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Water utilization in intercropping: A review

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ABSTRACT

Strip intercropping has been widely applied in arid and semi-arid regions due to high and stable productivity and efficient utilization of resources. Intercropping can increase water use efficiency (WUE) of crops and optimize the soil moisture environment for crop development. Competition and complementarity are two aspects of the same interspecific relationship between crops, and a quantitative understanding of the competition and complementary effects of intercrops on soil resources is important for advancement of intercropping systems. The characteristics and mechanisms of water utilization and interspecies relationships in intercropping are reviewed in this paper. The main regulation approaches for efficient water utilization in intercropping are based on interspecific competition and complementarity include crop species, irrigation and fertilization regimes, plant density, spatial arrangement, tillage and mulching practices, and environmental factors. Interspecific competition and complementarity are leading factors influencing water utilization of intercrops and studies on synergistic effects of competition and complementarity in intercropping systems are of importance for water utilization. Future research should investigate the relationship between water competition and complementation between different intercrops and inter-zone water migration. Integrating results from different studies could provide a basis for enhancing WUE of intercropping through advanced understanding of approaches for regulating interspecific interactions. This would provide support for the development and adoption of intercropping systems in water-deficient areas.

1. Overview of intercropping

The advantages of intercropping in improving the efficiency of resource utilization have been demonstrated across the world (Ma et al., 2017; Martin-Guay et al., 2017). Intercropping is widely used as an important means to provide food security, diversify cropping systems, promote sustainable agricultural development, and efficiently utilize limited labor on smallholder farms (George and Jeruto, 2010). Intercropping can increase the utilization efficiency of resources such as light, heat, water, and fertilizer to effectively improve the primary production of land per unit area, thereby making a significant contribution to global food security (Foley et al., 2011; Steen et al., 2015) and increasing water production efficiency and economic benefit for farmers (Agegnehu et al., 2008; Yin et al., 2018a). With the gradual transformation of agricultural production from resource-consuming to technology-efficient, improving the utilization efficiency of resources has become the top priority of intercropping research (Table 1). Many researchers have explored the theory and practice of optimizing resource utilization efficiency from the perspectives of intercrop strip widths (Nurbakhsh et al., 2015), intercrop species (Osunlaja et al., 2010), spatial layout (Hauggaard-Nielsen et al., 2006; Morais et al., 2018), sowing density and time (Ahmed et al., 2018; Fan et al., 2020; Nandy et al., 2013), water and fertilizer regulation (Sawyer et al., 2010; Yang et al., 2011), interspecific relationships (Hu et al., 2016), allelopathy (Gómez-Rodríguez et al., 2003), and tillage and mulching practices (Yin et al., 2018b). A series of theoretical systems to guide intercropping application can be constructed from the interaction of heterogeneous individuals in a composite population to provide a solid support for the wide application of intercropping.

In recent years with increasing shortage of resources, intercropping use has declined in water-scarce areas due to its high-water demand, which can reduce the yield per unit of cultivated land (Chai et al., 2014a). Therefore, researchers should continue to focus on how to maximize the advantages of intercropping system and achieve stable yields while saving water. This paper reviews the development of theory and technology of efficient water utilization of intercropping

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Table 1
Examples of improved water use efficiency (WUE) with intercropping compared to the corresponding sole cropping in different countries.

Country	Cropping system	References
China	Maize-wheat, pea, soybean, peanut intercropping	(Chen et al., 2014; Fan et al., 2020; Rahman et al., 2016; Yin et al., 2018b)
	Peanut-millet intercropping	(Feng et al., 2016)
	Alfalfa-maize intercropping	(Sun et al., 2018)
India	Wheat–chickpea intercropping	(Singh et al., 2017)
	Maize-coriander, radish, beet root, onion, mungbean	(Fanish and Jeyaraman, 2011; Roy et al., 2016)
	Pigeonpea-blackgram intercropping	(Kumawat et al., 2013)
	Millet-pigeonpea intercropping	(Jagadeesha et al., 2020)
Brazil	Maize-cowpea intercropping	(Barros et al., 2007; Souza et al., 2010)
	Forage cactus-sorghum intercropping	(Lima et al., 2018)
USA	Peanut-watermelon intercropping	(Franco et al., 2018)
	Maize-cowpea intercropping	(Gaiser et al., 2004)
	Blue panic-alfalfa intercropping	(Al-Shareef et al., 2018)
Egypt	Maize-soybean, cowpea intercropping	(Aa et al., 2017; Safina et al., 2015)
Nigeria	Maize-sorghum, millet-cowpea intercropping	(Oluwasemire et al., 2002; Sani et al., 2011)
South Africa	Cowpea-sunflower, sorghum intercropping	(Chimonyo et al., 2016; Mzezewa et al., 2011)
Austria	Lentil-mustard intercropping	(Devi et al., 2014)
Canada	Wheat-bean intercropping	(Chapagain and Riseman, 2015)
Iran	Maize-rapeseed, bean; maize-cowpea;	(Najibnia et al., 2014; Saudy, 2014)
	Barley-vetch intercropping	(Mohsenabadi et al., 2008)
Kenya	Maize-cowpea intercropping;	(Miriti et al., 2012)
	Potato-lima bean, dolichos intercropping	(Shadrack et al., 2019)
Argentina	Soybean-maize, sunflower intercropping	(Andrade et al., 2012; Coll et al., 2012)

from across several paleoclimatic areas from the world in order to provide a basis for the optimization of highly efficient intercropping production technology.

2. Water use characteristics of intercropping

2.1. Water consumption of intercropping

The water consumption of intercropping during the entire growth period is greater than that of monoculture, but the difference is smaller than the weighted mean value of corresponding water consumption in sole cropping (Morris and Garrity, 1993). Researchers summarized previous research results and concluded that the water consumption of intercropping systems vary greatly due to environmental conditions and crop types (Morris and Garrity, 1993). However, there is little difference compared to the weighted average of water consumption for the corresponding sole cropping systems (Morris and Garrity, 1993). Therefore, the development of intercropping has great potential in areas with sufficient water resources to meet the water requirements of high-yielding sole cropping systems. However, in irrigated areas, water consumption of intercropping is not a simple accumulation of water consumption of component crops, and is less than the accumulation value due to water competition and complementary utilization effects during the growing season (Yin et al., 2018b). At present, research on water consumption of intercropping mainly focuses on spatial distribution (Mao et al., 2012), fertilization system (Teng et al., 2016), irrigation method and system (Manjunatha et al., 2000), and tillage and mulching practices (Yin et al., 2018b). Optimal spatial layout of intercrop strips can reduce water consumption of intercropping. For example, maize (Zea mays L.) -pea (Pisum sativum L.) strip intercropping with (4:4 model, four rows of maize and four rows of pea) reduced water consumption by 10.2–13.7% compared to sole cropping, but maize-pea strip intercropping with (2:4 model, two rows of maize and four rows of pea) increased water consumption by 12.5–19.8% compared to sole cropping (Mao et al., 2012). It was found that the water consumption of maize-pea intercropping was not significantly affected by nitrogen fertilizer, was significantly greater than that of sole pea, but did not differ with that of sole maize (Teng et al., 2016). Water consumption of intercropping was reduced by 16.1 and 15.3 % by an alternate irrigation method (Fig.1) compared to flood irrigation at high and low water supply levels, respectively (Yang et al., 2011). Limited water supply after the booting stage of wheat (Triticum aestivum L.) in wheat-maize intercropping has been shown to save 15 % irrigation water and reduce water consumption by 4.4–8.5% (save 25.1–70.9 mm of soil water) without significantly reducing crop productivity (Wang et al., 2015). So, reduction of water consumption by intercropping is based on reasonable crop collocation and appropriate irrigation and fertilization. Water consumption can also be reduced by optimizing tillage practices and mulching methods. For example, reduced tillage with straw and plastic mulching in wheat-maize intercropping has been shown to reduce water consumption by 3.6–4.6% (Yin et al., 2015). These findings showed that water consumption in intercropping can be reduced by integrating water regulation measures commonly used in monoculture.

2.2. Soil evaporation of intercropping

Soil evaporation plays an important role in the total water consumption by cropping systems; therefore, it is important to take appropriate control measures to reduce it (Yin et al., 2019b). Previous studies have shown that soil evaporation during the whole growth period of intercropping was greater than that of sole cropping due to the longer growth period of intercropping, but daily soil evaporation of intercropping was less than that of sole cropping, indicating that intercropping has a significant advantage over sole cropping in improving crop water availability (Fan et al., 2013; Gao et al., 2013; Yin et al., 2019b). Over the years, research has revealed strategies to reduce ineffective field water consumption, such as soil evaporation through optimization of irrigation levels, fertilization systems, mulching methods, and tillage practices. Compared to conventional flood irrigation, alternate irrigation can significantly reduce evaporation of soil water by 17.7–31.9% in wheat-maize intercropping (Yang et al., 2011). Postponed topdressing of nitrogen fertilizer can reduce soil evaporation of maize-pea intercropping by 15–30%, compared to conventional fertilizer for farmer (Teng et al., 2016). The application of no-tillage with straw mulching in intercropping significantly reduced soil evaporation by 5.8–13.1% compared to conventional tillage without straw retention (Fan et al., 2013). The integration of no-tillage with straw mulching in wheat strips and residual plastic film mulching in maize strips can further restrain soil evaporation (32 − 71 mm) by 9.0–17.3%, compared to conventional tillage without straw retention in wheat strips and annual plastic film mulching in maize strips, and no-tillage with straw mulching measure in the intercropping system could favorably reduce soil evaporation (Yin et al., 2018b).

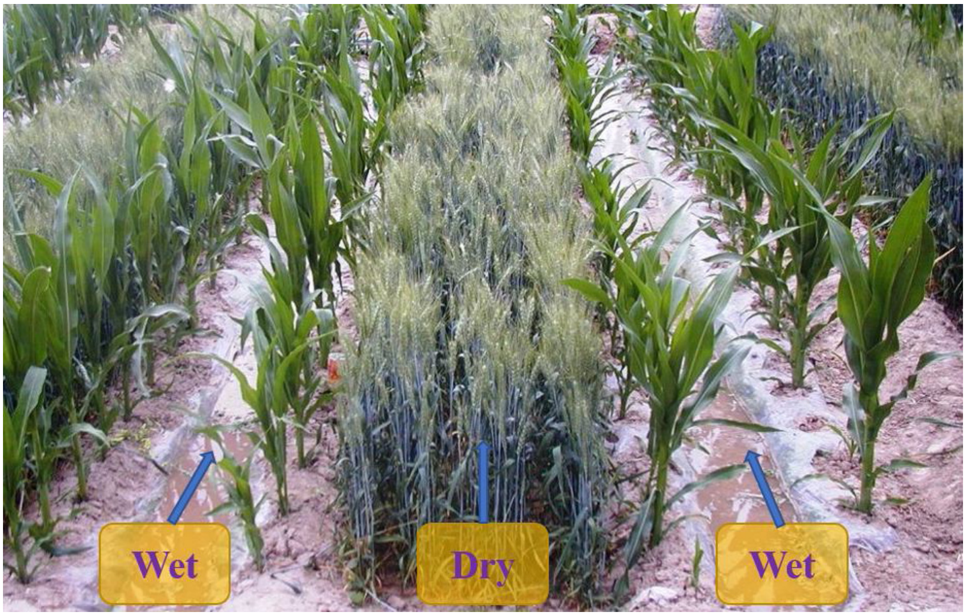

Fig. 1. A typical alternate irrigation system in which the maize srtips is irrigated, and the wheat strips is unirrigated and allowed to dry. The wet and dry sides of the wheat and maize are alternated so that the previously watered side of the strips are allowed to dry down while the previously dry crop strips are fully irrigated (Color photo was provides by Professor Caihong Yang).

2.3. *Yield and water use efficiency of intercropping*

Intercropping plays an important role in ensuring high and stable crop yields, and addressing food security under growing shortages of irrigation water and arable land (Chai et al., 2014b). Intercropping can increase total crop production and the ratio of production to investment by optimizing population structure and interspecific relationships between intercrops (Hu et al., 2016), increasing the use of resources such as light, water, and nutrients (Thorsted et al., 2006), and synchronously increasing intercropping component yield (Huang et al., 2015; Zhang et al., 2012). Additionally, under low-yielding environments, intercropping can achieve yield stability by reducing pests and diseases, and increasing land management (Brooker et al., 2015). Intercropping has a significant yield advantage over sole-cropping (Fig. 2), which has been verified for a variety of intercrop combinations including wheat-maize (Yin et al., 2016a), maize-pea (Hu et al., 2016), jujube (Ziziphus jujuba Mill.)-wheat (Wang et al., 2014), maize-potato (Solanum tuberosum L.) (Chapagain et al., 2012), and alfalfa (Medicago sativa)-maize (Sun et al., 2014). However, if the combination of intercrops is not appropriate and the spatial layout is not considered, the lower yield of the component crops compared to sole cropping is more obvious (Banik et al., 2008). Previous study showed that when nitrogen application level is higher than 120 kg N ha^{-1}, vegetative growth period is prolonged and grain filling of oat and pea is reduced, resulting in lower yield of oat-pea intercropping, in eastern Austria (Neugschwandtner and Kaul, 2014). When irrigation amount and fertilizer application are low, crop growth and development appear lack of water and fertilizer phenomenon and reduce crop production (Jannoura et al., 2014). Therefore, reasonable crop collocation, spatial distribution, and suitable irrigation and fertilization regimes are important for maximizing the yield advantage of intercropping compared to sole cropping.

The advantage of efficient water utilization in intercropping results from spatiotemporal differences in water demand between intercrops (Dong et al., 2018). According to the characteristics of crop water requirement, reasonable design of irrigation amount and time is important to improve the compatibility between crop water requirements and water supply (Morris and Garrity, 1993). Also, through optimized tillage and mulching measures, the consistency between water requirement for crop growth and water supply was enhanced to improve WUE of intercropping (Yin et al., 2016b, [Yin et al.,2018b]). Straw mulching integrated into wheat-maize intercropping can improve soil water utilization by regulating the soil water environment. For example, no-tillage with straw mulching in wheat-maize intercropping system increased WUE by 15.1–20.0% and 15.5–16.3%, respectively, compared to intercropping without straw retention and corresponding sole maize (Yin et al., 2015). These results show that the application of no-tillage with straw mulching in intercropping can improve water use more than that in sole cropping. Postponed topdressing of nitrogen fertilizers increased WUE of intercropping by 5.1 % compared to conventional fertilization system for farmers (Teng et al., 2016). Therefore, through the optimization of tillage and fertilization practices, the utilization of deep soil water by crop roots can be promoted and the coupling effect of water and nitrogen can be exerted, thus increasing water and fertilizer use efficiency. However, intercropping may not have the advantage of increasing WUE when crop layout or variety combination is unreasonable (Grema and Hess, 1994), the reasonable intercropping system can achieve high yield and water utilization. In order to further enhance the yield increase and the beneficial effects of intercropping, future research is needed to understand how to integrate the water-saving measures commonly used in sole-cropping into intercropping and increase efficient water utilization in intercropping system to enhance the sustainability of agricultural production.

3. Interspecies relationships of intercropping

Competition and complementation are two main types of interspecific interactions (Callaway and Walker, 1997; Yin et al., 2017). They coexist and play a crucial role in promoting the productivity of intercropping systems (Hauggaard-Nielsen and Jensen, 2005; Zhang and Li, 2003). Crops with different characteristics of resource demand provide the basis for niche differentiation in time and space utilization, and promote the efficient utilization of related resources by inter-species complementarity, or one crop directly provides resources for another crop (Takim, 2012). Therefore, interspecific competition promotes the use of different resources because intercrops utilize a given resource based on space–time differences (Mehrhoff and Turkington, 1996). Also, interspecific complementation refers to the fact that the resource utilization should be greater than the interspecific competition (Zhang and Li, 2003), and interspecific complementation is produced via one crop promoting the growth of another crop (Callaway, 1995; Yin et al., 2019a, b). Quantifying the competition and complementary effects of intercrops on soil resources is an important issue in intercropping research (Chen et al., 2014; Yin et al., 2019a). The yield advantage of intercropping over monoculture depends on the net effect of

Fig. 2. Typical intercropping patterns based on maize, including (a) maize-wheat intercropping; (b) maize-common vetch intercropping; (c) maize-pea intercropping; (d) maize-soybean intercropping; (e) maize-peanut intercropping; (f) maize-rape intercropping, respectively.

intercropping on complementary and competition for growth resources (García-Barrios and Ong, 2004).

When analyzing the effects of inter-species competition and complementarity on resource utilization, many assume that the two functions are mutually exclusive, but this is not always the case. For example, with inter-species complementary utilization of light resources, competition for nutrient and water may occur simultaneously. Also, the resource competition 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., 2017; Zhao et al., 2016). In addition, the competitive disadvantage formed in the period of crop symbiosis may be recovered after the early-maturity crop harvest, which shows a strong recovery effect (Li et al., 2001a). Therefore, the transition from interspecific competition to complementation is an important period of agronomic regulation, and the main goal of interspecific regulation is to delay the intersection of complementation and competition. The complementary use of limited resources indicates weakening of the competitive effect and formation of a yield advantage for intercropping. It is important to quantify the interspecific competitive and complementary effects in combination with the growth and development of intercrops, and the dynamic change of growth factor supply for optimization of intercropping systems.

4. Mechanisms of efficient water utilization in intercropping

4.1. Physiological basis of efficient water utilization in intercropping

The photosynthetic and physiological characteristics of plants are the basis for their productivity and have important influence on their growth and development (Jiao et al., 2017). In a specific intercropping system, nitrogen fertilizer has an influence on the physiological characteristics of crops. Across maize-cotton and maize-soybean intercropping systems with different nitrogen levels, intercropped maize had greater net photosynthetic rate, transpiration rate, and stomatal conductance compared to sole maize, but the improvement effect of these variables gradually weakened with increased nitrogen application (Zhang et al., 2014). The typical maize-peanut (Arachis hypogaea Linn.) intercropping system with tall and low collocation, has population structure similar to an umbrella, which is beneficial to improve the transmittance and interception rate of light energy of the composite population (Awal et al., 2006; Maddonni et al., 2001). Compared to sole cropping, chloroplast composition and photosynthetic characteristics of intercropped maize and peanut were changed, and the utilization of weak light in peanut and strong light in maize was promoted (Jiao et al., 2006). Higher photosynthetic product accumulation and conversion rate in the middle and late stages of the intercropping system is another reason for the significant yield increase of maize-peanut intercropping (Jiao et al., 2006). From the end of vegetative growth to the reproductive growth period of maize, leaf photosynthetic rate, transpiration rate, stomatal conductance, carboxylation efficiency, and maximum electron transfer rate of maize intercropped with peanut were higher than sole maize (Yang and Chai, 2016). Additionally, increasing strip with of maize-peanut intercropping can further enhance the increasing effect of the above indexes, and the appropriate application of phosphorus can enhance the utilization of light and delay the aging of maize (Jiao et al., 2016). In wheat-broad bean (Vicia faba L) intercropping, relative water content, chlorophyll content, and water potential of leaves of broad bean and wheat were significantly increased by intercropping compared to sole cropping (Yang and Chai, 2016). Compared to traditional flood irrigation, chlorophyll content of broad bean and wheat leaves in intercropping was increased with alternative irrigation method, but relative water content and water potential of leaves were decreased (Yang and Chai, 2016). According to the growth and development characteristics of intercrops, alternate irrigation can increase yield and resource use efficiency by improving physiological characteristics of intercrops; thus, alternate irrigation is an appropriate water supply method for intercropping.

Intercropping is beneficial for increasing the photosynthetic source (leaf area index, i.e., LAI, and leaf area duration, i.e., LAD) and promoting the movement of photosynthetic compounds from vegetative organs to grain, thereby enhancing WUE by increasing yield (Yin et al., 2017). In maize-cotton and maize-soybean intercropping systems with different nitrogen application levels, intercropping increased grain yield compared with sole cropping (Zhang et al., 2014). The main direct reasons for this were caused by the improvement of LAI and photosynthesis, and the indirect reason was the increase of leaf chlorophyll content (Zhang et al., 2014). The grain yield of intercropped soybean and maize was higher than that of the corresponding sole crops, which was attributed to higher photosynthetic radiation utilization rate (RUE) and LAI of intercropping (Liu et al., 2017). Similarly, in a wheat-maize intercropping system with straw mulching of wheat and plastic mulching of maize, increased yield of the intercropping system compared to the corresponding sole cropping was associated with increased LAI (Yin et al., 2016a). The main contribution to the increase in total yield of wheat plus maize in the intercropping system was from maize (Yin et al., 2016a). This was because straw mulching after wheat harvest enhanced water retention, so that more soil water could be compensated to the maize strips to meet the water demand in the vigorous reproductive period of maize (Yin et al., 2018b). In summary, intercropping can increase dry matter accumulation rate, enhanced the transfer of photosynthetic products from vegetative organs to grain, and realized the compensatory growth effect based on the dry matter accumulation rate and the super-compensatory effect of dry matter distribution and translocation (Yin et al., 2017).

4.2. Ecological basis of efficient water utilization in intercropping

Competition is a key factor affecting crop growth, water utilization, and yield formation of intercropping systems (Nassab et al., 2011). Previous studies showed that when inter-species competition is less than intra-species competition, inter-species competition is conducive to improving WUE, forming intercropping advantages, and improving yield stability of the intercropping system (Schroeder-Moreno and Janos, 2008). In agricultural production, two or more crops with differing growth periods and morphological characteristics are combined in the same production system to form a compensation effect in time and space for efficient utilization of resources (Horton and Hart, 1998; Yin et al., 2017). In terms of the compensation effect in time, except for the extension of the total growth period of the composite population and the increase of leaf area duration, the inhibitory effect of competition on the late-maturity crop during the co-growth period of intercrops could be significantly recovered after the harvest of the early-maturity crop (Li et al., 2001b). For instance, in wheat-maize or wheat-soybean intercropping systems, growth and nutrient uptake of the subsidiary maize or soybean was suppressed prior to wheat harvest due to interspecific competition, but after harvest of the early-maturity wheat, the later-maturity maize or soybean recovered, producing a significant compensatory effect (Zhang and Li, 2003). In terms of the compensation effect in space, the basic conclusion of canopy complementation is that canopy structure with high and low collocation in intercropping is more conducive to air flow than that of sole cropping with consistent canopy structure (Morris and Garrity, 1993). In particular, the open canopy of tall crops is conducive to reducing diffusion resistance of the boundary layer, changing the gradient of leaf gas and water vapor, or the diffusion resistance of the boundary layer, stomata, and leaf (Morris and Garrity, 1993). When the water absorption space and root distribution of intercropped components are different, which can produce a greater complementary effect compared to intercropped components with similar water absorption space and root distribution (Mu et al., 2013). Water transport by roots is also an important mechanism for complementary utilization of water (Mendel et al., 2003; Sekiya et al., 2010).

The formation of efficient water utilization advantage in intercropping involves the physiological and ecological characteristics of intercrops, as well as the competition and complementarity of intercropped components to water resources and related resources in time and space, which is determined by the dynamics of competition and complementarity. Therefore, analyzing the dynamics of competition and complementarity on water use of intercropping systems under water-limited conditions, and quantifying the relationship among water competition and complementarity, and their synergistic effect, and crop productivity, are important theoretical bases for establishing efficient water-saving irrigation technology for intercropping systems.

5. Regulation approaches to efficient water utilization in intercropping

Intercropping is an important croppig pattern for the sustainable development of agriculture, especially in arid and semiarid region and under the condition of limited water resources. To improve crop production and WUE by integrating with 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 (Table 2). Integrating results from different studies could provide a basis for improving WUE of intercropping systems through advanced understanding of approaches for optimizing interspecific interactions. This would provide support for the development and adoption of intercropping systems in water-deficient areas.

5.1. Crop species

Intercrops differ in their potential for competition and complementarity of limited resources (Li et al., 2001b). Many studies have confirmed that monoculture does not necessarily produce high yield compared to total system yield in intercropping systems (Zhang et al., 2012). Previous research has shown that barley (Hordeum vulgare L.) is more competitive than pea in barley-pea intercropping, and yield and nitrogen uptake of intercropped barley were almost the same as that of sole barley, while yield and nitrogen uptake of intercropped pea were less than half that of sole pea (Hauggaard-Nielsen and Jensen, 2001). Additionally, the interaction between pea varieties and planting patterns was significant. In gramineae-legume intercropping, 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). Studies have also shown that drought strongly affects the growth of sole crops, and the effect on LAI

Table 2
Regulation approaches to efficient water utilization in intercropping.

Main object	Management practice	Cropping system	Impacts on the use of water in agriculture	References
Intercrop species	Conventional local management practice	Maize-wheat, rape, pea, soybean intercropping	Maize-wheat intercropping had greater water use efficiency (WUE) than that of other intercropping treatments.	(Chai et al., 2014b)
Irrigation regime	Alternate irrigation; Irrogation level	Maize-wheat intercropping	Alternate irrigation save water by 16 % and increase WUE by 6.6 %, compared to conventional high level.	(Yang et al., 2011)
	Drip irrigation; flood irrigation	Maize-wheat intercropping	Drip irrigation with plastic mulching reduced water consumption of wheat-maize intercropping by 48–61% compared to traditional flood irrigation, at the same level of crop productivity.	(Su, 2001)
	Spray irrigation; surface flood irrigation	Cowpea-potato intercropping	Water savings of 26–37% were achieved for cowpea-potato intercropping using spray irrigation compared to surface flood irrigation.	(Manjunatha et al., 2000)
	Irrigation level, no-tillage with residual plastic mulching	Maize-pea intercropping	No-tillage with residual plastic method as a water-saving strategy that can sustain the productivity of maize-pea intercropping systems.	(Zhao et al., 2019)
Fertilization regime	The N-15 natural abundance method	Pea-oat intercropping	The nitrogen transfer from pea to the oat strip was enhanced by nitrogen fixation of pea, and the yield and water use efficiency were improved of intercropping.	(Tsialtas et al., 2018)
	Postponed topdressing 30 % of nitrogen Postponed topdressing 15 % of nitrogen Conventional nitrogen application	Maize-pea intercropping	Postponed topdressing 15 % of the total nitrogen fertilizer rate can improve grain yield and WUE by 6.0 % and 5.0 %, respectively.	(Teng et al., 2016)
Planting density	D1: 45,000 plants ha^{-1} D2: 52,500 plants ha^{-1} D3: 60,000 plants ha^{-1}	Maize-pea intercropping	Increasing maize density increased grain yield and WUE.	(Fan et al., 2020)
Spatial arrangement	M2S4: 2 rows maize × 4 rows soybean, M2S2: 2 rows maize × 2 rows soybean M4S2: 4 rows maize × 2 rows soybean	Maize-soybean intercropping	The M4S2 spatial arrangement had greater WUE by 14.0–44.6% than other treatments.	(Ren et al., 2017b)
Tillage and mulching practice	No-tillage with straw retention in wheat strips; residual plastic mulching in maize strips	Maize-wheat intercropping	No-tillage with straw retention in wheat strip and residual plastic mulching in maize strip had greater WUE by 12.4–17.2% than conventional intercropping treatment.	(Yin et al., 2018b)
Environmental factors	Soil moisture, available nutrients, light interception	Triticale-bean intercropping	Appropriate environmental factors can improve yield and WUE by optimizing interspecific relationship in intercropping system.	(Dhima et al., 2007; Sobkowicz, 2006)

Fig. 3. Drip irrigation systems are used to provide supplemental water under plastic film mulching at critical growth stages of maize.

and pod number of sole peanut was much greater than that of intercropped peanut, because interspecific complementarity of intercropping system has a stronger adaptation to drought (Soopramanien et al., 1992). In wheat-maize intercropping, wheat is more competitive than maize during the co-growth period and competes for soil water from the maize strips; as a result, soil evaporation in maize strips is reduced (Yin et al., 2019b, Yin et al., 2018b). On the contrary, after wheat harvest, intercropped maize obtains compensatory soil water from the wheat strips; thus, soil evaporation in wheat strips is reduced (Yin et al., 2018b, Yin et al., 2019b). These competitive and complementary effects also arise from the biological characteristics of different crops.

The different root configurations of various intercrops inevitably leads to the overlapping of root spatial distribution (Gao et al., 2010). In the overlapping region of crop roots, crop species that absorb water quickly and grow fast have an advantage over those that use soil water efficiently but grow slowly (Bramley et al., 2007). During the intercropping between maize and legumes, legumes can obtain the water below the root zone of maize and increase the water supply of maize by water lifting (Sekiya and Yano, 2004). Slower growth rate in early stage of deep root cassava can reduce interspecific competition through root niche separation and dislocation of resource demand peak, thus promoting the growth of dal (Cajanus cajan Millsp.) and maize intercrops (Mafongoya et al., 2006). According to 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.

5.2. Irrigation regime

Flood irrigation has been predominantly used for field crops, which water losses from evaporation and leaching are very high (Chai et al., 2014a). As a result of 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., 2014a; Du et al., 2010). Regulated deficit alternate irrigation where one crop is irrigated, while the other crop is exposed to drying soil, as shown in Fig. 1. 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 irrigated (Chai et al., 2016). Intercropping components of crops have different water requirements, so using alternate irrigation with appropriate water supply level can effectively reduce water consumption of intercropping systems by improving the coincidence between crop water requirements and water supply, and increase WUE (Medrano et al., 2015). 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).

Spray irrigation is currently being adopted in some small areas, where main channels are paved with reinforced concrete and other ditches heading to the fields are equipped with plastic pipes. The studies showed a 27 % increase in cowpea yield and a 25 % increase for potato crop while using spray irrigation instead of surface irrigation (Manjunatha et al., 2000). Water savings of 26 % were achieved for cowpea and 37 % for potato using spray irrigation compared to surface irrigation, thus impring WUE (Manjunatha et al., 2000). Pipe-based spraying systems reduce average irrigation amounts by as much as $7500\ m^3\ ha^{-1}$ and improve the water utilization rate by up to 80 % compared to traditional irrigation systems (Jia and Qian, 2017).

In arid regions, drip irrigation have been gradually adopted in recent years. This technology allows a small volume of soil to remain moist by frequent applications of low volumes of water (Du et al., 2010). This limits the rooting zone to the moist and reduces water drainage from the rooting zone soil (Assouline et al., 2002; Du et al., 2010). In particular, subsurface drip irrigation substantially minimizes soil evaporation compared to surface drip irrigation and improves irrigation WUE (Lamm and Trooien, 2003). In areas such as northwest China, irrigation tubing and drippers are placed under the plastic film used to cover the soil surface (Fig. 3). For the large enterprises and agriculture specialty companies, drip irrigation is the most popular technology and is used to produce high value cash crops such as tomato, sweet chili, hops, and grapes, and grain crops such as wheat, maize, and potato. When combined with plastic film mulching, drip irrigation effectively reduces soil evaporation and saves water (Yang et al., 2016). Studies have shown that drip irrigation with plastic film mulching reduced water use of wheat-maize intercropping by 48–61% compared to traditional flood irrigation, at the same level of crop productivity (Su, 2001).

Different soil water availability has different effects on water utilization by intercropping systems. When soil water availability is high, WUE of cowpea (Vigna unguiculata Walp) -maize intercropping is higher than that of the corresponding sole cropping; however, when soil water availability is low, intercropping has greater WUE than sole cowpea, but lower WUE than sole maize (Droppelmann et al., 2000). In addition, when the high growth period of intercrops coincides with the period of rainfall concentration, actual water consumption of maize-soybean intercropping system has been shown to be lower than that of the corresponding monoculture. The coincidence between rainfall and water demand of intercropping is higher than that of sole cropping, water consumption of intercropping is mainly for efficient transpiration of intercrops (Ren et al., 2017a). According to the water consumption characteristics of intercropping systems, water resources can be effectively used with reasonable irrigation methods and levels to increase crop production and WUE.

5.3. Fertilization regime

Managing fertilizer in conjunction with irrigation water is an important measure for water regulation in crop production (Ahlawat et al., 1985; Teng et al., 2016). According to differences in nutrient demand of different component crops in intercropping, timely and appropriate fertilization can enhance WUE (Ghosh et al., 2009). 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 (Li et al., 2001b). On the contrary, 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 (Li et al., 2001b; Yin et al., 2018b). Postponed 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 (Teng et al., 2016). Additionally, excessive fertilizer application can delay crop maturity, and consume more soil water (Neugschwandtner and Kaul, 2014). The contribution rate of nitrogen fertilizer decreases with increased fertilizer application, resulting in reduced yield and water utilization of intercrops (Wu et al., 2014). Therefore, appropriate fertilization level is important for efficient utilization of soil water.

5.4. Plant density and spatial arrangement

Appropriate plant density is the basis for crops to make use of light and heat resources in the ecological environment to optimize the physiological indexes of crops (Rasekh et al., 2010). The plant density of intercrops is usually higher than that of the corresponding sole cropping, and greater plant density contributes to increased yield and resources use efficiency of intercropping systems (Echarte et al., 2011; Pal et al., 1993). For the scientific application of dense density effects in intercropping, researchers have conducted studies on resource utilization efficiency (Martin and Snaydon, 1982), population colony structure (Munz et al., 2014; Yang et al., 2014), and the response mechanism of interspecific relationship (Neumann et al., 2009; Schroeder-Moreno and Janos, 2008) to plant density in intercropping systems. Appropriate plant density can enhance crop yield and WUE by improving photosynthesis, microclimate environment between populations, and increasing root length density and root absorption area (Fan et al., 2020; Wang et al., 2018). When the plant density of intercrops is too high, adverse phenomena in plant morphology, physiology, and ecology can occur, such as premature senescence (Antonietta et al., 2014), slow leaf growth (Bos et al., 2000), decreased panicle grain number (Maddonni and Otegui, 2006), decreased chlorophyll content, and decreased interception of photosynthetic active radiation of the panicle leaf layer and sublayer (Antonietta et al., 2014), but intercropping studies have not paid enough attention to them. Therefore, it is important to study how plant density affects yield and WUE of intercropping systems.

The spatial distribution of intercrops mainly refers to the occupation of different crops in the compound population, inter-row and intra-row plant spacing, the duration of the co-existence period of the two intercrops. A large number of studies show that interspecific interactions are important reason why total yield of intercropping systems different from that of sole cropping (Dhima et al., 2007). Intercrop strip widths significantly affects intercropping yield, resource utilization efficiency, and competitiveness dynamics and compensatory effect (Chen et al., 2004; Zhang et al., 2015). When the strip width of barley and pea was 100 and 50 cm respectively, rather than 50 and 100 cm, respectively, total nitrogen uptake of intercrops was significantly greater than that of the sole cropping (Hauggaard-Nielsen et al., 2006). This indicates that there is a compensatory effect between the two intercrops, which is mainly due to intercropped barley assimilating more nitrogen than pea, thereby forcing pea to be more dependent on biological nitrogen fixation.

5.5. Tillage and mulching practices

Conservation tillage techniques such as reduced tillage or no-tillage with straw retention can significantly improve crop yield and WUE (Huang et al., 2012; Yin et al., 2015) due to improved activity of crop roots and microorganisms, creating a favorable surface soil structure for crop growth (Ji et al., 2014; Spedding et al., 2004). Straw mulching techniques with reduced tillage have also been studied in intercropping (Fan et al., 2013; Yin et al., 2019b). The results 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., 2015). No-tillage changes soil physical and chemical properties (Rhoton et al., 1993), improves soil porosity (Holthusen et al., 2018), reduces soil evaporation (Baumhardt and Jones, 2002), and increases soil water infiltration rate and storage capacity (Dalmago et al., 2010; Hubert et al., 2007; Lipiec et al., 2006), and straw mulching combined with no-tillage further inhibits soil evaporation and thus reduces water consumption (Yin et al., 2016b).

In strip intercropping systems, during the early-maturing crop growing period, the early-maturing crop roots may expend into the territory of the late-maturing crop, enabling the early-maturity crop to compete for soil water in the late-maturing crops strips (Ye et al., 2005). However, roots of the late-maturing crop will extend into the early-maturing crop's rooting regions after the early-maturing crop has been harvested, thereby absorbing some of the remaining but unused soil water, resulting in a water compensation effect to the late-maturing crop (Chen et al., 2014). In terms of wheat-maize intercropping, after intercropped wheat has been harvested, wheat straw mulching on the soil surface can conserve more soil water in the wheat strips, and more soil water can then move from the wheat strips to the maize strips (Yin et al., 2018b). This movement compensates for the water requirement for growth of intercropped maize (Yin et al., 2017). Plastic mulching and straw residue are the two common soil water conservation measures which can enhance water infiltration and increase soil water retention (Chen et al., 2007; Ghosh et al., 2006). Previous research has shown that no-tillage with straw residue and plastic mulching integrated into intercropping can reduce soil evaporation and improve WUE compared with conventional tillage without straw retention and annual plastic mulching (Fan et al., 2013; Yin et al., 2015). Conventional tillage with annual new plastic mulching is associated with a higher soil temperature in the root zone at the flowering stage of crops, resulting in root and leaf senescence, thus reducing crop yield and water use (Bu et al., 2013). However, plastic mulching is imperative conserving soil moisture for maize production in arid areas which rely on irrigation for crop production (Gan et al., 2013). Therefore, no tillage with residual plastic mulching combined with straw residue has been applied into intercropping in arid areas. Intercropping with no-tillage and straw mulching in wheat strips and residual plastic mulching in maize strips has been shown to allow the greatest amount of the remaining, unused water to move from wheat strips to maize strips, while the conventional tillage treatment allowed the least (Yin et al., 2019b). These results show that no-tillage with straw mulching in wheat strips combined with residual plastic mulching in maize strips can weaken soil water competition during the wheat growth period and strengthen water compensation during maize-independent growth after wheat harvest, and thereby maintain water balance between the intercrop strips (Yin et al., 2018b). These improved practices can result in efficient utilization of water by regulating the water competition and complementary utilization relationship.

5.6. Environmental factors

Interspecific interactions are influenced by environmental factors such as soil water, available nutrients, and light resources, and these factors can strengthen or weaken interspecific relationships and place a crop in a strong dominant position (Sobkowicz, 2006), and significantly affect the growth of intercrops (Dhima et al., 2007). The main reason why environmental conditions affect interspecific relationships is that interspecific competition varies with resource availability (Hauggaard-Nielsen et al., 2001). The position of different components in the community stratification changes correspondingly, and the distribution pattern of assimilates of the intercrops are changed under competitive conditions, so as to enhance the organ of obtaining limited resources (James and Cahill, 2002). The resource competitiveness of intercropped components depends largely on the response of the crop itself to limiting factors. Intense competition between two intercrops may result in a decrease in the biomass and grain yields of one intercrop (Li et al., 2001b). However, when the paired crop is removed or harvested, a complementary effect on resource utilization is generated in time and space (Li et al., 2001b; Yin et al., 2017). This principle is also applied by optimizing tillage measures (Yin et al., 2019a), fertilization system (Hu et al., 2016), and adjusting plant density (Yahuza, 2012) to weaken competition between the two intercrops and enhance the recovery effect.

The time of competition for restricted resources can be shortened by means of external input, and different external input means have different regulatory effects. For instance, the total productivity and WUE of various intercropping systems can be increased by supplementary irrigation (Aggarwal and Sidhu, 1988) and optimizing nitrogen application system (Teng et al., 2016). For maize-string bean intercropping, the effect of spatial distribution on leaf area index of sole and intercropped maize was not significant, but irrigation could significantly improve leaf area index of maize, and leaf area index of string bean is more sensitive to cropping pattern (Oljaca et al., 2000). Alternate root-splitting irrigation improves crop WUE via integrating with the root system, crop physiological and biochemical characteristics, and coupling water and fertilizer (Yang et al., 2011). Therefore, it can be speculated that sprinkling irrigation enables intercrops to obtain roughly equal water resources, which may lead to faster growth of highly competitive crops and a serious decline in the yield of vulnerable crops. However, drip irrigation can regulate crop growth and development by controlling the water supply of different crops, which has the possibility of improving yield and WUE, especially drip irrigation under the plastic film mulching. These studies illustrate the dynamics and complexity of competition, and the complementary mechanism of crop coping with competition through niche separation. Studies on intercropping of wheat and barley found that competitiveness of barley is stronger than that of wheat, and the effect of interspecific competition on intercropped wheat yield was greater than that of interspecific competition (Woldeamlak et al., 2001). However, the yield of barley was greatly affected by intraspecific competition and the niche differentiation index between the two crops was always greater than one, demonstrating that niche differentiation promoted intercropping resource utilization more than interspecific competition (Woldeamlak et al., 2001). Therefore, competition does not bring negative effects, and moderate competition may be conducive to the improvement of comprehensive benefits in intercropping.

Water distribution in intercropping is the result of dynamic interactions between intercrops' roots and canopies, and intercrops and the environment. Therefore, the study of interactions between above- and below-ground components, and crop and environment are the basis for revealing the adaptation of intercropping to water-limited environments. However, previous studies on interspecific relationships of intercropping are usually based on data on crop harvesting at the same planting density, and the conclusions about competitiveness or other indicators are relatively stable. These conclusions cannot be used as the theoretical basis for the systematic and accurate development of water management in intercropping, so the range of tolerance of intercropping groups to water competition needs to be further defined.

6. Prospects on key research fields for efficient water utilization in intercropping

Water capture and conversion rate are two important indexes of water use in intercropping. The following factors should also be considered: (i) to improve crop water availability, soil water holding characteristics and crop water absorption characteristics should be considered; (ii) increase the total amount of water absorbed from the soil; (iii) increase the proportion of water consumed by effective transpiration of crops; and (iv) increase the proportion of water absorption used in grain organs.

In previous studies on interspecific competition, complementarity, and crop water efficient utilization, many results based on crop productivity measured at physiological maturity. However, there is limited information from studies revealing the dynamics of interspecific competition and complementarity, as well as the interspecific ecological processes of competition, complementarity, and their synergistic effects on WUE with above- and below-ground factors, crop and water environment, and time and space scales. The integration of modern high-efficiency water management technology and crop water physiological mechanisms has not been reported, resulting in shortcomings in the theory and technology for improving intercropping WUE through interspecific relationship regulation. In addition, the spatial and temporal distribution and physiological characteristics of roots are important factors in response to water changes, and they are widely used in sole-cropping research to tap the water-saving potential of crops. However, results from intercropping studies on how to regulate root systems through spatio-temporal variation of water supply and produce complementary utilization of water is rarely reported. Therefore, future research should focus on competitive and complementary utilization of water in intercropping systems to: (i) determine the dynamics of dry matter accumulation and allocation, and irrigation water productivity, to study compensation effects on water use in late-maturing crops after the early-maturing crops are harvested in intercropping systems, and to clarify the correlation between WUE of intercrops and interspecific interaction; (ii) investigate spatio-temporal dynamics of soil water potential and available soil water, and analyze the relationships among soil water movements within interspecific competition and complementarity, in order to provide theoretical basis for optimizing interspecific competition and complementarity under irrigation regulation; (iii) evaluate the effects of intercropping on crop moisture physiological and ecological characteristics to reveal the complementary mechanism of interspecific interaction with respect to hydro-physio-ecological viability; (iv) explore the correlations between root-shoot equilibrium and spatiotemporal distribution of roots, as well as water use characteristics and interspecific competition and complementarity, to elucidate how the root-shoot equilibrium works on improving WUE via the synergistic effects of inter-specific competition and complementarity. By integrating the main results at different scales, the theoretical basis for enhancing WUE of intercropping through regulating interspecific interactions could be established, which provides support for development and adoption of intercropping systems in water-deficient areas.

7. Conclusion

Global food demands are expected to double by 2050 due to a growing human population and increased needs for feed, fiber, and biofuel. To produce sufficient grain to meet demand, Family farms in populated countries must produce sufficient quantities of food to meet the ever-growing population needs. Land and water shortages have become major constraints on agricultural production, it is imperative to increase crop productivity per unit area. Thus, strip intercropping based on crop diversification configuration has been widely applied in arid and semi-arid regions due to high and stable productivity and efficient utilization of resources. Intercropping can increase water use efficiency (WUE) of crops and optimize the soil moisture environment for crop growth and development. Competition and complementarity are two aspects of the same interspecific relationship between crops, and a quantitative understanding of the competition and complementary effects of intercrops on soil resources is important for advancement of intercropping systems. This paper has reviewed more than 150 publications on water utilization of strip intercropping, and suggests that some of the water-shortage issues can be effectively addressed by adopting innovative technologies to achieve water savings and efficient use of water, without restraining future agricultural production. The main factors regulating the efficient water utilization of intercropping were expounded from crop species, irrigation and fertilization regimes, plant density, spatial arrangement, tillage and mulching practices, and environmental factors. Also, a comprehensive efficient water utilization in intercropping system needs to be established. Integrating results from different studies could provide a basis for enhancing WUE of intercropping through advanced understanding of approaches for regulating interspecific interactions. This would provide support for the development and adoption of intercropping systems in water-deficient areas.

CRediT authorship contribution statement

Wen Yin: Conceptualization, Methodology, Resources, Data curation, Formal analysis. **Qiang Chai:** Software, Validation, Resources, Supervision, Project administration, Formal analysis. **Cai Zhao:** Resources. **Aizhong Yu:** Data curation. **Zhilong Fan:** Resources. **Falong Hu:** Methodology, Resources. **Hong Fan:** . **Yao Guo:** Conceptualization, Data curation. **Jeffrey A. Coulter:** Software, Validation, Formal analysis, Supervision, Project administration.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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