontrol were similar.

The hard red spring wheat root growth varied depending on the WTD and indicated the effect of WTD on root distribution. The wheat plants root biomass across all the treatments was found to be higher at the upper zone of the soil profile 0-40 cm depth. The root biomass of plants in T30, T60, and Tcontrol treatments decreased as the soil depth increased, while the root biomass of the plants in T90 slightly decreased across the soil depths, with no substantial reduction at 40-70 and 70-100 cm soil depths. There was no significant difference ($P \leq 0.05$) between the average root biomass of the plants in T90 and Tcontrol treatments, with T90 having the highest total average root biomass values among the treatments.

The seed quality assessment showed that WTD did not influence the quality of hard red spring wheat grains. This may be due to the fact that the wheat plants were not exposed to water stress and/or fungal diseases, which are some of the main factors known to affect seed quality.

Overall, the yield, water use, and root distribution results indicated that 90 cm is the optimum WTD for the best hard red spring wheat production.

4.2. Future Work Recommendations

i. This study could be conducted in real field conditions using the lysimeter technique to correlate the greenhouse results.

ii. The WTD could be extended beyond 90 cm (up to 150 cm) to confirm if 90 cm is the optimum WTD, and also to observe if grain quality would be affected when the plants are exposed to water stress.

iii. Shallow groundwater quality is one of the critical factors affecting crop water use. In this experiment, groundwater salinity was not included. Hence, the combined effect of groundwater table depth and the impact of salinity could be included in future studies.

iv. The effect of the groundwater table on other wheat types like winter and durum wheats as well as other cultivars within each wheat type could be studied to determine the consistency in response to groundwater table contributions across wheat types and cultivars.

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APPENDIX. GERMINATION RATE

To understand the germination and growth stages of the spring wheat, ninety-six spring wheat seeds were planted in twelve pots containing wet field soils, with eight seeds in each pot. The pots were kept in the greenhouse at temperatures between 18 and 21 ºC and watered at least once every week. The seed germination per pot was monitored and recorded (Figure A1).

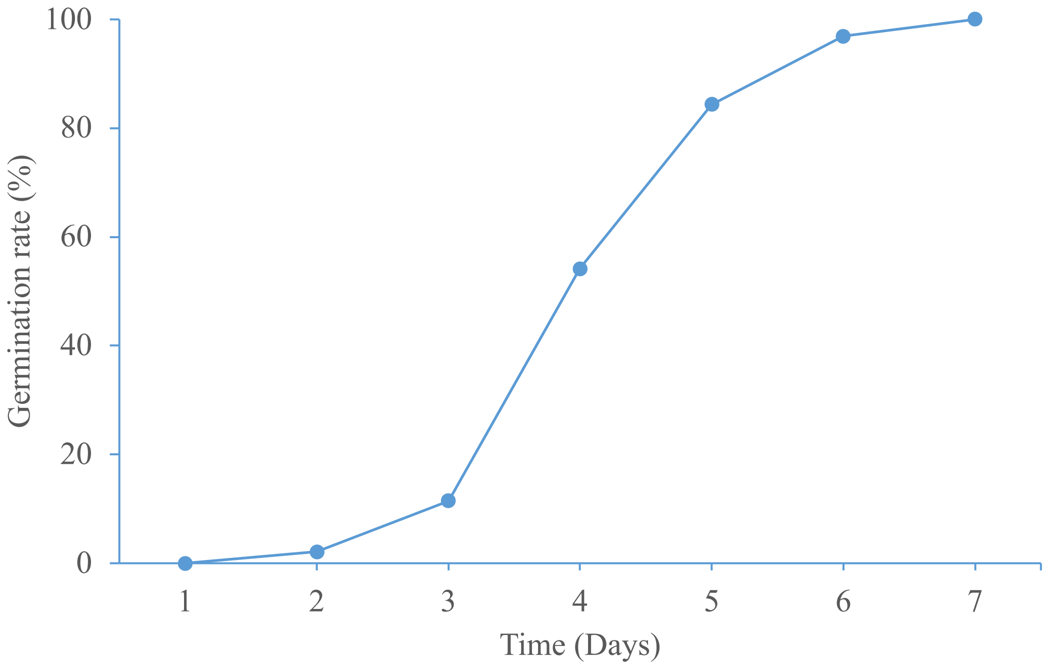

Figure A1. Germination rate of spring wheat.

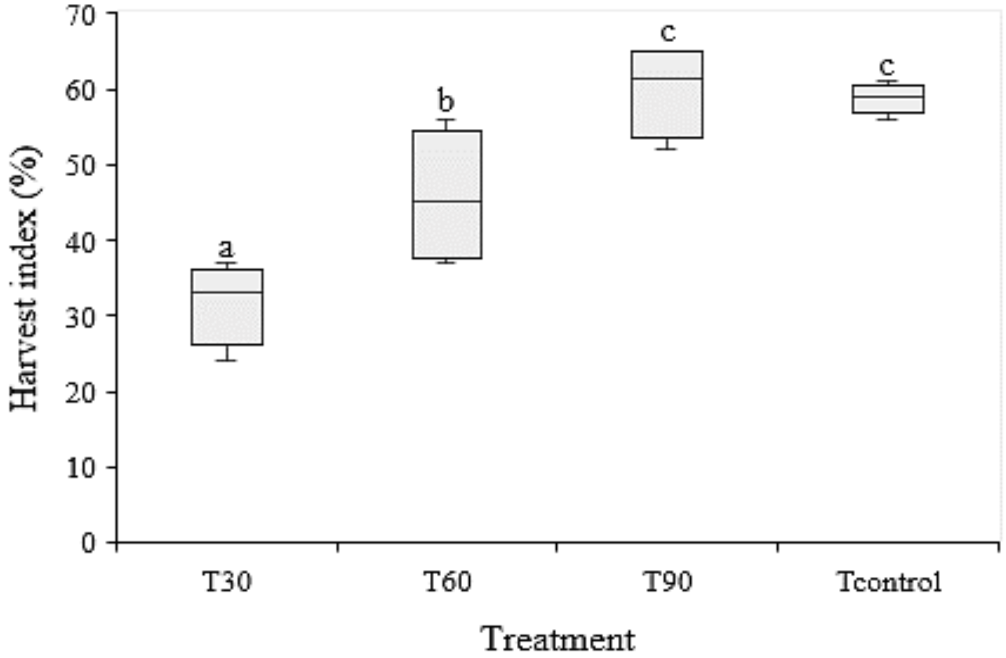

Figure A2. Spring wheat harvest index.

Table A1. Rapid visco analyzer (RVA) test of seed quality.

Treatment	Hot paste viscosity	Breakdown	Final viscosity	Setback	Peak time	Pasting temp.
	cP	cP	cP	cP	min	°C
Tcontrol	1049	688	1845	796	6.0	71.0
	1114	751	1945	831	6.1	70.2
T30	1125	759	1918	793	5.9	70.1
	1279	747	2086	807	6.1	70.2
T60	1033	728	1842	809	6.0	71.1
	1189	725	1993	804	6.1	71.0
T90	1071	711	1830	759	6.0	84.7
	1241	781	2088	847	6.1	70.2