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Review

An integrated irrigation strategy for water-saving and quality-improving of cash crops: Theory and practice in China

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ABSTRACT

The cash crop industry has been developed extensively around the world, but in some cases high yields are obtained at the expense of large water and fertilizer input. Although the yield is higher under these practices, it may not be a high-efficient approach from the perspective of crop quality, economical revenue and sustainability in a long term. To solve this problem, an integrated high-efficient irrigation strategy for water-saving and quality-improving of cash crops (WSQI) has to be proposed. Here, we review the research frontiers in this field and the findings of our research group, aiming to expound WSQI with the following perspectives (1) Deficit irrigation under certain conditions and reasonable fertilization can significantly improve the quality of cash crops. Based on the screening of water/nutrient-sensitive quality traits, comprehensive evaluation methods combining the determination of weight for single quality attributes can be used to evaluate and compare comprehensive fruit quality index. (2) Statistical models of water-yield-quality for cash crops were developed that consider the compromise between crop yield and quality. The exploration of biophysical models revealed the mechanisms underlying crop quality formation. (3) Linear, non-linear, dynamic and multi-objective programming models can be powerful tools for supporting irrigation decision-making while considering crop water-yield-quality relationships, market supply and demand, consumer preferences, crop price and resource availability. The integrated high-efficient irrigation strategy proposed in this review would motivate the transition of irrigation strategies from the conventional field irrigation theory, to a new chapter of irrigation management for water conservation and quality improvement in cash crops. The first one is based on water balance and water-yield models, while the second one is based on the information of crop water demand and comprehensive consideration of the water-yield-quality relationship. In addition, this review will provide a theoretical basis and decision-making guidance for research innovation and agricultural production.

1. Introduction

In recent decades, the development of the cash crop industry has become an expanding global phenomenon, which supports rural livelihoods and accelerates economic progress in production areas (Li et al., 2008; Su et al., 2016). The global cash crop area harvested is more than 11 billion ha, and the yield exceeds 1755 million hg/ha in 2018 (FAO Stat, 2019).

China is a major fruit and vegetable producer and consumer, orchards covered 11.135 million ha in China in 2017 (National Bureau of Statistics of China, 2017), accounting for approximately 8.3 % of the country's total cultivated land area (Statistical Bulletin of Land, Mineral and Marine Resources in China, 2017). The total fruit production of China has consistently ranked first in the world since 1994 (Dou and Shao, 2018), and the total fruit output in 2018 reached 257 million tons (National Bureau of Statistics of China, 2018). Although the internal fruit market of China is close to saturated, the impact of imported high-grade fruit and vegetables is becoming increasingly intense (Dou and Shao, 2018), mainly because of the consumers' attention to agricultural product quality. Further, many arid and semi-arid regions such as the northwest of China are facing water shortages (Kang et al., 2017). However, the production of cash crops still depends excessively on

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Table 1
List of symbols.

Symbols	Implication
θ_f	Field capacity
FW	Single fruit weight
FV	Single fruit volume
SI	Fruit shape index
FWC	Fruit water content
Fn	Fruit firmness
TSS	Total soluble solids
VC	Vitamin C
TA	Titrated acidity
OA	Organic acids
SSC	Soluble sugar content
RS	Reducing sugars
SAR	Sugar/acid content ratio
RSA	Ratio of TSS content to OA content
CI	Color index
NC	Nitrate concentration
PEF	Percentage of edible fruit
PRF	Percentage of rotten fruit
Pr	Soluble protein content
CDI	Conventional drip irrigation, both sides of the root-zone irrigated
CFI	Two root-zones were simultaneously irrigated during the consecutive irrigation
ADI	Alternate partial root-zone drip irrigation
AFI	Alternate partial root-zone furrow irrigation
RDI	Regulate deficit irrigation
CK	Regime of control group
ET_0	Reference crop evapotranspiration
AHP	Analysis hierarchy process
TOPSIS	Technique for order preference by similarity to an ideal solution
PCA	Principal component analysis
GRA	Grey relational analysis method
CPM	Catastrophe progression method
EWM	Entropy weight method
FCM	Fuzzy comprehensive evaluation method
CEM	Comprehensive evaluation method

large amount of irrigation and fertilization to obtain high yields, resulting in relatively high yields but no so as high crop quality and income in some cases (Du et al., 2015), together with massive wastes of water resources and pollution due to excessive fertilization (Munoz et al., 2008; Wang et al., 2015; Zhang et al., 2017b).

In order to enhance the competitiveness of cash crop production in the market and maintain sustainable development of the regional cash crop industry, the key solution is to consider cash crop yield and quality comprehensively, aiming to improve crop quality in a high-efficient and environment-friendly way. Scientifically based and reasonable water and fertilizer management for cash crops are essential for addressing these practical problems and urgently need to be developed to achieve agricultural sustainable development.

In recent years, the influence of irrigation and fertilization on fruit and vegetable quality has become a hot spot for international research. Numerous studies have shown that moderate deficit irrigation (sustainable deficit irrigation, regulated deficit irrigation, and alternate partial root-zone irrigation) may decrease fruit size and yield but can significantly improve fruit quality by, for example, increasing TSS, SSC, SAR, VC, Fn, etc. (the symbols are listed in Table 1) (Bertin and Génard, 2018; Chen et al., 2013; Favati et al., 2009; Johnstone et al., 2005; Patanè and Cosentino, 2010). Understanding the response patterns of fruits to mild or moderate water deficit and their underlying physiological and molecular mechanisms are the basis for optimizing deficit irrigation management. Further, quantifying the relationship among water-yield-quality is important for implementing an optimal irrigation strategy that takes into account the balance between yield and quality (Du and Kang, 2011). Empirical statistical models or mechanistic models based on mathematical equations are effective tools to address this question (Chen et al., 2014; Favati et al., 2009).

Studies have attempted to quantitatively describe the dynamics of fruit quality via mechanistic models since the 1990s. The water and carbon flux between plants and fruits is the crucial factor affecting fruit quality. Fishman and Génard (1998) established a biophysical model of fruit growth that can simulate the accumulation of water and dry mass in peach fruits. Liu et al. (2007) and Dai et al. (2009) used this model to simulate the responses of tomato and grape fruit growth to different external environmental conditions and source-sink relationships, respectively. Zhu et al. (2018) developed a 3D functional-structural grapevine model that couples water transport dynamics with gas exchange (Zhu et al., 2019). With regard to the sugar content of the fruit, a peach sugar mechanistic model was established and developed by Génard et al. (2003). This modeling concept was based on the fruit carbon balance and states that the conversion rate of carbon between two metabolites is proportional to the total carbon of the source material.

Currently, researches on the impacts of irrigation and fertilization on cash crop quality is mainly focused on the responses of individual quality trait to water and nutrient stress, but not to guide sustainable agricultural development through an integrated consideration of crop yield, quality and environment. Few studies have been conducted to quantify the effects of water/nutrients on quality, to comprehensively assess the relationships among water, yield and quality, and to optimize regional water resources allocation and irrigation strategy decision-making (Shang and Mao, 2006; Singh, 2012, 2014). Kang (2009) proposed a theoretical framework for improving crop quality and saving irrigation water. Du and Kang (2011) specifically expounded on the physiological, biological and engineering basis for this framework, and discussed research progress and existing problems in water-quality relationship studies. The integrated high-efficient irrigation strategy for water-saving and quality-improving in cash crops (WSQI) proposed in this paper grows from previous deficit irrigation theory, and includes the following: (1) The effect of different water and nutrient treatments on crop quality is analyzed in a global scope. Based on that, a comprehensive quality index evaluation system is constructed. (2) WSQI develops statistical water-yield-quality models for cash crops. Studies on biophysical models lay solid foundation for quality modeling. (3) Irrigation decision-making systems in WSQI are improved considering water-yield-quality relations, and widely application has been conducted, aiming to realize the sustainable utilization of regional water resources and the goal of water-saving, high-quality and high-efficient production in agriculture (Fig. 1). After more than a dozen years work by our research group, this scientific framework has been refined and developed. This article describes this high-efficient irrigation strategy, WSQI, from the theory to the models and decision-making process.

2. Experiments and analysis of water and nutrient effects on cash crop quality

Appropriate irrigation and fertilization management can ensure the fruit quality, acceptance and market grade of cash crops (Dorais et al., 2001). To explore the effects of different water and nutrient treatments on crop quality, many studies have conducted corresponding experiments and analysis. As shown in Fig. 2, in terms of water, studies have considered factors such as irrigation amount, timing, method, and technology. In terms of nutrients, factors such as type, amount, and method of fertilization have been considered. Quality traits such as appearance, flavour, nutrition, storage, and processing traits are measured, as well as the related enzyme activities. The studied crops include tomato, grape, pepper, melon, jujube, etc.. This study summarizes the impacts of deficit irrigation levels, timing, technology, and fertilization treatments on the quality traits of cash crops, as shown in Tables 2–5.

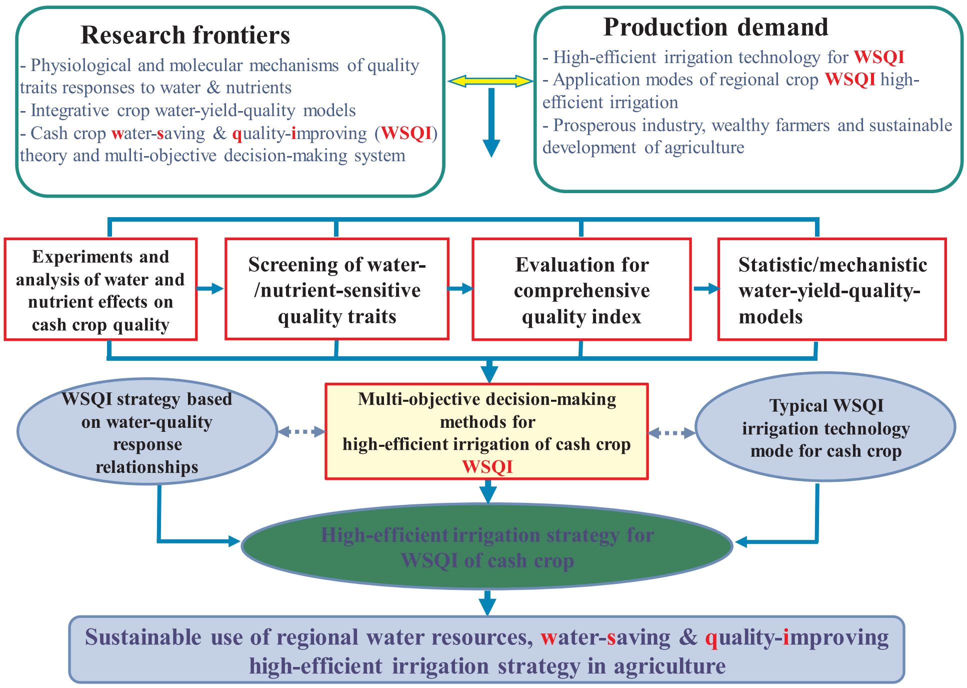

Fig. 1. The research framework of the high-efficient integrated irrigation strategy for water-saving and quality-improving of cash crops.

2.1. Water deficit impacts

2.1.1. Water deficit intensity

Studies have shown that reducing the irrigation amount by 20 %–50 % can improve the quality of cash crops without significantly affecting the single fruit weight or volume (Table 2) (Mahajan and Singh, 2006; Treeby et al., 2007; Wang et al., 2015; Zhou et al., 2014), Fig. 3 shows how fruit quality (FW, TSS, SSC and acid) can be affected with the increase of water deficit extent more intuitively. Water deficit can significantly improve fruit quality such as TSS, SSC and SAR (Fig. 3) (Favati et al., 2009; Guizani et al., 2019; Mahajan and Singh, 2006; Patanè and Cosentino, 2010; Treeby et al., 2007; Wang et al., 2015; Zegbe et al., 2003), but the acid content can be reduced (Guizani et al., 2019; Wang et al., 2015; Zhou et al., 2014) or increased (Favati et al., 2009; Lopez et al., 2010; Mahajan and Singh, 2006; Patanè and Cosentino, 2010) in different cases (Fig. 3). Carotenoid substance and vitamin such as lycopene and VC have also been improved to varying degrees under deficit irrigation (Favati et al., 2009; Guizani et al., 2019; Patanè and Cosentino, 2010; Wang et al., 2015). However, there are some contrary results showing that light or moderate water restriction can't lead to increase of fruit quality, only sever water restriction can improve fruit quality but together with yield reduction (Mercier et al., 2009). Further, water deficit may have negative effects on fruit quality (Zamljen et al., 2020).

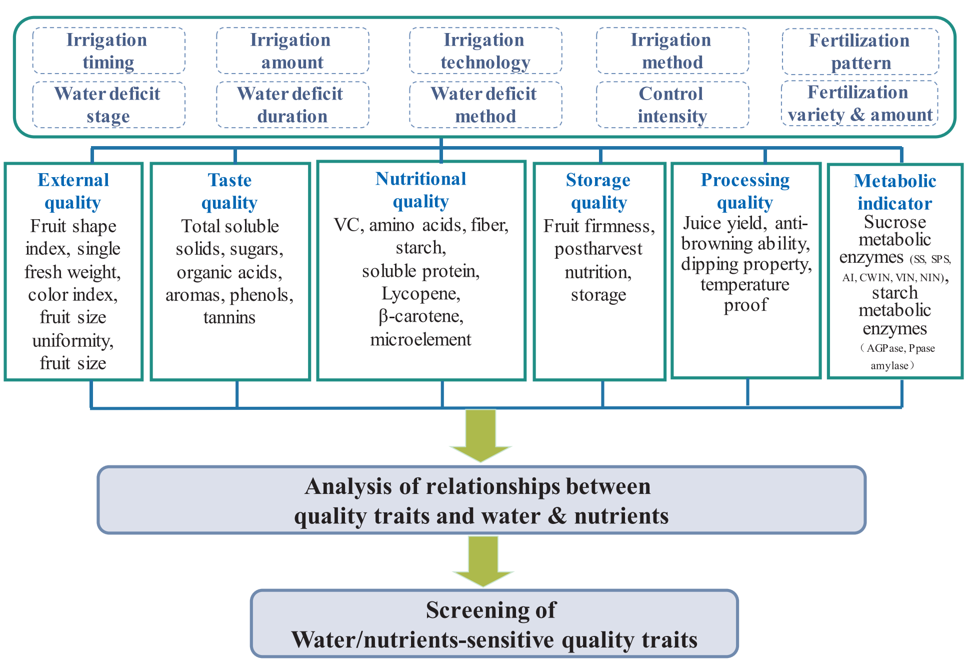

Fig. 2. Analysis of different water and nutrient treatments effects on cash crops quality, measurement traits and analysis process.

Table 2
Details of researches mainly considering the effect of irrigation amount on quality traits for cash crops.

Crop	Study No.	Location and time	Details of recommended irrigation regime	Details of control group	Relative fruit quality traits	Reference
Tomato	1	Palmerston North, New Zealand, 2001	50 % irrigation amount of CK	Daily irrigation up to field capacity	0.82* (FW); 0.91* (FWC); 1.12* (TSS); 0.96 Hue angle	Zegbe et al. (2003)
	2	Ludhiana, India, 2002-2004	50 % irrigation amount of CK	Irrigated on the basis of 1.0 cummulative pan evaporation	1.51* (FV); 1.10* (TSS); 1.12* (TA)	Mahajan and Singh (2006)
	3	Basilicata, Italy, 2002-2003	Irrigation amount of 300 m^3/ha	Irrigation amount of 4010 m^3/ha	1.56*-1.74* (TSS); 1.73*-1.81* (TA); 0.94–1.32* (VC); 1.04*-2.03* (Lycopene)	Favati et al. (2009)
	4	Sicily, Italy, 2002	50 % irrigation amount of CK	Irrigation amount of 380.8 mm	1.06* (Fn); 1.06* (SSC); 1.11* (TSS); 1.21* (TA); 1.95* (VC)	Patanè and Cosentino (2010)
	5	Wuwei, China, 2012-2013	66.7 % irrigation amount of CK	Full irrigation with upper and lower irrigation limits of 90 %, 75 % of θ_f,	0.99–1.11* (FW); 0.91* (SI); 0.94* (FWC); 1.37* (Fn); 1.09*-1.25* (TSS); 1.13*-1.63* (VC); 0.88*-1.17 (OA); 1.06-1.25* (SSC); 1.08-1.21* (SAR); 1.26* (CI); 0.94–1.16 (NC); 0.84 (Lycopene)	Wang et al. (2015)
	6	Linhe, China, 2013-2014	Irrigated at 80 % of CK	Full irrigation of 100 % of crop evapotranspiration	No significant difference in Fn, SSC and VC	Zhang et al. (2017a)
Orange	7	NewSouthWales, Australia, 1999-2001	59% irrigation amount of CK	10 ML ha^{-1} $season^{-1}$	0.88 (FW); 1.07*-1.11* (TSS); 1.11–1.15 (TA)	Treeby et al. (2007)
Peach	8	Huesca, Spain, 2003-2004	No irrigation	Full irrigation	0.71* (FW); 0.98* (FWC); 1.21* (Fn); 1.23* (TSS); 1.29*(TA)	Lopez et al. (2010)
	9	Yangling, China, 2010-2011	Irrigated at 75 % of CK	Full irrigation of 100 % of crop evapotranspiration	1.09*-1.29* (FW); 0.99–1.01 (FWC); 1.22*-1.29 (Fn); 1.03–1.05* (VC); 1.06–1.07 (TSS); 0.84-0.91 (TA); 1.17*-1.26 (SAR)	Zhou et al. (2014)
	10	Sidi Bouzid, Tunisia, 2016-2017	Irrigated at 100 % θ_f whenever the SWC dropped to 50% θ_f	Full irrigation of 100 % of crop evapotranspiration	0.97-0.98 (FW); 1.05-1.10* (Fn); 1.09*-1.13* (TSS); 0.84*-0.87* (TA); 1.09*-1.22* (VC); 1.14*-1.19* (SSC)	Guizani et al. (2019)

CK means the regime of control group. The relative fruit quality trait is the ratio of quality under recommended irrigation regime to that under CK. The experiments could be conducted in several years, thus in this Table, the relative fruit quality traits can be a range for several years experiments, or a specific number of each trait for one-year experiments. *means there are significant difference between recommended regime and CK.

Table 3
Details of researches also considering the effect of deficit irrigation timing besides irrigation amount on quality traits for cash crops.

Crop	Study No.	Location and time	Details of recommended irrigation treatment	Details of control group	Relative fruit quality traits	Reference
Jujube	1	Dali, China, 2005-2006	No irrigation at fruit growth stage	Full irrigation (90 mm for each stage)	0.93-0.95 (FW); 0.88*-0.89* (FWC); 1.15-1.31* (Fn); 1.23*-1.37* (TSS); 1.03–1.05 (VC); 0.37*-0.96 (OA); 0.90–1.04 (SSC); 1.37*-3.28* (SAR); 0.17*-0.36* (PRF); 1.16*-1.29* (Pr);	Cui et al. (2008)
Tomato	2	Wuwei, China, 2008-2010	66.7 % irrigation amont of CK at ripening stage	Full irrigation with upper and lower irrigation limits of 90 %, 75 % of θ_f	0.94-0.96 (FW); 1.08-1.09* (Fn); 1.05*-1.06* (TSS); 1.19*-1.22* (VC); 1.01–1.04 (OA); 1.08*-1.09 (RS); 1.04*-1.08* (SAR); 1.08*-1.19* (CI)	Chen et al. (2013)
	3	Wuwei, China, 2011-2013	44.4 % or 33.3 % irrigation amount of CK from flowering till ripening stage	Full irrigation with upper and lower irrigation limits of 90 %, 75 % of θ_f	1.11*-1.24* (Fn); 1.22*-1.27* (TSS); 1.23*-1.29* (VC); 1.12*-1.17* (OA); 1.43*-1.48* (RS); 1.26*-1.33* (SAR); 1.14*-1.15* (CI)	Chen et al. (2014)
	4	Bursa, Turkey, 2010-2011	No irrigation at fruit growth stage	Full irrigation amount of 417.0-435.3 mm	0.96*-0.98* (FW); 1.00–1.02 (SI); 1.10*-1.10* (TSS)	Kuscu et al. (2014)
	5	Linhe, China, 2014	66.7 % irrigation amount of CK at fruit setting stage	Full irrigation amount of 255 mm	1.06* (SI); 1.30* (Fn); 1.27 (TSS); 1.04 (OA); 1.07 (SAR)	Zheng et al. (2016)
	6	Seville, Spain, 2015-2016	With a threshold of midday leaf water potential of −1 MPa from the beginning of flowering	Full irrigation of 100 % of crop evapotranspiration	0.88*-0.92* (FW); 1.02*-1.06* (TSS); 1.00-1.08* (Fn); 1.01-1.30* (Total carotenoids); 0.99–1.10* (Total phenols)	Coyago-Cruz et al. (2019)
Muskmelon	7	Linhe, China, 2014	80 % irrigation amount of CK at fruit setting stage	Full irrigation amount of 203.91 mm	0.98* (FWC); 1.15* (SSC); 0.84* (TA); 1.21* (TSS); 1.95* (VC)	Jiang et al. (2016)
Olive	8	Venturina, Italy, 2012-2013	76% and 48 % irrigation amount of CK prior to pit hardening	Full irrigation of 100 % of crop evapotranspiration	1-1.15* (Free acidity); 1.21*-1.38* (Total phenols); 1.62*-2.17* (Verbascoside); 1.74*-2.01* (Oleuropein)	Gucci et al. (2019)

CK means the regime of control group. The relative fruit quality trait is the ratio of quality under recommended irrigation regime to that under CK. The experiments could be conducted in several years, thus in this Table, the relative fruit quality traits can be a range for several-years experiments, or a specific number of each trait for one-year experiments. *means there are significant difference between recommended regime and CK.

Table 4
Details of researches also considering the effect of irrigation technology besides irrigation amount on quality traits for cash crops.

Crop	Study No.	Location and time	Details of recommended irrigation treatment	Details of control group	Relative fruit quality traits	Reference
Grape	1	Wuwei, China, 2005-2006	ADI (50 % irrigation amount of CK)	CDI, irrigation amount of 134.4 mm	1.02-1.28* (FW); 1.15-1.42* (VC); 1.01–1.04 (TSS); 0.87*-1.00 (TA); 1.04*-1.07* (PEF)	Du et al., 2013
	2	Wuwei, China, 2005-2006	AFI (66.7 % irrigation amount of CK)	CFI, irrigated with upper and lower irrigation limits of 75 %, 60 % of θ_f	1.04-1.12* (FW); 1.26*-1.38* (VC); 0.96–1.01 (TSS); 0.82*-0.91* (TA); 1.03*-1.04* (PEF)	Du et al., 2013
Tomato	3	Palmerston North, New Zealand, 2001	AFI (50 % irrigation amount of CK)	Daily irrigation up to field capacity	0.82* (FW); 0.89* (FWC); 1.07* (TSS); 0.95* Hue angle	Zegbe et al. (2003)
	4	Huaibei, China, 2012	ADI, the same irrigation amount of CK for the dry part	CDI irrigated with upper and lower irrigation limits of 90 %, 60 % of θ_f for both parts	1.04* (Fn); 1.16* (VC); 1.22* (SSC); 0.76* (OA); 1.59* (SAR); 1.12* (NC)	Zhang et al. (2014)
Orange	5	Sicily, Italy, 2013-2014	ADI (50 % irrigation amount of CK)	CDI, irrigated by 100 % crop evapotranspiration	0.85*-0.90* (FW); 1.07*-1.11* (TSS); 1–1.25 (TA)	Consoli et al., 2017
Zucchini	6	Viterbo, Italy, 2002	Subirrigation	Drip-irrigation	1.03*-1.18* Glucose; 1.08*-1.28* Fructose; 0.96–1.05 Sucrose; 1.06–1.13 Starch; 1.05*-1.19* Total carbohydrate	Rouphael and Colla (2005)
Jujube	7	Akesu, China, 2009	Drip irrigation (50 % irrigation amount of CK)	Surface irrigation, irrigation amount of 1873 mm	0.93* (SI); 1.10* (FW); 0.90* (SSC); 0.70* (RS); 1.08 (TA); 2.25* (VC)	Ren et al. (2012)
Lettuce	8	Beijing, China, 2016	Side seam drip irrigation (36 % irrigation amount of CK)	Conventional irrigation, irrigation amount of 375 mm	0.95 (FW); 1.86* (VC); 0.94 (TSS); 0.95 (NC)	Xu et al. (2017)

CK means the regime of control group. The relative fruit quality trait is the ratio of quality under recommended irrigation regime to that under CK. The experiments could be conducted in several years, thus in this Table, the relative fruit quality traits can be a range for several-years experiments, or a specific number of each trait for one-year experiments. *means there are significant difference between recommended regime and CK.

Table 5
Details of researches also considering the effect of fertilization besides irrigation amount or timing on quality traits for cash crops.

Crop	Study No.	Location and time	Details of recommended agronomic treatment	Details of control group	Relative fruit quality traits	Reference
Tomato	1	Beijing, China 2004-2005	Nitrogen application at 18 mmol N L^{-1} in the nutrient solution	Nitrogen application at 0 mmol N L^{-1} in the nutrient solution	1.21* (Fn); 1.19* (TA); 1.16* (SSC); 0.97 (SAR); 1.19* (TSS)	Wang et al. (2007)
	2	Bellegarde, France, 2004	33.3 % concentration of CK	12 mM NO_3^- solution	1.18* (SSC); 0.84* (TA)	Bénard et al., 2009
	3	Shijiazhuang, China, 2007-2008	Irrigation with upper and lower irrigation limits of 80 %, 75 % of θ_f, Zn fertilization of 0.2% solution	Irrigation with upper and lower irrigation limits of 95 %, 90 % of θ_f, no Zn fertilization	1.07* (VC); 1.12* (SSC); 0.98 (OA); 1.15* (SAR); 1.11* (Pr)	Jiang et al. (2009)
	4	Yanan, China, 2009-2010	70% fertilization amount of CK	600 kg N/ha, 420 kg P_2O_5/ha, 718 kg K_2O/ha	0.97-1.00 (FWC); 0.93–1.11* (VC); 1.03-1.39* (Pr); 1.12-1.13* (SSC); 1.03-1.07* (OA); 0.79–1.21* (Free amino acid)	Lin (2011)
Pomegranate	5	Yazd, Iran, 2009	Potassium nitrate of 250 mg L^{-1}	Distilled water	1.04 (TSS); 1.04 (TA); 1.13VC	Khayyat et al. (2012)
Watermelon	6	Yangling, China, 2013	66.7 % irrigation, and twice fertilization amount of CK	Full irrigation amount of 1350 m^3/ha, fertilization amount of 81.53 kg N/ha, 33.43 kg P_2O_5/ha, 101.09 kg K_2O/ha	2.18* (SSC); 1.16* (VC); 1.23* (Pr); 0.95 (OA); 3.66* (Lycopene)	Yang et al. (2014)
Apple	7	Orondo, America	151 g N/ tree	908 g N/ tree	1.05* (Fn); 1.06* (SSC); 1.07 (TA)	Raese et al. (2007)
Blueberry	8	Mohe, China, 2012-2014	Compound fertilizer of potassium sulfate of 5 g/ plant	No fertilization	0.97 (VC); 1.21 (SSC); 0.85* (TA); 2.00* (SAR)	Zhou et al. (2015)
Hot pepper	9	Yangling, China, 2014	Irrigation of 75 % ET_0, and half amount of N application for CK	Irrigation of 105 % ET_0, and N application amount of 300 kg N/ha	1.67* (SSC); 0.91 (Capsaicin); 1.79* (VC); 0.88 (NC); 0.90 (TSS)	Xiang et al. (2018)

CK means the regime of control group. The relative fruit quality trait is the ratio of quality under recommended irrigation regime to that under CK. The experiments could be conducted in several years, thus in this Table, the relative fruit quality traits can be a range for several-years experiments, or a specific number of each trait for one-year experiments. *means there are significant difference between recommended regime and CK.

2.1.2. Water deficit timing

To regulate fruit quality, most studies chose to conduct deficit irrigation in the reproductive growth stage rather than the vegetative growth stage (Table 3). For example, studies on tomato have shown that reducing the irrigation amount by 33.3%–66.6% in the middle and late stages of fruit development can significantly improve flavour traits such as TSS, SSC, and OA (Chen et al., 2013, 2014), and other traits such as total carotenoids, phenols, and VC (Coyago-Cruz et al., 2019; Gucci et al., 2019; Jiang et al., 2016; Kuscu et al., 2014). In addition, SI and Fn can be affected when the water deficit occurs in the fruit setting stage; these traits would influence consumers' behavior (Coyago-Cruz et al., 2019; Zheng et al., 2016). Cui et al. (2008) found that water deficit during the fruit growth stage can improve the flavour and nutritional quality of jujube while reducing the proportion of rotten fruit and improving the quality of fruit storage and transportation. Further, regulated deficit irrigation could also improve fruit growth in some case due to better water utilization, higher uptake and use efficiency of nutrient and excellent soil-water-air relationship with higher oxygen concentration in the root zone (Mahajan and Singh, 2006). Besides, the water deficit during the stage of vegetative growth could inhibit the growth of vegetative organs, facilitate the transfer of carbohydrates to fruits, promoting fruit growth and yield (Consoli et al., 2017; Gucci et al., 2019).

2.1.3. Irrigation technology

With the development of irrigation technology and the modernization of irrigation concepts, many studies have emerged in recent decades that focus on the impact of different irrigation technologies or irrigation methods on the quality of cash crops (Table 4). Among them, alternate partial root-zone irrigation is widely used in China (Kang and Cai, 2002); in this method, irrigation is applied alternatively to different parts of the root zone, keeping some parts dry and the remaining parts wet. Studies of tomato found that alternate partial root-zone irrigation can significantly increase fruit TSS, SSC and SAR (Consoli et al., 2017; Zegbe et al., 2003; Zhang et al., 2014a,b), and obtain more vivid fruits (Bogale et al., 2016; Romero et al., 2015; Zegbe et al., 2003). In studies on grape, it was found alternate partial root-zone irrigation (drip irrigation, furrow irrigation) not only increased the fruit fresh weight by 2 %–28 % but also significantly increased the fruit VC (15 %–42 %) and the percentage of edible fruit (3–7 %), while reducing irrigation water use by 33.3 %–50 % (Du et al., 2008; Du et al., 2013). However, there are some studies showing that partial root-zone irrigation can not bring significant improvement on grape fruit TSS and acid content (Romero et al., 2015), but some other traits such as total phenolic, anthocyanin and amino acid concentrations can be enhanced (Bogale et al., 2016; Romero et al., 2015). In addition, compared with traditional surface irrigation, drip irrigation and side seam drip irrigation can also reduce water usage by 50 %–64 %, while increasing SSC and VC in cash crops such as jujube and lettuce (Ren et al., 2012; Xu et al., 2017). Compared to drip irrigation, sub-irrigation can improve zucchini sugar contents and carbohydrate accumulation, which are due to the super optimal electrical conductivity recorded on sub-irrigation plants (Rouphael and Colla, 2005).

2.2. Mechanisms of water deficit impacts

The improvement in cash crop quality due to water deficit can be ascribed to the modulation of the underlying physiological mechanisms of the plant from the following four perspectives: (1) Many studies hold the view that under water deficit conditions, the reduction of water flux into the fruit decreases fruit volume (Rančić et al., 2010) and increases the concentration of carbohydrates and related quality traits in fruit (Ho et al., 1987; Hou et al., 2020; Zhang et al., 2017a). (2) Water deficit regulates the distribution of photosynthetic assimilates by reducing vegetative growth and increasing the vigor of the fruit as a sink. Therefore, the carbohydrates that would normally be allocated to side

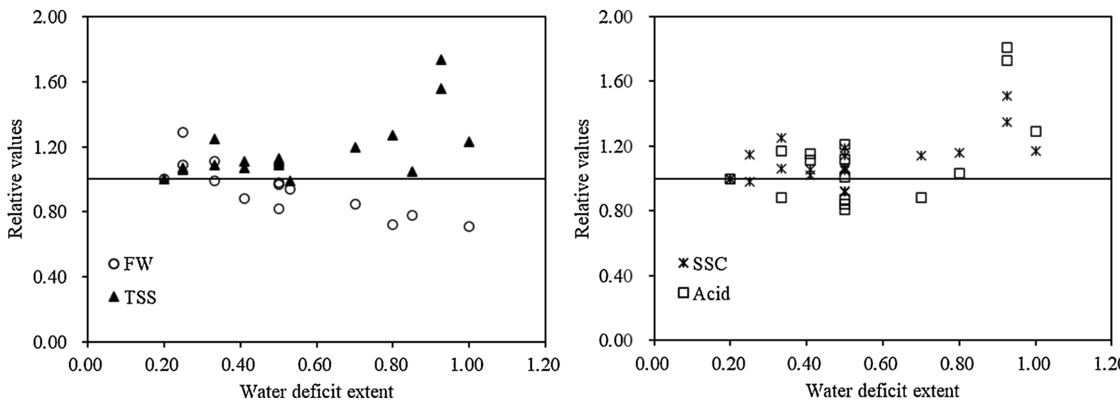

Fig. 3. Results of water deficit effects on single fruit weight (FW), total soluble solids (TSS), soluble sugar content (SSC) and acid content (Acid).
* Relative value is the ratio of quality trait under deficit irrigation to that under full irrigation. Water deficit extent equals to 1- (deficit irrigation amount/full irrigation amount). Data from references included in section 2.1.1 and Table 2.

branches are transferred to the fruit, which increases the accumulation of assimilates in the fruit (Davies et al., 2000; Patanè and Cosentino, 2010). (3) Moderate deficit irrigation increases the starch accumulation in the early fruit development stage, so a larger proportion of starch will be converted to sugar during the fruit ripening stage, thereby improving fruit quality (Zegbe et al., 2003). In addition, vegetative reproduction is reduced, and plant light transmittance is increased, which is beneficial to fruit colour and the corresponding nutrient element synthesis (Bénard et al., 2009). (4) Under water stress, plants will upregulate the expression of mRNA related to glucose metabolism and increase the contents of abscisic acid (ABA), ethylene and other substances (Deluc et al., 2007). These substances are related to the initiation and promotion of fruit maturity (Zaharah et al., 2013), can regulate the activities of carbohydrate and vacuolar metabolic enzymes, and play an important role in regulating the sugar concentration in fruits (Deluc et al., 2009; Downie et al., 2003; Johnston et al., 2009). Therefore, water deficit at fruit ripening stage triggers significant taste and nutritional quality improvements (Chen et al., 2013, 2014). Through the abovementioned physiological, material transformation, and signal regulation effects, crop quality traits can be improved under water deficit.

2.3. Fertilization impacts

There is some controversy about the effects of fertilization on the quality of cash crops. According to Table 5, compared with non or very low fertilization treatments, fertilization application can increase the TSS, SSC, and VC content of cash crops such as tomato, water melon, and blueberry and increase SAR (Jiang et al., 2009; Khayyat et al., 2012; Wang et al., 2007a,b; Yang et al., 2014; Zhou et al., 2015), since nutrients such as nitrogen, phosphorus, potassium and zinc are essential for crop growth and fruit development. Further, in the study of pineapple, it was found that soil application of potassium can decrease internal browning since it would lower polyphenoloxidase and phenylalanine ammonia-lyase activities (Soares et al., 2005). However, some studies have shown that reducing the amount of fertilization by 25 %–50 % based on the local recommended fertilization level can effectively increase fruit quality such as fruit firmness, VC and SSC in tomato, apple, and hot pepper (Bénard et al., 2009; Li et al., 2011; Raese et al., 2007; Xiang et al., 2018).

Taking nitrogen (N) application as an example, different conclusions have been drawn from many studies on the effects of N application on crop quality. These differences may have been caused by the different experimental conditions and the inconsistent sink-source ratio of plants (Bénard et al., 2009). When a plant is relatively small, N deficit will seriously affect its vegetative growth, fruit carbon input and metabolism and will adversely affect quality formation in its later stages. Moderate N application at a proper stage can promote root zone development, crop growth, and dry matter accumulation, thereby improving fruit quality (Huett and Dettmann, 1988; Flores et al., 2003; Kuscu et al., 2014). However, excessive N application, which is a common phenomenon worldwide (Munoz et al., 2008; Wang et al., 2015; Zhang et al., 2017b), might have a disadvantageous effect on crop quality. Wei et al. (2018) noted that a lack of N fertilizer can reduce vegetative growth in the leaf canopy, increase fruit received radiation and temperature, and cause changes in fruit secondary metabolism. These processes promote the synthesis and decomposition of assimilates in fruits, which in turn increases the contents of TSS, SSC and OA in fruits (Bénard et al., 2009; Wang et al., 2007a).

2.4. Screening for sensitive qualities

Table 2–5 show that some crop qualities are not sensitive to water or nutrient treatment. In the WSQI high-efficient strategy proposed in this article, water- and nutrient-sensitive quality traits are screened based on the above analysis (Fig. 2), which lays a foundation for the comprehensive fruit quality analysis and the following strategy decision making progress. Wang (2011) carried out a sensitivity analysis to identify the responses of individual quality to water deficit and screened out the water-sensitive quality of tomato as well as the growth stages of fruit in which fruit quality is water-sensitive. The sensitivity calculation formula is as follows:

$$S_j = \frac{1}{m}\sum_{k=1}^{m}\left|\frac{\Delta q_k'}{\Delta ET_k'}\right|, (j = 1, 2, \ldots, n) \quad (1)$$

where S_j is the sensitivity coefficient of trait j; m is the number of water treatments; n is the number of quality traits; $\Delta q_k'$ is the normalized variation in a single quality trait between two water treatments (when the quality variation between the two treatments is not significant, $\Delta q_k' = 0$); and $\Delta ET_k'$ is the normalized variation in crop evapotranspiration between the two water treatments.

Sensitivity analysis can screen water-sensitive quality traits for specific crop, genotype, and also water stress timing. In a study of water stress on grape berry quality, SSC and TA were very sensitive to water stress, following by tannin, but anthocyanin was not sensitive in this case (Chen, 2010). In a study of tomato fruit, Chen, 2009 pointed that FW, Pr and SSC were sensitive to water stress during fruit ripening, TSS and Fn were sensitive to water stress during fruit setting and ripening, VC was sensitive to water stress in all stages. However, Wei (2018) showed that fruit quality was more sensitive to water stress during fruit color changing stage, and was more sensitive under irrigation method of ADI than CFI. Results in Cui (2009) showed that water stress improved jujube fruit quality during fruit expanding and ripening stages, but the sensitive period of field and greenhouse experiments was slightly different, since rainfall is ignorable in greenhouse but not in field case.

Numerous studies on fruit quality highlight the variable responses of plants to water and nutrient treatments due to their different experiment locations, crop species, genotypes, etc. Besides, the water quality such as salt content of the irrigation water may influence plant growth and fruit quality (Yang et al., 2019). Reviews by Bertin and Génard (2018) and by Ripoll et al. (2014) also emphasized the complexity of quality traits underling mechanisms. It is difficult to predict the specific responses of quality traits to different water and nutrient stresses. Therefore, based on the selection of water- and nutrient-sensitive quality traits, further evaluation for comprehensive quality index should be performed to reflect farmers' comprehensive consideration of cash crop quality and provide clearer guidance for agricultural irrigation and fertilization management.

3. Comprehensive quality index evaluation for cash crops

The concept of quality in fruits and vegetables is comprehensive; it not only includes objective, quantifiable traits such as sugar, acid, and vitamin contents but also involves subjective traits such as taste and other "fuzzy" indicators, such as fruit shape index (SI) and size which might influence consumer preference. Therefore, it is difficult for a single quality indicator to accurately represent the comprehensive quality of cash crops. In order to meet the "quality expectations" for agricultural products from different consumers, using scientific methods to develop a comprehensive quality index will be an important breakthrough in the study of water-quality response relationships. In WSQI strategy, comprehensive evaluation methods have been introduced into the evaluation of comprehensive fruit quality index. The evaluation process includes two main steps: the determination of weights for individual quality attributes and the calculation of a comprehensive quality rank using the evaluation methods.

3.1. Weight determination and comprehensive evaluation methods

First, for the determination of the weights of individual quality attributes, the commonly used methods can be divided into two categories: subjective valuation methods and objective valuation methods. Subjective valuation methods include the expert survey method, the analytic hierarchy process (AHP) (Saaty, 1980), and the fuzzy statistical method; objective valuation methods include the standard deviation method, principal component analysis (PCA), the entropy weight method, and the CRITIC method, etc. (Wang et al., 2011b). Among these, AHP is a multi-criteria decision-making method that addresses how to determine the relative importance of a set of factors. In WSQI strategy, Wang et al. (2011b) introduced this method to evaluated tomato fruit comprehensive quality, the evaluation hierarchy can be divided into three levels (Fig. 4); the objective level on the top is the determination of the comprehensive quality, Q, of tomato, the criteria indicating quality are in the middle level, and the individual quality attributes are located at the lowest level. In their study, 1000 customers and 25 horticultural experts participated in the comparisons for the criteria and attribute levels, respectively.

After the weights are determined, multiple traits are integrated into a comprehensive quality index for evaluation and ranking. Commonly used comprehensive evaluation methods include PCA (Lan et al., 2014), technique for order preference by similarity to an ideal solution (TOPSIS) (Hwang and Yoon, 1981), the grey relational analysis method (GRA) (Lu et al., 2009), the aggregative index method, and the fuzzy comprehensive evaluation method, etc. (Wang et al., 2011b). TOPSIS is a classical method for multiple attribute decision making. By defining the positive and negative ideal solutions, alternatives can be ranked in TOPSIS based on their relative similarity to the positive ideal solution. Since there are many traits in multiple attribute decision making, information from observations might overlap due to traits correlation. The GRA method is a powerful tool analyzing processes with multiple performance characteristics (Lu et al., 2009). PCA is a useful method for feature extraction and data reduction that can accurately identify the sources of variance after reducing the dimensionality of data (Lu et al., 2009; Lan et al., 2014).

3.2. Applications of comprehensive quality evaluations

Table 6 lists our team studies on the evaluation of cash crops comprehensive quality in China under different agronomic treatments, and the quality traits which were taking into account. Wang et al. (2011a) used PCA to evaluate the comprehensive quality of tomato, the ratio of the actual product output to the total yield of each harvest was assumed as the weight in the PCA evaluation process. Further they used this method to evaluate tomato comprehensive quality performance under different irrigation treatments. Wang et al. (2011b) validated the effectiveness of the tomato comprehensive quality index established by AHP and TOPSIS, and recorded the responses of the tomato comprehensive quality index to different irrigation management treatments. Chen (2009) found that the comprehensive quality of tomato fruit decreased with increasing irrigation using AHP and fuzzy comprehensive evaluation. In the study of Wang et al. (2015), after the determination of the weights of individual quality traits with AHP, the comprehensive quality of tomato fruit under different irrigation and N conditions was assessed using GRA and PCA. Furthermore, the treatment with the best comprehensive quality ranking was the same under both evaluation methods. Considering the relationship between yield and quality, they suggested an optimal regime, irrigated at 63 % of ET_0 and N fertilization at the typical level for local agronomic practices (574.35 kg ha^{-1} in spring-summer season and 272.85 kg ha^{-1} in winter-spring season). Wei et al. (2018) found via PCA that under high N conditions and elevated CO_2 conditions, deficit irrigation, especially alternate partial root-zone irrigation, can significantly improve the comprehensive quality of tomato.

The above summary shows that by screening for an individual fruit quality of interest, researchers can conduct evaluation for cash crops comprehensive quality under different agronomic treatments. This evaluation process provides a certain theoretical basis and some methodological guidance for WSQI.

4. Statistical models of water-yield-quality relationships

Studies have shown that the improvement in cash crop quality caused by water deficit is often accompanied by a decline in yield (Bertin and Génard, 2018; Chen et al., 2013; Cui et al., 2008; Favati et al., 2009; Patanè et al., 2011; Yang et al., 2017; Zheng et al., 2013). In addition, the effects of deficit irrigation on crop yield and quality are closely related to the timing and extent of the water deficit occurrence (Du et al., 2008; Johnstone et al., 2005; Patanè and Cosentino, 2010; Wang et al., 2015), and depend on the crops (Dai et al., 2010; Yang et al., 2017). Therefore, acceptable yield and high quality in cash crops may be possible if the intensity and timing of water deficit are proper. To balance crop yield and fruit quality, that is, to improve fruit quality while ensuring yield, some studies explored the correlation of cash crop yield and quality with water supply during the full or parts of the growth stages. Different degrees of deficit irrigation were set to obtain an optimal irrigation strategy for processing tomato production (Favati et al., 2009). Many studies were performed aiming to explore the water-yield relations and built several water-yield models (Jensen, 1968; Minhas et al., 1974; Stewart et al., 2016). Unfortunately, there are currently few developed models for evaluating water-quality relationship. In WSQI strategy, water-quality models were developed through the adaptation from the water-yield models and they were calibrated and validated with 4 years of experimental data.

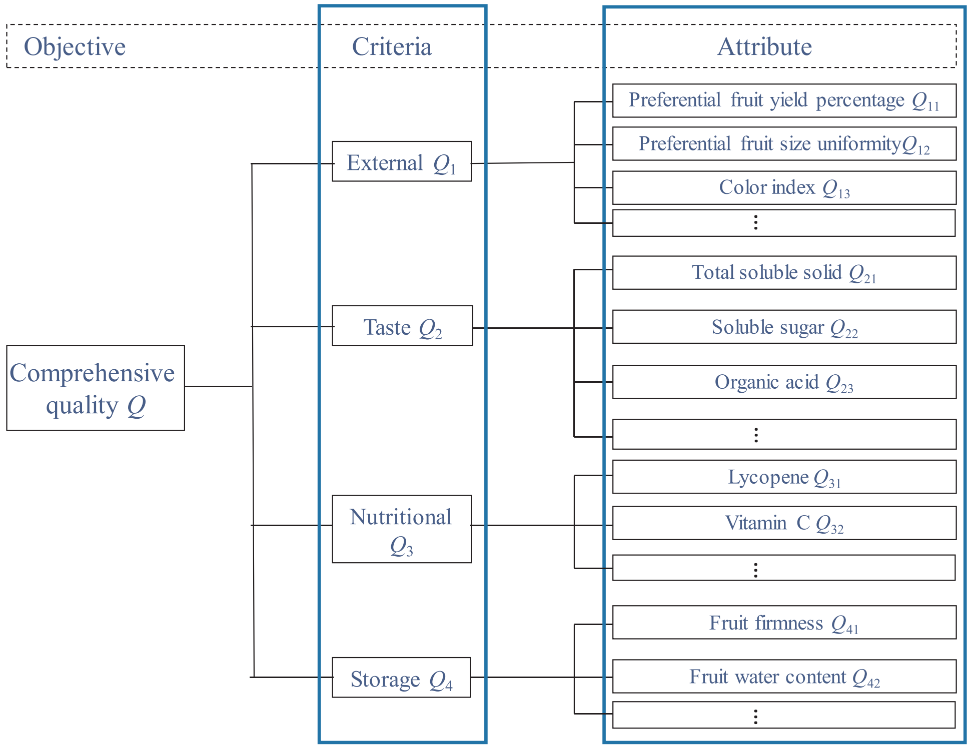

Fig. 4. Evaluation hierarchy of cash crop comprehensive quality, adopted from Wang et al. (2011b).

4.1. Water-yield statistical models

Water-yield models, i.e., crop water production functions, are mathematical models that describe the quantitative relationships of crop yield to water consumption during the whole growing season or at some specific growth stages; they include the effects of the timing and intensity of water deficit (Chen et al., 2014; Rao et al., 1988). These models can be roughly divided into two categories: one is additive models, which add the effect of the phase effect on the final relative crop yield, such as models proposed by Blank (1975); Stewart et al. (2016) and Singh et al. (1987). Another is multiplicative water-yield models, which use multiplicative ways to describe the effect of the relative water consumption or the stage water deficit on the final relative crop yield. Typical examples of multiplicative models are the models by Jensen (1968); Minhas et al. (1974) and Rao (1974). In WSQI strategy, Chen et al. (2014) estimated the parameters of water-yield models (Stewart, Jensen, Minhas) based on four-year greenhouse deficit irrigation experiment data, and then compared the performance of each model. The Minhas model was recommended for simulating the greenhouse tomato water-yield relationship, with an RMSE of 0.031, R^2 of 0.94, and a modeling efficiency of 0.90.

4.2. Water-quality statistical models

Compared to the numerous studies on the water-yield relationship, there is a knowledge gap in water-quality models for evaluating the effects of different degrees of water deficit at various growth stages on crop quality. In WSQI strategy, after analyzing the relationships between quality traits and the relative water consumption and the relative water deficit degree at each growth stage, six water-quality models (Additive, Multiplicative, Exponential, Q_Singn, Q_Minhas, Q_Rao) were developed, adapted from water-yield models, to simulate the relationships of tomato fruit quality with water deficit at various growth stages (Chen et al., 2014). Multiplicative model was recommended for simulating the relationships of fruit quality such as TSS, RS, SAR, and Fn with water deficit at various growth stages, with RMSE values in the range of 0.037-0.054 and R^2 values in the range of 0.63-0.88. Meanwhile, additive model was recommended for simulating the effects of water deficit at different stages on tomato fruit quality such as OA, VC, CI and comprehensive quality index, with RMSE values in the range of 0.027-0.065 and R^2 values in the range of 0.64-0.90. In the study of Shan et al. (2019), a comparison was conducted among additive, multiplicative, and exponential models simulating the relationship between water and comprehensive quality index of greenhouse tomato. Among them, the additive model performed best, with an R^2 of 0.91, and tomato comprehensive quality was the most sensitive to water deficit at the fruit ripening stage.

Although current statistical models can reach a certain degree of prediction accuracy, they cannot explain the underlying mechanisms of the relationships among crop yield, quality, and water consumption. In-depth research is needed to further reveal the mechanisms of the quality response to water/nutrient in terms of gas exchange, water/nutrient absorption, assimilate accumulation and distribution, and source-sink relations between plants and fruits. More physiological models of the crop water-yield-quality relationship need to be explored in addition to empirical and semi-empirical models.

5. Primary exploration of models related to fruit quality

In the 1990s, studies attempted to quantitatively describe crop quality characteristics through process-based models (Fishman and Génard, 1998; Génard and Huguet, 1996). Biophysical dynamic growth models and semi-mechanism sugar models were developed to simulate fruit growth and sugar accumulation responses to genetic variability, environmental fluctuations and agronomic management, combining biophysical and physiological processes via mathematical framework. These models provide a prospective way to designe innovative horticultural practices facing the challenge of water shortage and future climate changing (Beauvoit et al., 2018; Bertin et al., 2006; Fishman and Génard, 1998; Génard et al., 2007; Rahmati et al., 2018; Struik et al., 2005).

Table 6
Summary of studies reporting the evaluation methods for the comprehensive quality of cash crops in China.

Crop	Study No.	Location and time	Evaluation method	Quality traits	Reference
Jujube	1	Dali, Shaanxi, 2005-2006	PCA, EWM	FV, Fn, FWC, VC, SAR, Flavor	Cui (2009)
Grape	2	Wuwei, Gansu, 2009	AHP, Aggregative Index	Irrigation amount, SSC, SAR, Tannin, Anthocyanin, Yield, Extractable juice content, FV	Chen (2010)
Tomato	3	Wuwei, Gansu, 2008	AHP, FCM	FW, SI, CI, SAR, OA, TSS, SSC, Pr, Lycopene, Aromas, VC, Fn, FWC	Chen (2009)
	4	Wuwei, Gansu, 2008-2009	AHP, TOPSIS	Preferential fruit yield percentage, Preferential fruit size uniformity, CI, TSS, SSC, OA, SAR, Lycopene, VC, Fn, FWC	Wang et al., 2011b
	5	Wuwei, Gansu, 2012-2013	AHP, PCA, GRA	FW, SI, CI, SAR, OA, TSS, SSC, Lycopene, VC, Fn, FWC	Wang et al. (2015)
	6	Wuwei, Gansu, 2008-2013	AHP, Aggregative Index	CI, SAR, OA, TSS, SSC, VC, Fn	Chen (2016)
	7	Yangling, Shaanxi, 2012-2013	PCA	TSS, OA, SSC, Lycopene, VC, NC, SAR	Wang et al. (2017)
	8	Wuwei, Gansu, 2010-2014	TOPSIS, EWM, PCA, CEM	TA, SSC, SAR, TSS, Fn, NH_4^+, K^+, Mg^{2+}, Ca^{2+}, NO_3^-, SO_4^{2-}, PO_4^{3-}, Total cation concentration, Total anion concentration, Total ionic concentration	Wei (2018)
Melon	9	Wuwei, Gansu, 2008-2009	CPM	Marketable yield, TSS, VC, RSA, Marketable water productivity	Wang et al. (2017)
Pepper	10	Yangling, Shaanxi, 2014	PCA	SSC, Capsaicin, VC, NC, TSS	Xiang et al. (2018)

5.1. Process-based models related to fruit quality

Lescourret and Génard (2005) proposed the "virtual fruit" model applied to peach fruits, this model reorganized and integrated three process-based models they had previously proposed, which respectively described the fruit growth of dry mass (Lescourret et al., 1998), fresh mass (Fishman and Génard, 1998), and the accumulation of sugar in the flesh (SUGAR model) (Génard et al., 2003). The integrated model is an important breakthrough for understanding the response of fruit quality traits to environmental fluctuations at the plants and fruits scales, and this progress has promoted further research perspectives in quality trait modeling. In the carbon sub-model (simulation of dry mass), it calculates leaf carbon assimilation, fruit carbon assimilation, carbon coordination of other storage organs, so as to define the carbon allocation and the dry mass of fruits (Lescourret et al., 1998). In the sugar sub-model (SUGAR model), the main principle is carbon balance and the conversion rate of carbon between two compounds is proportional to the total carbon of the source material (Génard et al., 2003). In the water sub-model, fruit is virtualized into a “big cell” connecting with the plant through phloem and xylem vessels. Water enters the fruit from xylem and phloem and is lost through transpiration. Sugar is unloaded from phloem through active transport, mass flow, and passive diffusion (Bertin et al., 2006; Fishman and Génard, 1998). The model has proven to be quite robust and generic, and been applied on many species, e.g. grape, blueberry, tomato, pear to simulate fruit sugars dynamics, under different genotypes, water conditions and fruit loadings (Dai et al., 2009; Jorquera-Fontena et al., 2017; Liu et al., 2007; Prudent et al., 2011; Quilot et al., 2004).

An integrated view of plant functioning is essiencial to predict fruit growth and composition since the plant is the main source of water, carbohydrates and minerals for the fruit. Functional-structural models explicitly descibe the architecture of the plant and formalize the processes of decelopment, growth, acquisition and allocation of rescources (carbon and water) at the level of organ. QualiTree, a virtual fruit tree model, is one of the functional-structural models linking fruit and plant growth of peach (Lescourret et al., 2011; Mirás-Avalos et al., 2011), and was applied to simulate peach fruit quality and size under changing water stress degree (Mirás-Avalos et al., 2013). QualiTree model allows to disentangle the effects of water stresses on carbon aqauision, vegetative growth, and fruit quality of peach (Rahmati et al., 2018).

Another functional-structural model was developed for tomato (Baldazzi et al., 2013), which can estimate the resource acquisition, transpiration, carbonhydrate laoding and leakage along the phloem pathway and transfer within the plant, such formalization enables to simulate the within plant variability of water and carbonhydrate. Further, leaf gas exchenge was also coupled with the dynamics of water transport to simulate grape fruit growth and quality under different climate scenarios (Zhu et al., 2018, 2019).

5.2. TOM-SUGAR model

Based on the sugar metabolisms and feedback loops of tomato fruits, in WSQI, Chen et al. (2020) adapted the SUGAR model (Génard et al., 2003) and established a tomato fruit sugar mechanism model, TOM-SUGAR model. In TOM-SUGAR, carbon supply is mainly the sucrose unloaded from the phloem, and carbon is depleted by respiration. The carbon is divided into three pools: soluble sugars, starch, and the other carbon-compounds like organic acids, amino acids, proteins, cell wall compounds etc. Starch, as a transient reserve pool, interconverts with the soluble sugars. The soluble sugars provide the raw material for the biosynthesis of the other carbon-compounds. The metabolic activities involved in carbohydrate metabolism were reflected by the reaction rates (k values) which regulate the carbon fluxes among the pools. Fruit water content was introduced to modify the sugar metabolism related reaction rates in the model, assuming that fruit water content imposes an influence on carbohydrate metabolism in fruit. The model better simulated the dynamics of carbohydrate accumulation in the tomato fruit growing under different conditions by considering the influence of fruit water content on sugar metabolism. Further, Chen (2016) coupled fruit sugar and fruit growth model, soluble sugar content simulated from TOM-SUGAR model was used to be the input of tomato fruit growth model. The coupled model was applied to simulate tomato fruit growth and sugar dynamics under different water conditions, which showed good fittings.

However, this type of model also has certain limitations. First, the model involves many physiological and biochemical parameters, which can not be directly obtained and validated through experiments. Thus, a large amount of input data is required for parameter calibration, which increases the threshold for model application. Besides, although the rationality of parameters variation was analyzed in their studies, the self-correlation between parameters made the calibration process quite difficult. Further, more attention can be paid to simulate some other important fruit compounds, such as antioxidants and vitamins, and influencing factors can be included as model variables such as fertilization or atmospheric CO_2 concentration.

6. Decision-making methods of irrigation and applications

In the conventional theory of deficit irrigation, the optimal irrigation schedule is set based on water balance and water production functions, with the maximization of yield or the minimization of economic losses as the objective function. (Shang and Mao, 2006; Shangguan et al., 2002; Singh, 2012, 2014). This kind of optimization method, which only aims to maximize yield or regards income as only related to production yield is not suitable for cash crops, since stress in certain stages can increase marketable produce performance by improving or keeping crop quality (Carvalho et al., 2014; Pardo et al., 2020). In the new high-efficient irrigation strategy for WSQI of cash crops, irrigation decisions should be supportted by comprehensive consideration of the relationships between water-yield and water-quality, through methods such as linear/non-linear programming, dynamic programming, genetic algorithms and multi-objective programming (Singh, 2012, 2014), or some improved methods based on those programmings (Brown et al., 2010; Paul et al., 2000; Vedula and Kumar, 1996; Yang et al., 2009), to allocate limited agricultual irrigation water resource while maintaining high yields, improving quality, and increasing high efficiency (Fig. 5).

6.1. Decision-making methods of irrigation

In WSQI, non-linear programming is one of the most commonly used methods for the optimization of irrigation schedules. In non-linear programming, first, the objective function needs to be determined, for example maximizing farmers' income; second, the effect of water/fertilization management on the income to be maximized is determined through water-yield, water-quality or quality-price functions. Further, economical aspect is also invoved in WSQI, the relatoinship of price to crop quality and the relationship between fruit price and fruit quality varied with economic and social development. To consider the different economic conditions in different regions, a flexible price coefficient was used to determine the quantitative relations between crop price and its quality (Chen, 2016). Then, the economic revenue was obtained by multiplying the crop yield and the quality-related price. The optimal irrigation strategies were designed by maximizing the economic revenue through linear/nonlinear programming methods (Chen, 2016; Shan et al., 2019). In addition, constraints can be set according to the local available water resources, soil water status, upper and lower irrigation limits, and the optimization can be performed for different scenarios. In linear/non-linear and dynamic programming models, there is usually only one objective function. In WSQI strategy, the optimization of water/fertilization management considers crop yield, quality and final income; multiple conflicting targets are involved, with multiple constraints. The multi-objective programming model is an effective tool for addressing this situation (Ghahraman and Sepaskhah, 2002; Lachhwani, 2012; Liu et al., 2019; Singh, 2012; Zeng et al., 2010).

In the studies of WSQI, the optimal irrigation schedule for greenhouse tomato water saving and quality improvement was determined to be 100 % of ET_0 at the seedling stage, 90 % of ET_0 at the fruit setting stage, and 63 % of ET_0 at the fruit ripening stage (Chen, 2009). Theses levels were determined based on the crop water-production and water-quality functions and the production practice, through dynamic programming with the goal of maximizing the total economic benefit. In a non-linear case of Chen (2016), compared with full irrigation, although the optimized irrigation schedule reduced the yield by 10 %, the comprehensive fruit quality index and income increased by 14.0 % and

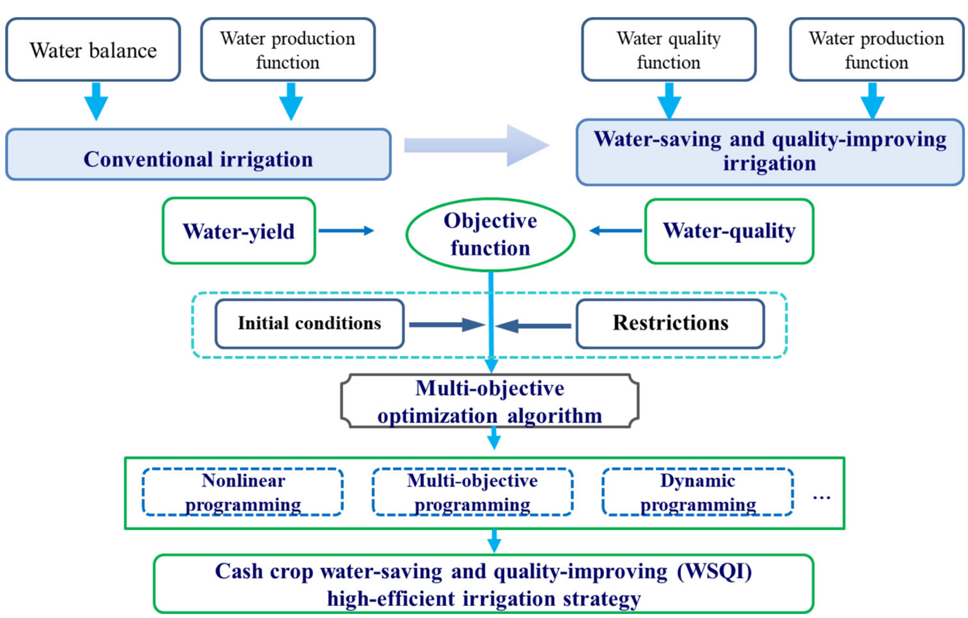

Fig. 5. Framework of decision-making methods in water-saving and quality-improving high-efficient irrigation strategy based on comprehensive function of water-yield-quality of cash crops.

11.7 %, respectively, with an irrigation water savings of 26.9 %. In a multi-objective programming model that comprehensively considers tomato yield and fruit quality traits (Chen, 2016), the minimum deviation between the actual value of each optimization target and the target value for each is set as the objective function. Based on the priority for each objectives, a sequential algorithm is used to solve the multi-objective programming. Further, this study obtained the optimal irrigation amount and the corresponding optimal relative yield, relative quality traits, and comprehensive quality index under different scenarios. Agricultural production decision-makers, with the help of the new proposed high-efficient irrigation strategy, can determine optimal irrigation schedules based on market supply and demand, consumer preferences for various quality traits, fruit prices, available irrigation water resources, and future water prices. With the expected goals and the definition of priority levels for cash crop yield, quality and irrigation amount, multi-objective programming can be a powerful tool for optimizing irrigation schedules and achieving customized and diversified irrigation management.

6.2. Cultural practices

High-efficient production technology modes for saving water and improving the quality of cash crops have been widely promoted and applied in China. Given the paritcular climatic conditions of the early frost stage in the arid inland river basins of Northwesr China, and the requirements for improving crop quality, we propose a joint irrigation control technology for field-grown cash crops. Reasonably delaying early irrigation, optimally allocating limited water, and appropriately advancing the end of irrigation can promote root growth, control redundancies, creat a stimulus compensation effect, and improve fruit quality, with an irrigation water savings of 20 %. This result has been demonstrated in Gansu, Shaanxi, Shanxi, Xinjiang and other provinces. Based on the water-quality-yield relationships in greenhouse tomato, a high-efficient mode of "less irrigation at the seedlings-moderate irrigation at flowering-no irrigation at harvesting" was developed. This method maintained tomato yields at 181.01 t/ha and 280.12 t/ha in two seasons (no significant reduction), saved 12.40 % and 7.53 %, respectively, of water consumption, and improved the tomato quality traits such as SSC and VC (Wang, 2011).

Research findings of high-efficient irrigation strategy for cash crops have been widely used in greenhouses and orchards in the Shiyang River Basin, Gansu Province. More than 2500 government staff in charge of agriculture, forestry, and technology promotion from cities to villages participated in the training and demonstrations of this strategy at the Wuwei Experimental Station. These events are essential in guiding local farmers to perform scientific agricultural water and fertilizer management and promoting the sustainable development of the cash crop industry.

7. Conclusion

To improve the current situation of cash crop industry, combining the findings of international research frontiers and our team research results in recent decades, this article proposed the integrated high-efficient irrigation strategy for water-saving and quality-improving of cash crops (WSQI).

Based on the analysis of the effects of different water and nutrient treatments on the quality of cash crops, water- and nutrient-sensitive quality traits were screened. The comprehensive evaluation method was used to scientifically evaluate the comprehensive quality of cash crops and then to build statistical models of water-yield-quality for cash crops. Combined with biophysical models, quantitative simulations of key crop qualities were conducted, which offers more information of quality formation mechanisms. With all the above analysis and simulation, irrigation decision making can proceed considering crop water-yield-quality relationships to achieve the sustainable use of regional water resources and high-efficient agricultural production.

This research has helped the conventional agricultural irrigation strategy based on water balance and crop water-yield functions to move forward to high-efficient irrigation strategy, aiming for water-saving and quality-improving in cash crops. This development has important scientific and practical significance for promoting the sustainable development of the regional economy.

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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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.agwat.2020.106331.

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