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Melkamu Dugassa
Department of Plant and
Horticulture Sciences, College of
Agriculture, Hawassa University,
Hawassa, Po Box 05, Ethiopia

Crop management options for water use efficiency: Review

Melkamu Dugassa

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Abstract

The objective of this review paper is to organize relevant literature on management options for increasing water use efficiency. The review was organized by searching the research out puts from the various corners of the world. Water the major agricultural input whose scarcity is a major problem worldwide. The scarcity of water is one of the major limiting factors to crop production in the world. Water use efficiency refers to the rate at which water is used during plant growth while the ratio of yield to transpiration is transpiration efficiency. Agriculture consumes the most water and produces the most total evapotranspiration from agricultural land. Crop management starts with the sowing of seeds, continues with crop maintenance during growth and development, and ends with crop harvest, storage, and distribution. Improving the efficiency of agricultural water use is a major concern as water scarcity problems are becoming the key threats to agriculture. With growing concerns about the availability of water resources in both irrigated and rain fed agriculture, there is a renewed interest in trying to improve understanding of how the water use efficiency can be developed and how farming systems can be changed to be more efficient in water use. In order to use the available water for effective crop production, different management practices including crop residue return, organic fertilizer application, intercropping and optimization of water use are among the methods that can be employed for maximization of water use efficiency.

Keywords: Crop management, water scarcity, water use, water use efficiency, optimization of water use

Introduction

Water is one of the major agricultural inputs in the world and its scarcity is a major problem worldwide. Agriculture is the largest consumer of water and total evapotranspiration from agricultural land could double in the next 50 years if food consumption patterns and current production processes continue (Sharma *et al*., 2015) [46]. As the world's fossil fuel consumption and the population continues to grow, the water supply per person will continue to decrease which leads to water scarcity or pressure in some areas (Fonteh *et al*., 2013) [21]. Water scarcity is one of the major barriers to crop production in the world. Improving the efficiency of agricultural water use is a major concern as drought problems are becoming the key threats to agriculture. Plant water stress occurs when the need for evaporation exceeds the water from the soil. Water stress causes stomata blockage and reduces carbon dioxide absorption, leading to slower plant growth (Zhao *et al*., 2016) [63]. There is a pressing need to increase water efficiency, and more crucially, water productivity (Sharma *et al*., 2015) [46].

Crop water use efficiency (CWUE) can be defined in a number of ways. The term basically describes the amount of harvestable biomass produced by a crop per unit of consumed water. The value of crop water use efficiency is generally constant for a given crop but will vary slightly due to differences in environmental conditions that affect a crop's water requirements such as relative humidity and radiation intensity (Fan *et al*., 2016) [17]. Water use efficiency also commonly used to describe the crop yield produced per unit of irrigation water or rainfall received. Irrigation efficiency or precipitation efficiency can vary widely for a given crop and will be influenced by both environmental conditions and crop management practices (Chen *et al*., 2010) [12].

Based on the current and future water requirement for crop production and the importance of efficient water utilization, this review was compiled having the following objectives:

Corresponding Author:
Melkamu Dugassa
Department of Plant and
Horticulture Sciences, College of
Agriculture, Hawassa University,
Hawassa, Po Box 05, Ethiopia

1. To identify the role different crop management options for efficient use of water
2. To have a thorough understanding of the various mechanisms that affect water use efficiency under different crop management options.

Materials and Methods

This term paper is as a whole a review paper. All the data and information are adopted from sources. It was compiled through an exclusive going through different books, articles, and Journals. After collecting the necessary information, it has been compiled and arranged for better understanding and clarification.

Review findings

Crop management

Crop management is agricultural practice performed to improve the growth, development and yield of crops. Crop management starts with the sowing of seeds, continues with crop maintenance during growth and development, and ends with crop harvest, storage, and distribution (Tivy, 1990) [50]. Crops can be grown under a range of water management regimes, from simple soil tillage aimed at increasing the infiltration of rainfall to sophisticated irrigation technologies and management. Of the estimated 1.4 billion ha of crop land worldwide, around 80 percent is rain fed and accounts for about 60 percent of global agricultural output (Abdul Haris, 2018) [2]. In essence, crop management practices affect the subsurface habitat by means of two independent mechanisms. First, the physical shape of soil (hence the infiltration rate of water) is altered by using farm equipment passing over the soil, through cultivation implements, and by the penetration of soil by roots of the growing crop plants (Hamza and Anderson, 2005) [22]. Soil conditions like initial organic matter and pH of the soil had been of greater importance for increasing soil pH in field-based experiments. The type of the liming material and methods of using are most essential for enhancing crop yield (Li *et al.*, 2019) [35]. Similarly, for areas affected by salinity, appropriate crop selection for satisfactory yield under existing and predicted saline conditions is needed (Toderich *et al.*, 2008) [51].

Water use efficiency

Water efficiency (WUE) is a theory coined several years ago (Briggs and Shantz, 1913) [8] shows the relationship between crop production and water use. Water efficiency (WUE) can be defined on a variety of scales from leaf to field. In its simplest terms, WUE refers to the rate at which water is used during plant growth while the ratio of yield to transpiration is transpiration efficiency (Waraich *et al.*, 2011) [56]. According to (Fang *et al.*, 2010) [19], water use efficiency in agricultural system is generally defined as grain yield production per unit evapotranspiration. Proper water use represents the amount of biomass or grain yield per unit of water used by a plant (Amini Fasakhodi *et al.*, 2010) [4]. WUE is a reliable indicator of plant biomass production compared to water use, and is a measure between two physiological entities (transpiration and photosynthesis) or agronomic (yield and water use by plants), (Blum, 2005). WUE works best when there is a significant gain in the small amount of water available to a plant (Mueller *et al.*, 2005) [37], and it can be measured by efficiency of water in biomass growth or in the Harvest Index (Rebetzke *et al.*, 2002) [41].

Plants vary in their ability to use water and WUE vary from place to place. More importantly it may also vary due to soil conditions, agricultural processes including fertilization, and atmospheric factors (Mueller *et al.*, 2005) [37]. Typically, high water consumption occurs in the area of high biomass production (Cox *et al.*, 2002) [13]. WUE is much higher under limited irrigation conditions such as dry season in the tropics (Kang *et al.*, 2002) [28]. Water use efficiency can be increased by changing soil management practices that include changing the properties of the soil to increase water availability to plants because better monitoring of crops and soil healthiness are the important components of improving WUE. It can be calculated as follows:

$$\text{W.U.E} = \frac{\text{Total above ground dry matter produced}}{\text{Unit Soil water used over entire season}}$$

Source: (Singh *et al.*, 2007) [48]

Role of crop residue return in water use efficiency

Returning crop residues showed an improvement in WUE of wheat in India by 13% to 25% compared to no straw treatment according to (Chakraborty *et al.*, 2010) [11]. Similarly, returning crop residues has been reported to maintain soil moisture and reduce diurnal changes in soil temperature and ultimately increase WUE (Huang *et al.*, 2016) [26]. Incorporation of crop residues improve WUE by improving crop yields, maintaining soil moisture retention, and reducing soil moisture loss throughout the growing season even under normal soil water and mild drought conditions (Wang *et al.*, 2021a) [53]. In another study on residue return, it has been shown that the effect of residues on potato WUE depends on soil fertility, temperature, and inorganic fertilization conditions (Li *et al.*, 2018) [34]. The study conducted on impact of rice straw compost reported that the WUE and the productivity of grains of wheat and maize (Mgm^{-3}) acquired from every cubic meter water in each seasons (2017/2018) were improved (El-Gamal *et al.*, 2019) [16] as indicated in Table 1. The values for WUE ranged between 1.73 and 1.90 Mgm^{-3} for the wheat crop while it ranged between 1.15 and 1.46 Mgm^{-3} for maize crop. This may be attributed to the supply of rice straw compost as natural fertilizer and higher water retention in the root zone. In this respect, it has been reported that the use of rice straw-compost for tomatoes improved (WUE) water use efficiency (Ali *et al.*, 2006) [3]. Optimizing water consumption is a type of management options that may establish relationship between land and water under limitation of water/land conditions. So that crop production is economically affordable and technically possible (Kiani and Abbasi, 2012) [30].

Role of organic fertilizer application in water use efficiency

Organic amendments incorporation may enhance the organic matter content of the soil leading towards the sufficient moisture conservation and plant nutrient availability (Bot and Benites, 2005) [7]. The soil temperature is inversely correlated with the organic matter content, so the moisture depletion rate might decrease with the increased organic matter content (Shaver *et al.*, 2006). Increase organic matter concentrations in soil have showed to enhance the yield of cereals (Tahir *et al.*, 2011) [49], improve soil properties i.e. soil density, soil aeration and enhance the soil water holding capacity for plant growth and development (Bot and Benites, 2005) [7]. It has been indicated that there is a direct relationship between water use, nutrient uptake and biomass yield in plants (Nwachukwu and Ikeadigh, 2012) [39]. Water holding capacity of soils which has role for water use efficiency of crops is controlled primarily by the number of pores and pore-size distribution of soils; and the specific surface area soils (Hati *et al*., 2007) [23]. Increased aggregation and total pore spaces results in decreased bulk density, the pore-size distribution is altered and the relative number of small pores increases, especially for coarse textured soils (Khaleel *et al*., 1981). At the conditions of higher tensions close to wilting range, nearly all pores are filled with air and the moisture content is determined largely by the specific surface area and the thickness of water films on these surfaces (Vengadaramana and Jashothan, 2012) [52]. Because of their much less surface area than clayey soils, sandy soils retain much less water at higher tensions.

With the application of organic matter, specific surface area increases resulting in increased water holding capacity at higher tensions. Soil "holds" water available for crop use, retaining it against the pull of gravity and it is one of the most important physical facts for agriculture (Abdelraouf, 2014) [1]. We would have to constantly irrigate if the soil did not hold water and free to flow downward with the pull of gravity as in a river or canal, or hope that it rained every two or three days and there would be no reason to pre-irrigate and there would be no such thing as dry-land farming (Vengadaramana and Jashothan, 2012) [52]. Soil texture and organic matter are the key components that determine soil water holding capacity (Nath, 2014). Wastes application as either for plant nutrient supply or for disposal purposes, increases the C content of the soil that increases aggregation, decreases bulk density, increases water holding capacity, and hydraulic conductivity (Vengadaramana and Jashothan, 2012) [52]. Compost is an important source of plant nutrients as it contains greater organic matter content and with its increment with soil organic matter also improves the physico - chemical attributes of soil and it ultimately results in increased yield of crop (Iqbal *et al*., 2019) [27].

The role of intercropping in water use efficiency

The effect of intercropping in improving the of resource utilization efficiency have been demonstrated across the world (Seran and Brintha, 2010) [45]. The transformation of agricultural production from resource-consuming to technology-efficient, improving the efficiency of utilization of resources has become the top priority of intercropping research as indicted in table two. The competition for resources in the early growth stage of intercropping crops may evolve into complementary effect of sharing resources in later growth stages, especially following the harvest of an early-maturity intercrop (Yin *et al*., 2019) [60]. The distribution of roots spatially and their density in the soil determines the ability of a crop to acquire the nutrients and the water necessary to sustain plant growth (Li *et al*., 2006) [33]. Crop species that absorb water quickly and grow fast have an advantage over those that use soil water efficiently but grow slowly in the overlapping region of crop roots (Yin *et al*., 2020) [62]. In maize and legumes intercropping, legumes can obtain the water below the root zone of maize and increase the water supply of maize by water lifting (Rusinamhodzi *et al*., 2012) [44]. Given the resource conditions in different regions and on the basis of understanding the biological characteristics of different crops, reasonable allocation of different types of composite population can flexibly utilize different forms of complementary effects to achieve the goal of maximizing intercropping advantages (Yin *et al*., 2020) [62].

It has been shown by previous studies that inter-species competition is less than intra-species competition, inter-species competition is conducive for improving WUE, forming intercropping advantages, and improving yield stability of the intercropping system (Yin *et al*., 2020) [62]. In instances of water absorption, space and root distribution of intercropped components are different can produce a greater complementary effect compared to intercropped components with similar water absorption space and root distribution.

The research conducted by Raza *et al*. (2021) [40] in maize soybean intercropping showed that the averaged over the years WUE of intercropped maize (14.6 kg ha^{-1} mm^{-1} in 2M2S and 14.1 kg ha^{-1} mm^{-1} in 2M3S) and soybean (2.0 kg ha^{-1} mm^{-1} in 2M2S and 2.5 kg ha^{-1} mm^{-1} in 2M3S) was significantly ($P < 0.05$) lower than that of the sole maize (18.0 kg ha^{-1} mm^{-1}) or sole soybean (3.8 kg ha^{-1} mm^{-1}), (Table 3). However, in intercropping systems, planting pattern 2M2S increased the WUE of maize by 4% compared to 2M3S, and planting pattern 2M3S enhanced the WUE of soybean by 18% compared to 2M2S. The intercropping impact on WUE was measured using the water equivalent ratio (WER).

The WER helps to characterize whether intercropped maize and soybean yield in 2M2S and 2M3S would be produced with less water (WER < 1) or more water (WER > 1) in SM and SS. The average of the total WER (pWERm + pWERs) values of both intercropping systems (1.35 for 2M2S and 1.44 for 2M3S) were higher than one, indicating the water use advantage over the sole cropping systems (Raza *et al*., 2021) [40]. For the total WER, the differences in 2018 and 2019 were non-significant ($P < 0.05$), while in 2020 it was significant ($P < 0.05$) (Table 3). However, the planting pattern 2M3S increased the WER by 7% in 2018, 6% in 2019, and 7% in 2020 compared to 2M2S. Moreover, in all years of the experiment, the pWERm (0.82 in 2M2S and 0.79 in 2M3S) was considerably higher than the pWERs (0.54 in 2M2S and 0.66 in 2M3S), (Table 3).

Regulation approaches to efficient water utilization in intercropping

Intercropping is an important cropping pattern for the sustainable development of agriculture, especially in arid and semiarid region and under the condition of limited water resources (Deng *et al*., 2006) [14]. Improvement of crop production and WUE can be effected by incorporating main regulation approaches for optimizing soil moisture environment and interspecific interactions in intercropping systems, such as crop species, irrigation and fertilization regimes, plant density, spatial arrangement, tillage and mulching practices, and environmental factors, into intercropping systems.

Crop species

According to Li *et al*. (2001), intercrops differ in their potential for competition and complementarity of limited resources. It has been confirmed by many studies that monoculture does not necessarily produce high yield compared to total system yield in intercropping systems (Wang *et al*., 2021b; Xiao *et al*., 2018) [54, 57]. In the intercropping system of gramineae-legume, underground competition promotes stem growth in gramineae but not in legumes, and greater competitiveness of gramineae crops is caused by stronger root competition (Mariotti *et al*., 2009) [36].

Based on to the resource conditions of different regions and the basis of understanding the biological characteristics of different crops, reasonable allocation of different types of composite population can flexibly utilize different forms of complementary effects to achieve the goal of maximizing intercropping advantages.

Irrigation regime

For field crops production, flood irrigation has been predominantly used in which water losses from evaporation and leaching are very high (Chai *et al*., 2014) [9]. Due to the water-saving campaign in recent years, the development of regulated deficit alternate irrigation, spray irrigation, surface irrigation and subsurface drip irrigation technology has been recognized (Chai *et al*., 2014) [9]. Regulated deficit alternate irrigation where one crop is irrigated, while the other crop is exposed to drying soil (Yu *et al*., 2020) [62]. The wetting and drying of the root zone for the different crops is alternated at a frequency allowing the previously well-watered side of the root zone to dry down while the previously dried side is fully irrigate (Chai *et al*., 2016) [10]. In intercropping system, components have distinct water requirements and therefore adopting alternate irrigation with an appropriate water supply level can effectively reduce intercropping systems water consumption by improving crop water requirements, water supply and boost WUE. Studies have shown that the application of alternate irrigation to wheat-maize intercropping can save water by 16 % and increase WUE by 6.6 %, compared to conventional high level (Yang *et al*., 2011) [58].

Fertilization regime

The difference in requirements for nutrients in intercropping by different crops needs timely and appropriate fertilization to enhance WUE (Yin *et al*., 2020) [62]. When nitrogen application rate is low in wheat-maize intercropping, intercropped wheat grows slowly and requires less water, which reduces competition for water from maize strips, thereby improving the soil water condition of intercropped maize strips (Wang *et al*., 2015) [55]. In contrary to this, when nitrogen application is high, intercropped wheat grows vigorously and transpiration consumes more water than intercropped maize, leading to competition for soil water from maize strips and reduced WUE of wheat strips (Yin *et al*., 2020) [62]. It has been shown that the postponed of topdressing 15 % of the total nitrogen fertilizer rate can reduce soil evaporation and the ratio of evaporation to water consumption (E/ ET) in maize-pea intercropping, and improve crop productivity and WUE (Yin *et al*., 2020) [62].

Plant density and spatial arrangement

Usually the plant density of intercropped plants is higher than the corresponding sole cropping, and greater plant density contributes to increased yield and resources use efficiency of intercropping systems (Ren *et al*., 2016). WUE can be improved by appropriate plant density and can enhance crop yield by improving photosynthesis, microclimate environment between populations, and increasing root length density and root absorption area (Fang *et al*., 2018) [20]. The distribution of intercrops spatially refers to the occupation of different crops in the compound population, intra-row and inter-row plant spacing and the duration of the co-existence period of the two intercrops. Studies have shown that interspecific interactions are important reason why total yield of intercropping systems are different from that of sole cropping (Dhima *et al*., 2007) [15].

Tillage and mulching practices

Conservation tillage techniques such as reduced tillage or no-tillage with straw retention can significantly improve WUE crop yield as well as improved activity of crop roots and microorganisms, creating a favorable surface soil structure for crop growth (Li *et al*., 2007) [32]. Reduced tillage with straw mulching techniques has also been studied in intercropping (Fan *et al*., 2013) [18]. The results of the intercropping under reduced tillage and mulching showed that no-tillage with straw mulching significantly improved WUE compared to straw incorporation, and the increasing WUE effect of intercropping was greater than that of monoculture (Yin *et al*., 2018) [61]. No tillage changes the physical and chemical properties of soil (Rhoton *et al*., 1993) [43], improves soil porosity (Holthusen *et al*., 2018) [25] reduces soil evaporation (Baumhardt *et al*., 2017) [5].

Environmental factors

Environmental factors including soil water, available nutrients, and light resources can influence interspecific interactions by strengthening or weakening the interspecific relationships and place a crop in a strong dominant position (Yin *et al*., 2020) [62] and significantly affect the growth of intercrops (Dhima *et al*., 2007) [15]. The main reason why environmental circumstances affect interspecific relationships is that interspecific competition differs with resource availability (Hauggaard-Nielsen and Jensen, 2005) [24]. The resource competitiveness of intercropped components depends largely on the response of the crop itself to limiting factors (Launay *et al*., 2009) [31].

Optimization of water consumption

Optimization of water consumption is a sort of management options that may establish relationship between land and water under limitation of water/land conditions so that crop production is economically affordable and technically possible (Kiani and Abbasi, 2012) [30].

Conclusion

Water is one of the major agricultural inputs and its scarcity is a major problem worldwide. Agriculture consumes the most water and produces the most total evapotranspiration from agricultural land. Water scarcity is the major barriers to crop production in the world. Improving the efficiency of agricultural water use is a major concern as water scarcity problems are becoming the key threats to agriculture. With growing concerns about the availability of water resources in both irrigated and rain fed agriculture, there is a renewed interest in trying to improve understanding of how the WUE can be developed and how farming systems can be changed to be more efficient in water use. In order to use the available water for effective crop production, different management practices including crop residue return, organic fertilizer application, intercropping and optimization of water use are among the methods that can be employed for maximization of water use efficiency.

Conflict of interest

No conflict of interest

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