



A review on food subsystem simulation models for the water-food-energy nexus: development perspective

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Abstract

Agricultural crops are the primary food source because livestock and poultry products also indirectly depend on crops. A significant obstacle to adopting the water, food, and energy (WFE) nexus is the lack of a comprehensive and easy-to-use simulation model for the food subsystem focusing on crops. By reviewing the articles in Scopus and Google Scholar databases, WFE nexus studies can be divided into two categories: simulation-based and conceptual-based studies of WFE nexus. Based on the developmental perspective on food subsystem modeling in the WFE nexus, the conceptual studies were excluded, and the modeling studies were reviewed. Two points of view can be used for WFE nexus modeling: 1. hard-link modeling and 2. soft-link modeling. Comparing these two types of modeling showed that hard-link modeling cannot model the interrelations of the food subsystem, and this shortcoming is of great importance. This study reviewed the crop growth models (CGMs) used in the WFE nexus system from the development perspective. The technical characteristics of the CGMs have been evaluated according to the requirements of the CGMs. Finally, a checklist based on the criteria defined for the nexus system has been provided, which can guide researchers in choosing the appropriate CGMs for the food subsystem with the nexus approach. The analysis revealed that none of the CGMs studied alone were sufficient to develop a simulation model for the food subsystem with the WFE nexus. However, the AquaCrop model met more criteria.

Keywords Food simulation · Water-energy-food nexus · Crop growth model · Sustainable development · Food security

Introduction

Humanity is at the point in its history where it must question its ability to live without irreversibly damaging the biophysical and environmental conditions it depends on (D'Odorico et al. 2018). Increasing anthropogenic pressure is causing ecological change to become abrupt, and sustainable global development seems like a dream. With rapid international

development and accelerated population growth, water, food, and energy (WFE) resources have been under tremendous pressure, which has led to the problems of water scarcity, food shortages, and energy insecurity (Mahlknecht et al. 2020; Afshar et al. 2021; Liu and Zhao 2022). Remarkably, the interconnectedness of WFE subsystems is fundamental to global sustainability (Fuso Nerini et al. 2018). These problems have also been exacerbated by extreme weather conditions and the COVID-19 epidemic (Udmale et al. 2020). Previous studies have emphasized the importance that the only solution ahead is a fundamental change in understanding the management of WFE resources, and integrated system approaches should be replaced instead of traditional approaches. However, before realizing the importance of connecting these three resources (WFE resources), management strategies usually worked for one resource independently of the others (Smajgl et al. 2016; Soleimanian et al. 2022). As a result, these strategies did not consider the internal interactions between these three inseparable sectors, and subsequently, the results obtained from the strategies used were utterly contradictory. Also, due to not paying

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attention to the meaningful interactions between these three inseparable sectors and wrong management, the competition over these three resources increased. The WFE nexus concept refers to the interconnections between WFE subsystems to address the aforementioned problems and offers insight into how strategies in one subsystem will influence the other subsystems and vice versa (Huang et al. 2020; Molajou et al. 2021a).

The WFE nexus is a dynamic and complex system in which WFE resources are intimately intertwined (Ma et al. 2021; Qi et al. 2022). Throughout the WFE nexus system, energy is needed to pump, transport, distribute, and treat water, and likewise, water is consumed for energy generation and processing (Roidt and Avellán 2019; Vahabzadeh et al. 2022). Much water and energy are also consumed in agricultural planting and food production (Molajou et al. 2021a; Afshar et al. 2022). WFE's nexus system is complex because of its intricate interweaving relationships. The emergency resource shortage crisis must be alleviated by clarifying the interrelationships between WFE and comprehensively managing the WFE nexus system (Ma et al. 2021).

The food subsystem is one of the essential parts of the WFE nexus system. Throughout the food subsystem, people are linked to their food as they pursue production, distribution, and consumption activities, and these activities also affect society and the environment as a whole (Ingram 2011; Schipanski et al. 2016; D'Odorico et al. 2018). One of the most critical challenges of the Food and Agriculture Organization of the United Nations (FAO) is defining projects in line with planning to feed 9 billion people by 2050 (van Dijk et al. 2021). As a result, global food production should increase by 70%, and in developed countries, the amount of food production should be doubled. According to FAO reports, in the past decades, the number of people who cannot provide food has reached one billion, of which about 65% live in Asia (United Nations 2019).

Generally, the food subsystem in the WFE nexus can be divided into four main categories: 1, livestock products; 2, poultry products; 3, agricultural crop products; 4, fisheries products. Natural resources and human labor are used in producing, processing, and transporting food and in individuals' food consumption decisions. The food subsystem is therefore shaped by agricultural, trade, and food policies and food consumers' cultural, economic, and educational dimensions (Ingram 2011; Zhang et al. 2018; Bhunnoo and Poppy 2020; Mahdavian et al. 2022). Agricultural crop products make up the most important and diverse part of the food chain. In other words, agriculture is the primary source of food supply because livestock and poultry products are also indirectly dependent on agricultural products. In addition, agriculture relies heavily on energy, so energy is consumed directly or indirectly in agricultural lands (Tyczewska et al. 2018; Grote et al. 2021; Vahabzadeh et al. 2022). Currently, the food subsystem consumes 30% of the world's total

energy (Li et al. 2021). In modern agriculture, most of the activities are mechanized and agricultural operations such as tillage, planting, irrigation, and harvesting are done with high efficiency using agricultural equipment. As a result, all these activities require energy carriers. According to earlier research, 3400 million joules of energy is needed to grow winter wheat, and 800 and 650 million joules of energy are used to cultivate and harvest the crop, respectively (Chang et al. 2016; Taghizadeh-Hesary et al. 2019).

Simulation and modeling play a crucial role in the WFE nexus by comprehensively comprehending the intricate interdependencies and trade-offs among these interdependent subsystems. By integrating data, knowledge, and multiple factors, models assist decision-makers in assessing various scenarios, optimizing resource allocation, assessing sustainability, and developing policies based on data. Simulation and modeling contribute to an integrated method of managing the water, food, and energy nexus, thereby facilitating the development of sustainable strategies that balance the demands of these vital WFE resources while avoiding adverse social and environmental effects (Afshar et al. 2021). Various studies have been conducted in order to evaluate and analyze the WFE nexus system, and simulation and modeling have been used for numerical evaluation in some of them. Of course, one group of these modeling has been done in an integrated manner, such as mathematical programming or data-based modeling for all three WFE subsystems (Giampietro et al. 2009; Davies and Simonovic 2010; Daher and Mohtar 2015; Wicaksono and Kang 2019), and in the other group, modeling has focused on the food subsystem and agricultural crop products, and the crop growth simulation model has been used (Liu et al. 2019; Shrestha et al. 2015; Anderson et al. 2018; Cuberos Balda and Kawajiri 2020).

Considering the undisputed importance of agricultural crop products in the food subsystem, from the nexus point of view, the simulation model of crops is fundamental in the food subsystem. The crop growth model (CGM) is a model that simulates the growth stages of leaves, branches, and roots gradually over time, like a natural plant. The CGMs can calculate crop growth, development, and yield by solving the governing equations of soil, crop, weather, and management measures (such as irrigation, fertilizer, and pesticides) (van Keulen et al. 1982; di Paola et al. 2016). Therefore, a crop simulation model predicts the results of a specific management or environmental condition. One of the applications of crop simulation models is to understand better the performance of different parts of the crop growth process. Also, by changing various parameters such as seed type, soil type, weather conditions, irrigation amount, type, and amount of fertilizer, pesticides, etc., the amount and manner of the effect of those parameters can be calculated. As a result, these models can perform thousands of

test plans for different products during their growth period, which takes place in a minimal time (Steduto et al. 2009; Siad et al. 2019).

With the advancement of computers and increasing the ability of calculations, the simulation of crop growth takes place in the shortest time. For this reason, the acceptance of CGMs has increased in recent years (Rauff and Bello 2015). However, this point should be noted that agricultural crop products and food subsystem are highly dependent on energy and water for the production of agricultural food products (el Gafy et al. 2017); however, agricultural crop products and food subsystem are highly dependent on energy and water for production; thus, developing a food subsystem simulation model with the WFE nexus approach should be done in such a way that the food subsystem interacts with water and energy in the nexus subsystem and calculate the water and energy consumption for different cropping patterns. In order to develop a model with these specifics, it is first required to assess the pros and cons of WFE nexus food subsystem modeling in previous studies, including those that applied CGM and those using alternative modeling methodologies. Finally, considering the need for CGMs in the developing food subsystem simulation model using the nexus method, CGM development advantages and disadvantages should be compared. As a result, in the first step, this review introduces two types of simulation models of the WFE nexus system. Then in the next step, the framework related to the CGMs, in which the mandatory nexus criteria are applied, is defined. Then, food subsystem simulation models for crop growth, which are used in the nexus system simulations, have been technically reviewed from the development perspective. It is worth mentioning that in some cases, the CGMs which have not been used in the WFE nexus system have been assessed. Finally, a checklist is provided based on the appropriate choice of CGMs that can be used in the nexus system.

Interrelations and interactions in the WFE nexus system

Using the nexus system approach, two types of connections are within each WFE subsystem. In the first category, there is a relationship between the subsystem's internal components in the sense that changes to one variable of the subsystem's sector result in changes to another variable. This category of relationships is known as interrelation. In the food subsystem, for instance, the relationship between fertilizer and yield is regarded as an interrelation because the yield is affected by changes in fertilizer consumption (Stewart et al. 2005; Molajou et al. 2021a).

The second category of connections, known as interactions, comprises connections between subsystem components. These interactions give meaning to the WFE nexus

system approach. For instance, the quantitative and qualitative return flow from agricultural farms to water bodies is considered an interaction. It is also important to note that the variables exchanged between subsystems are known as nexus variables (Vahabzadeh et al. 2023). The values of the nexus variables at each time step depend on the state of other subsystems, and these variables facilitate interactions. The relevant subsystems simulate the nexus variables and export them as input to other subsystems (Molajou et al. 2021b; Afshar et al. 2022).

Moreover, interrelations and interactions affect one another. In other words, in the WFE nexus simulation models, interrelations may influence interactions with another subsystem by altering the interrelation between two components of the same subsystem. For instance, increasing a crop's fertilizer consumption decreases its water consumption and energy consumption (Zhou et al. 2011; Ati et al. 2012; Afshar et al. 2022). In this example, the amounts of fertilizer consumption and yield are regarded as an interrelation, whereas the amount of energy and water consumption in relation to the food subsystem is regarded as interactions (see Fig. 1).

What is depicted in Fig 1 is a simple example of the complex relationship between interrelations and interactions of food subsystems within the WFE nexus. It shows that the management of fertilizer consumption is not only effective in food production but also affects water and energy consumption. Therefore, it is necessary to pay attention to both interrelations and interactions for the analysis of trade-offs and synergies in the WFE nexus. As a result, in order to understand to what extent the food subsystem can cause changes in the water and energy subsystems, it is first necessary to identify and model the important interrelations within the food subsystem.

Methodology for developing food subsystem simulation under the WFE nexus system

The review methodology of food subsystem simulation in the comprehensive nexus system simulation models with a development perspective is shown in Fig. 2.

Step 1: In this step, Scopus and Google Scholar databases were searched to find articles related to the nexus system. First, the keyword “nexus” was searched, and subsequently, many articles were found due to the broad scope of its research. Then, the keyword “nexus” was combined with the phrase “water,” “energy,” and “food.” In addition, the search was limited to the field of environmental science.

Step 2: In this stage, the found articles were explored according to whether these studies examine the nexus system in a conceptual or modeling way. Studies conceptually

Fig. 1 An example of interrelations and interactions of food subsystem within the WFE nexus system

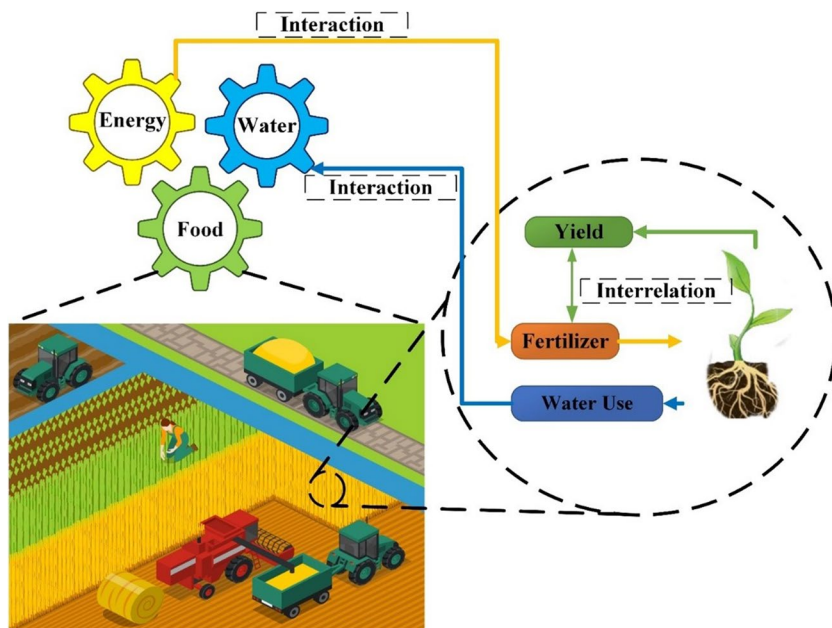
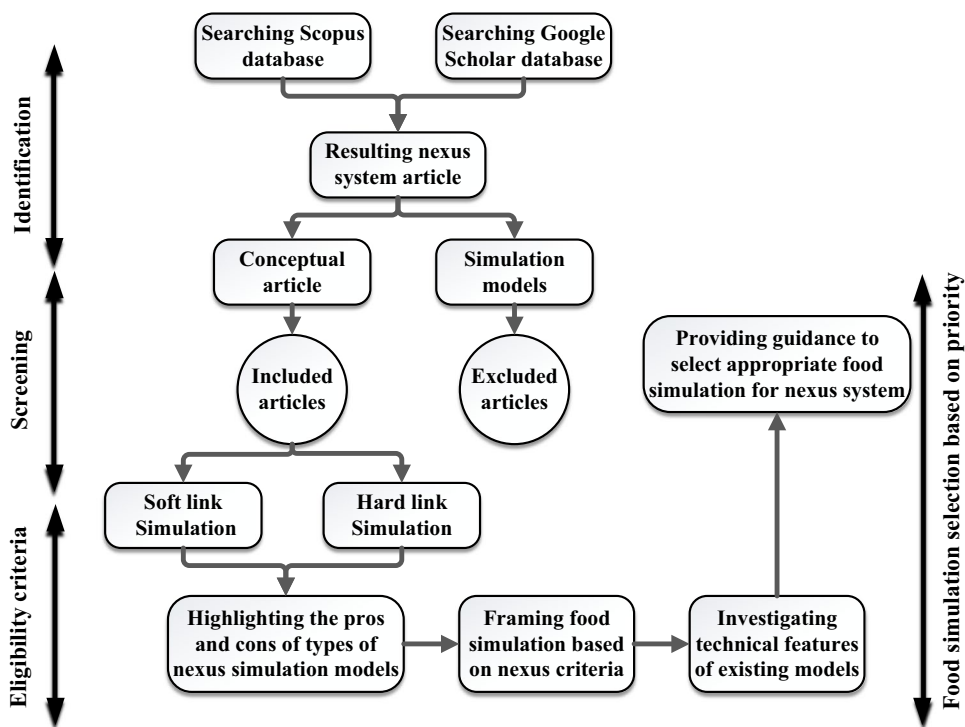


Fig. 2 The methodology of food subsystem simulation selection under the WFE nexus system



investigating the nexus system were excluded, and simulation articles were included.

Step 3: In the third step, the nexus simulation studies were categorized into soft and hard links. Also, the authors carefully investigated the studies carried out to simulate the nexus system in several stages. Each simulation category’s performance, advantages, and disadvantages were carefully studied.

Step 4: By this step, considering the dependencies of the food subsystem on water and energy, the required criteria of nexus for food simulation were carefully selected by the nexus research group under the supervision of the group’s supervisor. Then, a conceptual framework of the food subsystem was presented to simulate crop growth according to defined criteria. Finally, by detailed examination of the CGMs of the WFE nexus system was recognized, and according to the defined criteria to be

linked in the holistic nexus system simulation, their technical characteristics were carefully examined.

Step 5: Finally, a checklist for food subsystem simulators was provided to check their suitability or inappropriateness to be applied in holistic WFE nexus system simulation models. It is worth mentioning that the simulation that can address the most nexus criteria is selected. Since this review study was examined from the development perspective, it is suggested that the rest of the nexus criteria be developed in future research works.

Types of WFE nexus simulation modeling

According to the literature conducted, we can categorize and name the simulation of the WFE nexus system in two ways: soft link and hard link. In the soft-link simulation, the food subsystem is modeled with an existing previous CGMs, such as Decision Support System for Agrotechnology Transfer (DSSAT). Some studies link it to water model software, such as Water Evaluation and Planning System (WEAP), to evaluate water and food subsystems (Amjath-Babu et al. 2019). As a result of defining the scenario in one subsystem, the responses of the other two subsystems are evaluated in the context of the WFE nexus system. The interaction between subsystems is one-way, and its implementation and modeling are less time consuming. Soft-link simulation studies adequately address interrelation by using a model for the subsystem under study, but their primary flaw is that they cannot account for interactions sufficiently.

In hard-link simulation, the WFE subsystems are programmed in a single programming language environment and integrated formulation for all subsystems within the WFE nexus approach; usually, simulating the WFE nexus system with this approach is complex and time consuming. In this approach, the interaction between the subsystems is two-way, and usually, the definition of the scenario for all three subsystems is done simultaneously, and this is the meaning of the multicentricity of the nexus system (Daher and Mohtar 2015; Wicaksono and Kang 2019). It should be noted that their main problem is that they cannot address interrelations in the WFE subsystems.

According to the various categories of nexus system simulators and the concepts presented for interrelation and interaction in the second section and the presented categories hard link and soft link in this section, the literature that was carried out to investigate food subsystem modeling with the nexus approach is shown in Table 1.

According to Table 1, hard-link and soft-link food simulation models of the WFE nexus system fall into two categories: data based and process based, respectively. Data-based models are models that utilize data intensity. In other words, the quantity of water and energy required to produce one

mass unit of wheat. Process-based CGMs generally consider the effects of various agricultural inputs and environmental variables on agricultural products. In addition, food modeling with the nexus approach has been performed at various spatial scales, including irrigation districts, basins, and the national level with different data-based and process-based approaches; this shows that it is possible to model both approaches in a variety of scales. Also in some studies, a single crop was used to investigate the nexus effects of WFE, whereas, in other studies, multiple crops were used to investigate various cropping patterns with varying nexus indices, so, it is necessary to evaluate both hard and soft connection approaches. Based on several studies that simulate the WFE nexus system with soft- and hard-link modeling approaches, the advantages and disadvantages of types of nexus system simulations are shown in Table 2.

As a result of comparing the models of hard link and soft link that were examined in Tables 1 and 2, it can be concluded that due to the importance of the interrelation of the food subsystem in a nexus analysis of different cropping patterns, it influences the interactions with the water and energy subsystems. Thus, the process-based food models utilized by soft link nexus simulators become crucial.

The interactions between the WFE subsystem and the nexus variables circulation among them are according to Fig. 3. The nexus variables stand for the variables which are exchanged between WFE subsystems, so examination and evaluation of the interaction between WFE subsystems because these interactions are one of the most important factors that determine what interrelations should be modeled (Afshar et al. 2022).

As shown in Fig. 3, the modeling of the food subsystem should be able to show the effects of the amount of allocated water and the effects of water salinity on food production should be able to model the amount of water returned to the water subsystem. Also, in relation to the energy subsystem, it should be able to consider and model the amount of energy required for the food subsystem in the agricultural inputs and agricultural machinery sector.

Food subsystem simulation framework within the nexus system approach

In previous studies, sufficient attention has not been paid to the food subsystem with the nexus approach. The food subsystem highly depends on the water and energy subsystems in producing food byproducts. In the previously developed models, the nexus variables received by the food subsystem from the two water and energy subsystems have not been considered simultaneously. Also, the interactions that occur in previous modeling for the simulation of the food subsystem with the nexus approach have been considered offline. However, in some research, the

Table 1 Hard-link and soft-link simulation literature for food subsystem in the context of the WFE nexus system

Cite	Interconnection	Scale	WFE model	Water model	Food model	Agricultural energy demand	Multi-crop	Research priority
Giampietro et al. (2009)	Hard link	Nasional	MUSIASSEM	Data based	Data based	-	+	Exposing players to the main trade-offs and co-benefits by using a quantitative framework of relationships between the nexus elements based on environmental footprint indicators.
Davies and Simonovic (2010)	Hard link	Global	ANEMI	Data based	Data based	-	+	Evaluate interactions between climate systems, carbon, nutrient, water demand and water supply development, hydrologic cycles, land use, food production, sea-level rise, energy production, population dynamics, and economy.
Howells et al. (2013)	Soft link	National	CLEWs	Process based (WEAP)	Process based (WEAP-FAO56)	+	-	Uses a module-based method to quantitatively and simultaneously examine the interconnectedness of land, energy, and water resource systems (as well as climate) inside a modeling framework that incorporates specific models from other tools. Between sectoral models, the tool iteratively transfers data.
Daher and Mohtar (2015)	Hard link	National	Nexus Tool 2.0	Data based	Data based	+	+	Evaluating scenarios and identifying sustainable national resource allocation strategies
Shrestha et al. (2015)	Soft link	Irrigation district	-	-	Process based (AquaCrop)	+	+	Assessing the WFE nexus when evaluating the performance of groundwater-based irrigation systems

Table 1 (continued)

Cite	Interconnection	Scale	WFE model	Water model	Food model	Agricultural energy demand	Multi-crop	Research priority
de Vito et al. (2017)	Hard link	Irrigation district	-	-	Process based (Crop-Wat)	-	+	Proposing an index-based approach to assessing irrigation practices, environmental impacts, and economic aspects
Martinez-Hernandez et al. (2017)	Hard link	Local	NexSym	Data based	Data based	-	+	Integrates ecosystem, technological, and WFE production and consumption models for modeling local techno-ecological interactions
Yan et al. (2018)	Soft link	National	-	-	Process based (DSSAT)	+	-	Assessing sweet sorghum-based ethanol potential due to possible energy-water conflicts
Anderson et al. (2018)	Soft link	Irrigation district	-	-	Process based (DSSAT)	-	-	Of fertilizer use and crop population on energy use, water use, and greenhouse gases
Wicaksono and Kang (2019)	Hard link	National	WFESiM	Data based	Data based	-	+	Simulating the resource connections and two-way feedback analysis
Momblanch et al. (2019)	Soft link	River basin	-	Process based (WEAP)	Process based (WEAP-FAO56)	-	+	Evaluation impacts of climate change and alternative socio-economic development scenarios
Hatamkhani and Moridi (2019)	Soft link	River basin	-	Process based (WEAP)	Process based (WEAP-FAO56)	-	+	Developing a simulation-optimization model to best trade-off between hydropower and agricultural development
Liu et al. (2019)	Soft link	National	-	Process based (DBH)	Process based (EPIC)	-	+	Assessment of trade-off between food production and water requirement and hydropower potential

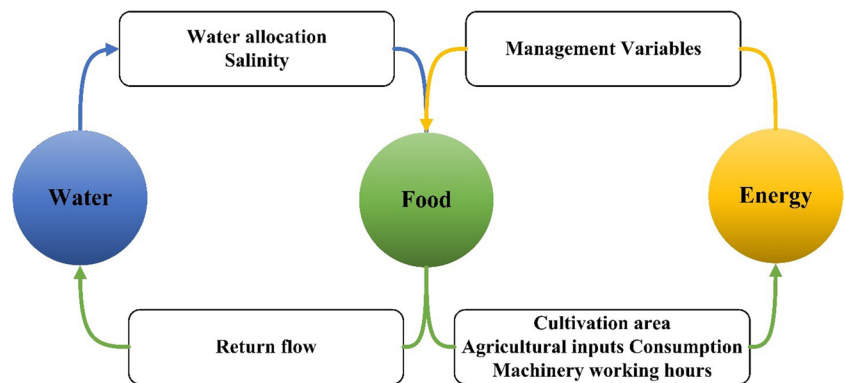
Table 1 (continued)

Cite	Interconnection	Scale	WFE model	Water model	Food model	Agricultural energy demand	Multi-crop	Research priority
Sadegh et al. (2020)	Hard link	Country	EWF Nexus Tool	Data based	Data based	-	+	Estimating the amount of water resources required in a country to produce various types of food and energy, the amount of energy needed to supply a particular amount of water or agricultural product, and CO ₂ -equivalent emissions
Cuberos Balda and Kawajiri (2020)	Soft link	Regional	-	-	Process based (WOFOST)	-	+	Estimating the potential for biomass and bioenergy and talking about the trade-off between food and energy
Ren et al. (2021)	Soft link	Pluvial Plain	-	Data based	Process based (DSSAT)	-	+	Predicting the effects of cropping adjustments on groundwater sustainability and food production
Shen et al. (2022)	Soft link	Irrigation district	-	-	Process based (AquaCrop)	+	+	Exploring the optimal arrangement of agronomic and water-saving measures in farmland systems under the water-energy-food nexus

Table 2 The pros and cons of types of WFE nexus system simulation models

	Soft link	Hard link
Interconnectedness	Unilateral linkage	Bilateral linkage
Advantages	<ul style="list-style-type: none"> • Less time consuming to model the WFE nexus simulation model • Demonstrates how one subsystem affects or is affected by other subsystems • Further evaluation of the interrelations of the investigated subsystem 	<ul style="list-style-type: none"> • WFE subsystems can be linked to each other holistically • Simulating the nexus system comprehensively from the food perspective • Import/export nexus variables to/from other subsystems • Further evaluation of the interactions of the investigated subsystem
Disadvantages	<ul style="list-style-type: none"> • Cannot reflect the mutual impacts of WFE subsystems • Defining the scenario in one subsystem, then obtaining feedback from the other two subsystems, and vice versa. 	<ul style="list-style-type: none"> • Costs a lot of time modeling to link WFE subsystems • Requires a massive number of data

Fig. 3 The nexus variables flow among WFE subsystems in the nexus system approach



food subsystem is considered online to achieve a better and more accurate response, and the interaction of the subsystems is two-way. Therefore, the first important step in framing the framework of the food subsystem with the nexus approach is to recognize and identify the relevant requirements related to water and energy subsystems.

In previous research, food subsystem simulation models did not address the existing interactions with water and energy subsystems in hard-link and soft-link simulations in a comprehensive manner. However, a holistic framework that can incorporate these crucial interactions into CGMs is required. The nexus variables received from the water and energy subsystems by considering the WFE nexus approach holistically are shown in Fig. 4. The nexus variables received in the food subsystem act as constraints, and the food subsystem provides its response, which is the yield of crops, return water, water, and energy consumption.

On the other hand, there are interrelationships within the food subsystem (such as the relationship between fertilizers and crop growth rate) whose effects can influence the interaction of food subsystem with other subsystems if they are not addressed (such as the energy subsystem). In this way, ignoring the effects of used fertilizer can result in ignoring the energy required to produce used fertilizer.

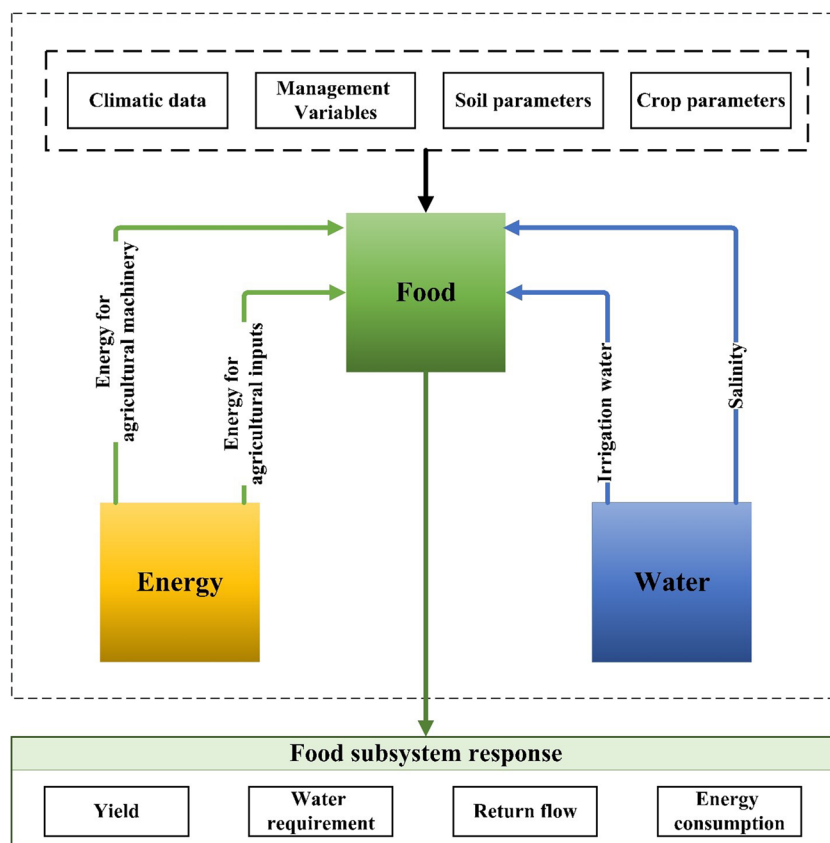
The framework of the food subsystem in the comprehensive simulation of the WFE nexus system is shown in Fig. 5.

The framework in Fig. 5 illustrates the crop growth process from planting to the harvesting stage, considering its interactions and interrelations with water and energy. In the following, the existent CGMs used in the WFE nexus simulation models will be reviewed according to the defined mandatory criteria for the nexus system within the novel framework. It should be noted that considering that this review study is from the perspective of food simulation development, other models that have not been used in the nexus system simulators will be reviewed and evaluated based on nexus simulation criteria.

Classification of crop simulation models

A crop simulation model simulates the growth stages of leaves, branches, and stems gradually over time. In crop simulation models, crops’ growth, development, and yield are calculated by solving the governing equations of the soil, crop, weather, and management operations (such as irrigation, fertilizer, and pesticides). Hence, crop simulation evaluates the effects of specific management practices or environmental conditions (Jones et al. 2017). Crop simulation

Fig. 4 Inputs and outputs of the food subsystem simulation using the WFE nexus system model



models are used to understand the performance of different parts of the crop growth process. It is also possible to calculate how different parameters such as seed type, soil type, weather conditions, irrigation volume, type and amount of fertilizer, pesticides, and other management variables affect the crop. This way, these models can implement thousands of scenarios for different crops during their growth period within a brief period. Due to computer advancements and the increased ability to calculate, crop simulation can occur in the shortest amount of time. In this way, it is not only economical but also very time efficient. As a result, crop simulation models have become more prevalent in recent years (Whisler et al. 1986).

Agricultural crop products can be simulated using many different modeling approaches. The most famous approach is to classify crops based on their growth processes. Accordingly, crop simulation models are classified into two categories based on this type of classification.

Statistical models

Statistical models are the first method of simulating crops. These models calculate how and how much the crop reacts to changes in various parameters based on historical data sets. Biophysical and biological processes that exist between variables are not taken into account in statistical models.

Therefore, these models are also called experimental models. The basic assumption in this method is that the data used are samples of a population that can be used for prediction in different conditions (Jones et al. 2017).

In most cases, the results of statistical models cannot be used for conditions different from the conditions of the samples. Therefore, these models cannot be used to predict and calculate crop growth results under the effect of climate change, pests, increasing CO₂ concentration beyond the range of historical data, etc. Regression and artificial neural networks are examples of methods used from this point of view. Also, combining these models with models that consider crop growth processes makes it possible to check and predict different conditions with the input data (Dourado-Neto et al. 1998).

Dynamic models

In contrast to a statistical model, dynamic models can consider different conditions on crop growth stages. Dynamic models define functions to represent different states and conditions. In dynamic models, functions express the state of different crop parts, so it is possible to investigate how different policies or decisions affect the crop's response. The output of these models is the state of crop parts over time. However, it should be noted that all models are empirical to

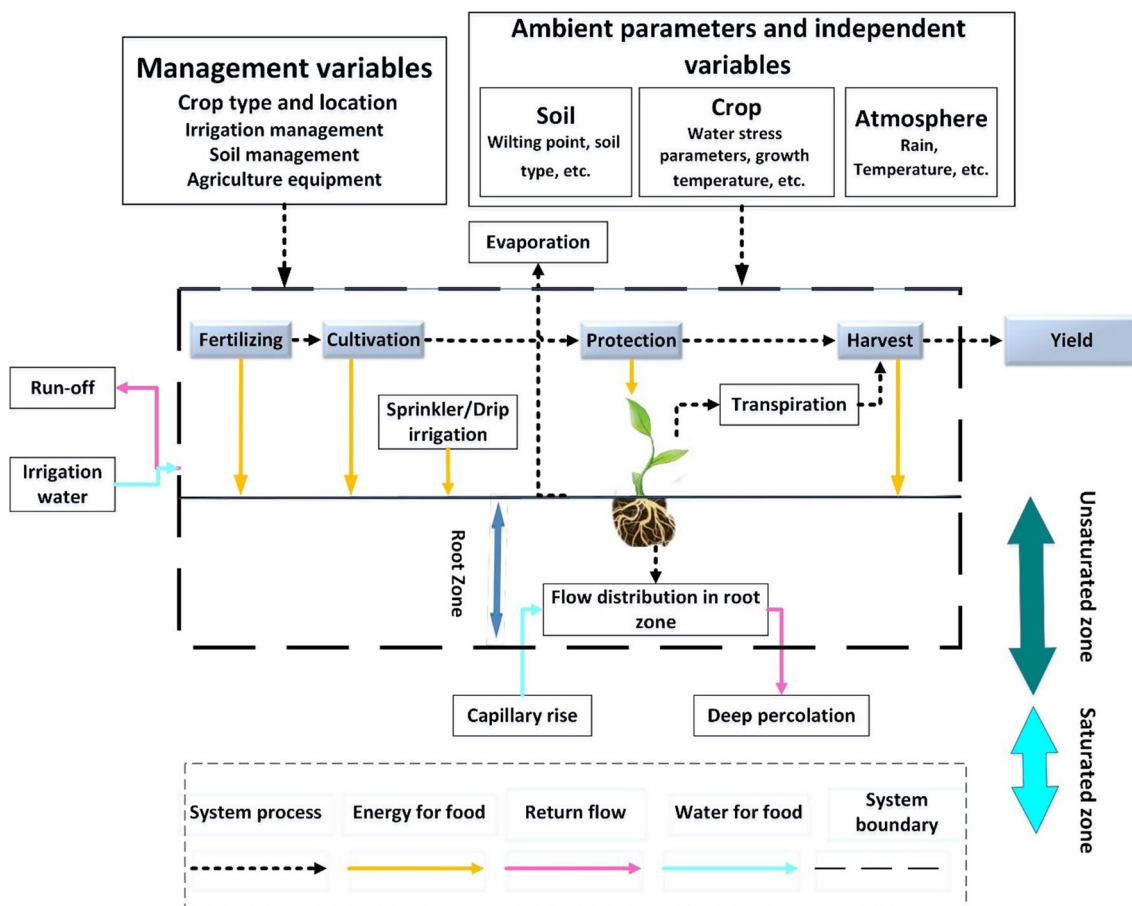


Fig. 5 Crop growth simulation framework considering interactions with water and energy subsystems

calculate some processes, which means that even dynamic models use empirical relationships to calculate parameters after dividing crop growth into more detailed processes (Whisler et al. 1986; Jones et al. 2017). Dynamic models are divided into mechanical and functional models depending on how much the model examines the processes in more detail.

Mechanistic models

These models are also called explanatory models. These models try to make connections between variables using the cause-effect relationship. The fundamental processes in soil and plants are simulated in these models to obtain the desired output values. The fundamental processes in soil and plants are simulated in these models to obtain the desired output values. For example, in mechanistic models to simulate photosynthesis, processes such as receiving sunlight, absorbing CO₂ and converting it into biomass, dividing biomass between different crop components, and consuming biomass in crop respiration are considered (Ritchie and Alagarswamy 2002). Mechanistic models deal with parameters that change instantaneously, and their changes

must be calculated on a microscopic temporal scale. For example, to calculate photosynthesis and crop transpiration, effective parameters change hourly, and mechanistic models must alter these parameters for the simulation. Since these models require a lot of input information, they usually have a minimal application (Ritchie and Alagarswamy 2002). Among the examples of mechanical models, we can refer to the biochemical model of photosynthetic CO₂ absorption in leaves presented by Farquhar et al. (1980).

Functional models

Another dynamic model is the functional model. In these models, unlike mechanistic models, very detailed processes of the crop growth process are not considered, but cause-effect relationships between parameters are still considered to simulate the product. For example, these models use only the amount of daily solar radiation and soil water stress to calculate photosynthesis. Therefore, these models can be used to simulate the crop on a daily time scale. Furthermore, functional models usually require less input information than mechanistic models. Therefore, the functional

models are applied to the food subsystem simulation from the WFE nexus system perspective. Among the examples of functional models, we can mention the DSSAT, APSIM, EPIC, CropSyst, etc., which have been compared (Ritchie and Alagarwamy 2002; Jones et al. 2017).

Investigating functional crop simulation models

AquaCrop

The AquaCrop model was presented as an alternative to the FAO publication, Irrigation and Drainage No. 33, for estimating crop yield based on water supply and management measures. The primary basis of this model is to calculate the crop yield based on the function of the amount of water consumption under different irrigation conditions, including rainfed, low, and stress-free irrigation. AquaCrop model inputs include weather data, crop, soil, and management characteristics. Management characteristics mean the same environment in which the crop is grown. In this model, the processes of water infiltration, water drainage out of the root zone, growth of leaves and roots, evapotranspiration rate, biomass production, and crop yield are simulated (Raes et al. 2009; Steduto et al. 2009).

The simulation steps in the AquaCrop model are as follows: first, simulation of crop development and growth; second, the amount of crop transpiration is calculated; and then the amount of biomass produced is obtained using Eq. (1):

$$B = WP \times \sum Tr \quad (1)$$

B , WP , and Tr are produced biomass, water productivity of biomass produced (biomass produced per cumulative transpiration of crop unit), and crop transpiration, respectively. The biomass water productivity parameter must be available to convert transpiration into produced biomass. This parameter is normalized based on the amount of atmospheric evaporation and CO_2 concentration. The model can calculate the crop growth process for different places and times. The cover canopy is used instead of the leaf area index to calculate crop transpiration. By doing this, the amount of crop transpiration can be separated from soil evaporation (Steduto et al. 2009).

The crop yield is calculated using the amount of biomass produced and the harvest index. At a particular time, the harvest index increases linearly and continues for several days after physiological maturity. The reaction of the crop to the lack of water is applied in the model through four correction coefficients, all of which are a function of the percentage of water in the soil. Correction coefficients are obtained according to the four crucial stages of crop growth:

leaf opening, transpiration, stomatal control, and harvest index. It should be noted that the harvest index can act both positively and negatively according to the crop's stress level and time (Steduto et al. 2009).

APSIM

The agricultural production systems simulator (APSIM) model with a module-oriented structure is presented by the Agricultural Production Systems Research Unit in Australia. This model was developed to simulate the biological process of agricultural systems. Several modules are included in the model, including crops, pastures, orchards, soil, and management activities. Several important variables have been considered in this model, including soil pH, water, nitrogen, phosphorus, and erosion. A daily time scale simulates key processes in the crop module. Several input parameters are required, including daily weather data, soil characteristics, and crop management practices (Keating et al. 2003). In the APSIM model, each farm is regarded as a point, and its characteristics are expressed as the average of the entire farm. When the land features are very scattered, the study area can be converted into a series of fields, and each field is entered as a point in this model. Accordingly, this work incorporates the different characteristics of a region into the model (Keating et al. 2003).

WOFOST

The world food studies (WOFOST) model for simulating crop growth was developed by the World Center for Food Studies in Wageningen, the Netherlands (Todorovic et al. 2009). This model describes crops' growth and annual production using physical parameters such as crop type, soil type, and hydrological and weather conditions during the growing season. The specific point of this model from other models is that the growth process is simulated based on carbon. It uses Eq. (2) to calculate the growth rate:

$$\Delta W = C_e \times (A - R_m) \quad (2)$$

ΔW , C_e , A , and R_m are the growth rate, biomass absorption coefficient produced by the crop, the amount of gross absorption of CO_2 , and the amount of CO_2 absorption that is not used for growth (maintenance absorption), respectively. Therefore, the WOFOST model is designed to calculate the production potential for each type of agricultural product in different soil and climate conditions. Also, this model considers the main limitations in crop production, such as sunlight, temperature, water, nitrogen, phosphorus, and potassium nutrients. The spatial scale of this model is lumped and considers the studied area as a point and the time scale daily (van Diepen et al. 1989).

In order to calculate crop production, the model first determines the potential yield based on types of crops, planting times, and weather conditions. In this case, water and nutrients are assumed to be completely supplied to the crop. As a result, the amount of crop that can be obtained depends on soil conditions, the amount of water supplied to the crop, and the number of nutrients in the soil. There is an essential distinction between this amount and the actual yield because pests and diseases are not considered (de Wit et al. 2019). The soil-water-atmosphere-plant (SWAP) model is designed to simulate soil, water, atmosphere, and crop, using the WOFOST model to simulate the crop section (Uniyal and Dietrich 2021).

EPIC

This model was developed in the early 1980s to evaluate the relationship between soil erosion and the efficiency of agricultural production as the erosion efficiency index calculator. Therefore, there was a need for crop simulation to evaluate the efficiency of crop production. In the following years, the simulation of many essential management processes in agriculture was expanded in this model. As a result, the project's name was changed to the integrated climate of environmental policies over time. In recent years, this model has also considered aspects of agricultural sustainability, such as wind erosion, water quality, supply, soil quality, etc. In addition, this model includes several management evaluations, including irrigation, drainage, fertilization, rotating crops, pesticides, and tillage (Wang et al. 2022).

There are several components to the EPIC model, including climate simulation, hydrology, sedimentation, erosion, nutrient cycling, pesticides, crop growth, tillage, economics, and crop environmental control. The model runs on a daily time scale. However, it should be noted that some processes, such as penetration rate, are calculated on a smaller scale than daily. This model is written in FORTRAN language and has a graphical user interface. In addition to these capabilities, it can predict greenhouse gas emissions (such as carbon dioxide, methane, and nitrous oxide), evaluate the potential for soil erosion and sediment transport, and estimate the loss of nutrients due to leaching or runoff (Wang et al. 2022).

DSSAT

The DSSAT model was developed by the international network of scientists cooperating with the international network of crop transfer benchmark projects to simulate crop models. When developing this model, researchers felt the void of a comprehensive model for soil, climate, crops, and management to make better decisions about where to grow different crops. For this purpose, the DSSAT model was developed. As a result, a framework was provided to

research the performance of the system and its components so that researchers can predict the system's behavior under specific conditions. As a result, the DSSAT model helps decision-makers make decisions requiring complex analysis in the shortest time by reducing time and human resources (Jones et al. 2003).

Before the development of the DSSAT model, there were models for simulating products. However, these models used different input data with different structures. Therefore, the environment and structure specific to that model were needed to use each. In the DSSAT model, by harmonizing the input data and the structure of the existing crop simulation models, a framework was provided for those models to work together consistently. For example, the CERES model was used to simulate corn and wheat, the SOYGRO model was used to simulate soybeans, and the PNTGRO model was used to simulate peanuts in the past. The DSSAT model uses these models to simulate the crop (Jones et al. 2003).

In addition to crop simulation, the DSSAT model simulates soil and atmosphere. Based on CROPGRO and CERES simulator models and the module-oriented structure, a new simulator model named DSSAT-CSM was built. This model simulates crops using climate, genetics, water in the soil, carbon and nitrogen in the soil, and management in any place modules. So, the simulation is done with the minor input data [38]. DSSAT-CSM crop simulation model on a uniform land surface under defined or mandated management measures (a set of management operations whose values are not known in advance and are carried out when needed), and also taking into account water changes in the soil, nitrogen, and carbon in the soil, simulates the processes of growth, development, and productivity of crops (Jones et al. 2003).

CropSyst

CropSyst is a multi-year, multi-crop, daily time-step cropping system simulation model developed by a team of researchers at Washington State University to serve as an analytical tool to study the effect of climate, soils, and management on cropping system productivity and the environment. It simulates soil water budgets, soil-crop nitrogen budgets, crop phenology, canopy and root growth, biomass production, crop yield, residue production and decomposition, soil erosion by water, and salinity. The processes of crop rotation, cultivar selection, irrigation, nitrogen fertilization, soil, and irrigation water salinity, tillage operations, and residue management are all influenced by weather, soil characteristics, crop characteristics, pests and diseases, management practices, and cropping system management options (Stöckle et al. 2003).

CropWat

CropWat is a CGM developed by the United Nations Food and Agriculture Organization (FAO) that helps farmers, agronomists, and water managers make knowledgeable decisions regarding irrigation scheduling and water management practices. In addition to crop type, climate data, soil characteristics, and management practices, this tool calculates water requirements for crops and water consumption throughout their growing season. Also, CropWat provides information on the quantity and schedule of water required by various crops at each growth stage, enabling users to optimize irrigation strategies and reduce water stress. CropWat contains the FAO Penman-Monteith equation, an accepted approach to estimate reference evapotranspiration (ET₀), an essential factor in crop water requirement calculations. CropWat is widely recognized for its precision and has been validated with field data from various agroclimatic regions to facilitate agricultural water management worldwide (Allen et al. 1998).

Essential criteria for food subsystem under the WFE nexus system

The criteria selected for the food subsystem simulation with the nexus approach should be chosen in a way related to the interactions of the water and energy subsystem. In other words, those criteria are required to simulate the food subsystem. Mandatory criteria for the food subsystem include fertilizer effect, salinity effect, energy consumption, water requirement, return flow, modeling accuracy, and data.

The amount of fertilizer used is effective in the crop's growth and affects the crop's performance based on its consumption. On the other hand, the amount of fertilizer used in crop growth is related to energy and water subsystems. Energy is used to produce fertilizer in petrochemical factories, and the amount of fertilizer used affects the quality of water resources. Therefore, it is necessary to apply the effect of fertilizer in the food subsystem due to its interactions with water and energy. In addition, as a result of irrigation and allocation of water to agricultural lands, the irrigation water may have some concentration of salt that enters the root zone and affects the growth rate of crops. Therefore, applying the effect of salinity stress is also one of the required criteria of the food subsystem simulation with the nexus approach that should be considered because leaching in the root zone increases the irrigation requirement of the crop.

Furthermore, the food subsystem in crop production is heavily dependent on allocated water and energy. Energy is consumed in different stages of planting, growth season, harvesting, and post-harvesting, such as agricultural machinery operation, groundwater pumping, and fertilizer

consumption. On the other hand, crops need irrigation water to grow and consume it through the evapotranspiration process. It is worth mentioning that the irrigation water is unavoidably returned to the water bodies and affects water availability. The modeling accuracy and the amount of input data to crop growth simulators are essential criteria for the food subsystem with the WFE nexus system approach because the comprehensive WFE nexus simulation model is more likely to be implemented at least at the watershed scale. Therefore, the CGMs should require fewer data and have more accuracy to be able to be scaled up (Siad et al. 2019).

Providing guidance to select appropriate food simulation for the nexus system

Based on the defined essential criteria for the food subsystem simulation with the nexus system approach, the famous and used CGMs have been explored and evaluated in the comprehensive simulation of the WFE nexus system. It should be noted that these CGMs are suitable for their use in the comprehensive WFE nexus system simulation with the hard link approach. As mentioned in the third section, hard-link simulation models help employers and managers in making holistic decisions due to addressing two-way interactions. The provided checklist is shown in Table 3.

As shown in Table 3, DSSAT and APSIM are complete CGMs that provide accurate simulations of crops. These CGMs are open source and assess salinity, fertilizer, and water stress on the crop. These models are unsuitable for applying to nexus system simulation because they theoretically provide unique equations for each crop. Due to the large volume of input data, unique CGM for each crop, and inability to scale up when used in holistic nexus models, WFE nexus simulation models increase the running time when used in larger spatial scales, such as watersheds.

The CropSyst model is software based and cannot be linked with the water and energy subsystems since open-source models must be linked together for modeling the WFE nexus system with the hard-link approach. On the other hand, this model cannot address the return flow from agricultural lands to water bodies, which is one of the significant interactions between water and food subsystems.

A significant variable that affects the interactions between all three WFE subsystems in the comprehensive nexus simulation is salinity in the root zone of crops. The higher the salt concentration in the root area, the more leaching is required. Therefore, with the increase in salt concentration, the water required for crop production increases, and the trade-off between energy production and agriculture systems under the nexus system increases. The CropWat, EPIC, and WOFOST models are CGMs that

Table 3 The guidance for selecting suitable CGMs under the WFE nexus system approach

Crop simulation models	Open source	Integration	Modeling accuracy	Low data	Return flow	Water stress	Fertilizer stress	Salinity stress	Temperature stress	Water requirement	Energy consumption
DSSAT	✓	✗	✓	✗	✓	✓	✓	✗	✓	✓	✗
EPIC	✓	✓	✓	✓	✓	✓	✓	✗	✓	✓	✗
WOFOST	✓	✓	✓	✗	✗	✓	✗	✗	✓	✓	✗
CropWat	✓	✓	✗	✓	✗	✓	✗	✗	✗	✓	✗
APSIM	✓	✗	✓	✗	✓	✓	✓	✓	✓	✓	✗
CropSyst	✗	✓	✓	✓	✗	✓	✓	✓	✓	✓	✗
AquaCrop	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✗

do not consider salinity. Therefore, the mentioned models are inappropriate for use in the WFE nexus system simulation.

It is worth noting that none of the CGMs evaluates the crop’s energy consumption to provide a suitable cropping pattern for an area with the nexus approach, each crop’s energy consumption must be calculated separately. AquaCrop is one of the most suitable GCMs for developing a food simulation model in the WFE nexus approach. The AquaCrop model can address salinity, fertilizer, temperature, and water stresses and evaluate the amount of water returned to water bodies. Alternatively, this model can reduce the simulation time by taking a small amount of data and providing a specific relationship for all crops. More importantly, scaling this model up and running it on spatial scales such as watersheds is possible. Another benefit of the AquaCrop crop growth simulation model is that it effectively addresses most of the interrelationships and interactions of the WFE nexus system. It does these purposes by incorporating various components related to the soil, the development of the root system, and the development of the canopy to simulate and predict crop growth and yield. The interrelationships between these components are dynamic and reliant upon one another. Therefore, AquaCrop provides a comprehensive illustration of the growth and development of crops due to the integration of these various components. The component of soil water balance affects the quantity of water available to the crop, which in turn affects the growth of the roots and the amount of water that the crop takes in, and the exploration of soil water and nutrients by the root system is determined by the root development component. The amount of available water and nutrients has an effect on the canopy development component, which in turn has an effect on photosynthesis, the formation of biomass, and, ultimately, the crop yield. Interrelation and interaction are fundamental to the WFE nexus system’s nature. The simulation of the nexus system incorporates the concepts of interrelation and interaction. Interrelation refers to the interconnectedness of internal components of a subsystem, such as water, exchanging variables. For instance, agricultural lands use chemical fertilizers and pesticides to improve crop yield, and the quantity of agricultural inputs utilized is considered an interrelation for the food subsystem. Additionally, interaction refers to the interconnection between two subsystems in which variables are exchanged. For example, at each stage of crop development, plants require water, which they take in through a process called evapotranspiration. After the plants have been irrigated, a portion of the water that was used to grow the plants also drains back into the bodies of water. One of the ways in which the food and water subsystems interact with one

another is through the water used by the crops and the water that is then returned to the bodies of water.

Limitations of study

According to what is stated in the manuscript, the purpose of this review was to determine which is the most effective and applicable crop growth simulation model for use in food subsystem modeling from the viewpoint of a WFE nexus system. During this time, the horticulture products, livestock, and processing units that comprise the food subsystem should have been discussed. It has been attempted to center this investigation on crop production because of the preponderance of crops and the inability of crop growth simulation models to accurately model the production of livestock and horticulture products. Also, one of the most important limitations of this study was that some of the existing simulators were not open access, and this factor made us unable to examine their internal relationships more accurately and in more detail.

As mentioned earlier, CGMs are divided into two categories: statistical and dynamic models. As another limitation of this study, it can be mentioned that statistical (or experimental) models were not reviewed in this study.

Conclusion

In the modern industrial world, crop production is highly dependent on water and energy. On the other hand, ignoring the interactions of the food subsystem with water and energy causes the unsustainable development of the agricultural production system. Therefore, WFE subsystems should be addressed as a single system so that the effects of action in one subsystem can be easily assessed in other subsystems. Recent research has focused on the interactions between WFE. This interaction has been examined in an integrated manner using a new approach called the “nexus system.” This study has tried to identify the food subsystem simulations applied in the nexus system context. The CGMs were reviewed from the development perspective so that their strengths and weaknesses were examined. Finally, the most suitable food subsystem simulation was selected to develop it with the criteria defined by the nexus system approach.

The food subsystem has been modeled in the literature as the soft and hard links in the WFE nexus system simulations. In soft-link simulations, food subsystem software is coupled with other subsystems, and interactions are addressed in a one-way manner. In this category

of simulations, the answers are not more accurate; consequently, comprehensive decision-making does not happen. In hard-link simulations, WFE subsystems are programmed in a programming environment. In this category of simulations, the interactions are two-way, scenarios can be defined for all three subsystems simultaneously, and the effects of each can be observed in the integrated WFE nexus system.

The CGMs were carefully evaluated based on the defined criteria for the food subsystem and its novel framework with the nexus approach. Finally, the AquaCrop simulation model was selected as the most suitable open-source simulation to be developed for the integrated WFE nexus system. The AquaCrop model was the most appropriate for the holistic nexus system simulation in several ways. Since the water simulation model is usually used on the watershed scale, therefore, the food simulation model should be able to be scaled up from the farm scale to the watershed. On the other hand, in nexus system simulations, where water is a limited resource, different scenarios can be explored by allocating water to the food and energy subsystems. According to the mentioned issues, the AquaCrop model can be scaled up on the watershed scale and is also a water-driven simulation model. It is suggested to develop the AquaCrop simulation model with the nexus approach in future research works as follows:

- Simulating and seeing the simultaneous effects of water, salinity, and fertilizer stress on crop yield.
- Scaling up the simulation model to adapt to the scales of the water and energy subsystem in the integrated nexus system.
- Analyzing the energy consumption of crops during the stages of planting, growth season, harvesting, and post-harvesting according to different cultivation patterns.

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Data availability The authors declare that the data are not available and can be presented upon the request of the readers.

Declarations

Consent to participate The authors declare that they agree with the participation of the journal.

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References

- Afshar A, Khosravi M, Molajou A (2021) Assessing adaptability of cyclic and non-cyclic approach to conjunctive use of groundwater and surface water for sustainable management plans under climate change. *Water Resources Management* 35(11):3463–3479. <https://doi.org/10.1007/S11269-021-02887-3>
- Afshar A, Soleimanian E, Akbari Varianni H et al (2022) The conceptual framework to determine interrelations and interactions for holistic water, energy, and food nexus. *Environ Dev Sustain* 24:10119–10140. <https://doi.org/10.1007/S10668-021-01858-3>
- Allen RG, Pereira LS, Raes D, Smith M (1998) Crop evapotranspiration - guidelines for computing crop water requirements - FAO Irrigation and drainage paper 56. *Irrig Drain*. <https://doi.org/10.1016/j.eja.2010.12.001>
- Amjath-Babu TS, Sharma B, Brouwer R et al (2019) Integrated modelling of the impacts of hydropower projects on the water-food-energy nexus in a transboundary Himalayan river basin. *Appl Energy* 239:494–503. <https://doi.org/10.1016/j.apenergy.2019.01.147>
- Anderson R, Keshwani D, Guru A et al (2018) An integrated modeling framework for crop and biofuel systems using the DSSAT and GREET models. *Environ Model Softw* 108:40–50. <https://doi.org/10.1016/j.envsoft.2018.07.004>
- Ati AS, Iyada AD, Najim SM (2012) Water use efficiency of potato (*Solanum tuberosum* L.) under different irrigation methods and potassium fertilizer rates. *Ann Agric Sci* 57:99–103. <https://doi.org/10.1016/J.AOAS.2012.08.002>
- Bhunnoo R, Poppy GM (2020) A national approach for transformation of the UK food system. *Nature Food* 1(1):6–8. <https://doi.org/10.1038/s43016-019-0019-8>
- Chang Y, Li G, Yao Y et al (2016) Quantifying the water-energy-food nexus: current status and trends. *Energies* 9:65. <https://doi.org/10.3390/EN9020065>
- Cuberos Balda M, Kawajiri K (2020) The right crops in the right place for the food-energy nexus: potential analysis on rice and wheat in Hokkaido using crop growth models. *J Clean Prod* 263:121373. <https://doi.org/10.1016/j.jclepro.2020.121373>
- D'Odorico P, Davis KF, Rosa L et al (2018) The global food-energy-water Nexus. *Rev Geophys* 56:456–531. <https://doi.org/10.1029/2017rg000591>
- Daher BT, Mohtar RH (2015) Water–energy–food (WEF) Nexus Tool 2. 0: Guiding integrative resource planning and decision-making. *Water Int* 40:748–771. <https://doi.org/10.1080/02508060.2015.1074148>
- Davies EGR, Simonovic SP (2010) ANEMI: a new model for integrated assessment of global change. *Interdiscip Environ Rev* 11:127–161. <https://doi.org/10.1504/ier.2010.037903>
- de Vito R, Portoghesi I, Pagano A et al (2017) An index-based approach for the sustainability assessment of irrigation practice based on the water-energy-food nexus framework. *Adv Water Resour* 110:423–436. <https://doi.org/10.1016/j.advwatres.2017.10.027>
- de Wit A, Boogaard H, Fumagalli D et al (2019) 25 years of the WOFOST cropping systems model. *Agric Syst* 168:154–167. <https://doi.org/10.1016/j.agsy.2018.06.018>
- di Paola A, Valentini R, Santini M (2016) An overview of available crop growth and yield models for studies and assessments in agriculture. *J Sci Food Agric* 96:709–714. <https://doi.org/10.1002/JSFA.7359>
- Dourado-Neto D, Teruel DA, Reichardt K et al (1998) Principles of crop modeling and simulation: I. Uses of mathematical models in agricultural science. *Sci Agric* 55:46–50
- el Gafy I, Grigg N, Reagan W (2017) Dynamic behaviour of the water–food–energy nexus: focus on crop production and consumption. *Irrig Drain* 66:19–33. <https://doi.org/10.1002/IRD.2060>
- Farquhar GD, von Caemmerer S, Berry JA (1980) A biochemical model of photosynthetic CO₂ assimilation in leaves of C₃ species. *Planta* 149:78–90. <https://doi.org/10.1007/BF00386231>
- Fuso Nerini F, Tomei J, To LS et al (2018) Mapping synergies and trade-offs between energy and the sustainable development goals. *Nat Energy* 3:10–15. <https://doi.org/10.1038/s41560-017-0036-5>
- Giampietro M, Mayumi K, Ramos-Martin J (2009) Multi-scale integrated analysis of societal and ecosystem metabolism (MuSIASEM): theoretical concepts and basic rationale. *Energy* 34:313–322. <https://doi.org/10.1016/J.ENERGY.2008.07.020>
- Grote U, Fasse A, Nguyen TT, Erenstein O (2021) Food security and the dynamics of wheat and maize value chains in Africa and Asia. *Front Sustain Food Syst* 4:317. <https://doi.org/10.3389/FSUFS.2020.617009/BIBTEX>
- Hatamkhani A, Moridi A (2019) Multi-objective optimization of hydropower and agricultural development at river basin scale. *Water Resour Manag* 33:4431–4450. <https://doi.org/10.1007/s11269-019-02365-x>
- Howells M, Hermann S, Welsch M et al (2013) Integrated analysis of climate change, land-use, energy and water strategies. *Nat Clim Chang* 3(7):621–626. <https://doi.org/10.1038/NCLIMATE1789>
- Huang D, Li G, Sun C, Liu Q (2020) Exploring interactions in the local water-energy-food nexus (WEF-Nexus) using a simultaneous equations model. *Sci Total Environ* 703:135034. <https://doi.org/10.1016/J.SCITOTENV.2019.135034>
- Ingram J (2011) A food systems approach to researching food security and its interactions with global environmental change. *Food Sec* 3(4):417–431. <https://doi.org/10.1007/S12571-011-0149-9>
- Jones JW, Antle JM, Basso B et al (2017) Brief history of agricultural systems modeling. *Agric Syst* 155:240–254. <https://doi.org/10.1016/j.agsy.2016.05.014>
- Jones JW, Hoogenboom G, Porter CH et al (2003) The DSSAT cropping system model. *Eur J Agron* 18:235–265. [https://doi.org/10.1016/S1161-0301\(02\)00107-7](https://doi.org/10.1016/S1161-0301(02)00107-7)
- Keating BA, Carberry PS, Hammer GL et al (2003) An overview of APSIM, a model designed for farming systems simulation. *Eur J Agron* 18:267–288. [https://doi.org/10.1016/S1161-0301\(02\)00108-9](https://doi.org/10.1016/S1161-0301(02)00108-9)
- Li J, Cui J, Sui P et al (2021) Valuing the synergy in the water-energy-food nexus for cropping systems: a case in the North China Plain. *Ecol Indic* 127:107741. <https://doi.org/10.1016/j.ecolind.2021.107741>
- Liu S, Zhao L (2022) Development and synergetic evolution of the water–energy–food nexus system in the Yellow River Basin. *Environ Sci Pollut Res*. <https://doi.org/10.1007/s11356-022-20405-9>
- Liu W, Yang H, Tang Q, Liu X (2019) Understanding the water–food–energy nexus for supporting sustainable food production and conserving hydropower potential in China. *Front Environ Sci* 7. <https://doi.org/10.3389/fenvs.2019.00050>
- Ma Y, Li YP, Zhang YF, Huang GH (2021) Mathematical modeling for planning water-food-ecology-energy nexus system under uncertainty: a case study of the Aral Sea Basin. *J Clean Prod* 308:127368. <https://doi.org/10.1016/j.jclepro.2021.127368>
- Mahdavian SM, Ahmadpour Borazjani M, Mohammadi H et al (2022) Assessment of food-energy-environmental pollution nexus in Iran: the nonlinear approach. *Environ Sci Pollut Res*. <https://doi.org/10.1007/s11356-022-19280-1>
- Mahlknecht J, González-Bravo R, Loge FJ (2020) Water-energy-food security: a nexus perspective of the current situation in Latin America and the Caribbean. *Energy* 194:116824. <https://doi.org/10.1016/j.energy.2019.116824>
- Martinez-Hernandez E, Leach M, Yang A (2017) Understanding water-energy-food and ecosystem interactions using the nexus simulation tool NexSym. *Appl Energy* 206:1009–1021. <https://doi.org/10.1016/J.APENERGY.2017.09.022>
- Molajou A, Afshar A, Khosravi M et al (2021a) A new paradigm of water, food, and energy nexus. *Environ Sci Pollut Res*. <https://doi.org/10.1007/s11356-021-13034-1>

- Molajou A, Pouladi P, Afshar A (2021b) Incorporating social system into water-food-energy nexus. *Water Resour Manag* 35:4561–4580. <https://doi.org/10.1007/s11269-021-02967-4>
- Momblanch A, Papadimitriou L, Jain SK et al (2019) Untangling the water-food-energy-environment nexus for global change adaptation in a complex Himalayan water resource system. *Sci Total Environ* 655:35–47. <https://doi.org/10.1016/j.scitotenv.2018.11.045>
- Qi Y, Farnoosh A, Lin L, Liu H (2022) Coupling coordination analysis of China's provincial water-energy-food nexus. *Environ Sci Pollut Res* 29:23303–23313. <https://doi.org/10.1007/s11356-021-17036-x>
- Raes D, Steduto P, Hsiao TC, Fereres E (2009) AquaCrop—the FAO crop model to simulate yield response to water: II. Main algorithms and software description. *Agron J* 101:438–447. <https://doi.org/10.2134/agronj2008.0140s>
- Rauff KO, Bello R (2015) A review of crop growth simulation models as tools for agricultural meteorology. *Agric Sci* 06:1098–1105. <https://doi.org/10.4236/AS.2015.69105>
- Ren D, Yang Y, Hu Y, Yang Y (2021) Evaluating the potentials of cropping adjustment for groundwater conservation and food production in the piedmont region of the North China Plain. *Stoch Env Res Risk A* 35:117–128. <https://doi.org/10.1007/s00477-019-01713-y>
- Ritchie JT, Alagaraswamy G (2002) Overview of crop models for assessment of crop production. In: Effects of climate change and variability on agricultural production systems. Springer, In, pp 43–68
- Roidt M, Avellán T (2019) Learning from integrated management approaches to implement the Nexus. *J Environ Manage* 237:609–616. <https://doi.org/10.1016/j.jenvman.2019.02.106>
- Sadegh M, AghaKouchak A, Mallakpour I et al (2020) Data and analysis toolbox for modeling the nexus of food, energy, and water. *Sustain Cities Soc* 61:102281. <https://doi.org/10.1016/j.SCS.2020.102281>
- Schipanski ME, MacDonald GK, Rosenzweig S et al (2016) Realizing resilient food systems. *Bioscience* 66:600–610. <https://doi.org/10.1093/BIOSCI/BIW052>
- Shen Q, Niu J, Liu Q et al (2022) A resilience-based approach for water resources management over a typical agricultural region in Northwest China under water-energy-food nexus. *Ecol Indic* 144:109562. <https://doi.org/10.1016/j.ecolind.2022.109562>
- Shrestha S, Adhikari S, Babel MS et al (2015) Evaluation of groundwater-based irrigation systems using a water–energy–food nexus approach: a case study from Southeast Nepal. *J Appl Water Eng Res* 3:53–66. <https://doi.org/10.1080/23249676.2014.1001881>
- Siad SM, Iacobellis V, Zdruli P et al (2019) A review of coupled hydrologic and crop growth models. *Agric Water Manag* 224:105746. <https://doi.org/10.1016/J.AGWAT.2019.105746>
- Smajgl A, Ward J, Pluschke L (2016) The water–food–energy nexus—realising a new paradigm. *J Hydrol (Amst)* 533:533–540. <https://doi.org/10.1016/j.jhydrol.2015.12.033>
- Soleimani E, Afshar A, Molajou A (2022) A review on water simulation models for the WFE Nexus: development perspective. *Environ Sci Pollut Res* 29:79769–79785. <https://doi.org/10.1007/s11356-022-19849-w>
- Steduto P, Hsiao TC, Raes D, Fereres E (2009) AquaCrop—the FAO crop model to simulate yield response to water: I. Concepts and underlying principles. *Agron J* 101:426–437. <https://doi.org/10.2134/AGRONJ2008.0139S>
- Stewart WM, Dibb DW, Johnston AE, Smyth TJ (2005) The contribution of commercial fertilizer nutrients to food production. *Agron J* 97:1–6. <https://doi.org/10.2134/AGRONJ2005.0001>
- Stöckle CO, Donatelli M, Nelson R (2003) CropSyst, a cropping systems simulation model. *Eur J Agron* 18:289–307. [https://doi.org/10.1016/S1161-0301\(02\)00109-0](https://doi.org/10.1016/S1161-0301(02)00109-0)
- Taghizadeh-Hesary F, Rasoulinezhad E, Yoshino N (2019) Energy and food security: linkages through price volatility. *Energy Policy* 128:796–806. <https://doi.org/10.1016/J.ENPOL.2018.12.043>
- Todorovic M, Albrizio R, Zivotic L et al (2009) Assessment of AquaCrop, CropSyst, and WOFOST models in the simulation of sunflower growth under different water regimes. *Agron J* 101:509–521. <https://doi.org/10.2134/agronj2008.0166s>
- Tyczewska A, Woźniak E, Gracz J et al (2018) Towards food security: current state and future prospects of agrobiotechnology. *Trends Biotechnol* 36:1219–1229. <https://doi.org/10.1016/J.TIBTECH.2018.07.008>
- Udmale P, Pal I, Szabo S et al (2020) Global food security in the context of COVID-19: a scenario-based exploratory analysis. *Prog Disaster Sci* 7:100120. <https://doi.org/10.1016/j.pdisas.2020.100120>
- United Nations (2019) The Sustainable Development Goals Report 2019. United Nations, In <https://unstats.un.org/sdgs/report/2019/The-Sustainable-Development-Goals-Report-2019.pdf>. Accessed 20 Nov 2022
- Uniyal B, Dietrich J (2021) Simulation of irrigation demand and control in catchments – a review of methods and case studies. *Water Resour Res* 57:e2020WR029263. <https://doi.org/10.1029/2020WR029263>
- Vahabzadeh M, Afshar A, Molajou A (2022) Energy simulation modeling for water-energy-food nexus system: a systematic review. *Environ Sci Pollut Res* 30:5487–5501. <https://doi.org/10.1007/s11356-022-24300-1>
- Vahabzadeh M, Afshar A, Molajou A (2023) Framing a novel holistic energy subsystem structure for water-energy-food nexus based on existing literature (basic concepts). *Sci Rep* 13:6289. <https://doi.org/10.1038/s41598-023-33385-8>
- van Diepen CA, Wolf J, van Keulen H, Rappoldt C (1989) WOFOST: a simulation model of crop production. *Soil Use Manag* 5:16–24. <https://doi.org/10.1111/j.1475-2743.1989.tb00755.x>
- van Dijk M, Morley T, Rau ML, Saghai Y (2021) A meta-analysis of projected global food demand and population at risk of hunger for the period 2010–2050. *Nat Food* 2:494–501. <https://doi.org/10.1038/s43016-021-00322-9>
- van Keulen H, Penning De Vries FWT, Drees EM (1982) A summary model for crop growth. Simulation of plant growth and crop production, In Wang Z, Ye L, Jiang J et al (2022) Review of application of EPIC crop growth model. *Ecol Modell* 467:109952. <https://doi.org/10.1016/j.ecolmodel.2022.109952>
- Whisler FD, Acock B, Baker DN et al (1986) Crop simulation models in agronomic systems. In: Brady NC (ed) *Advances in Agronomy*. Academic Press, pp 141–208
- Wicaksono A, Kang D (2019) Nationwide simulation of water, energy, and food nexus: case study in South Korea and Indonesia. *J Hydro Environ Res* 22:70–87. <https://doi.org/10.1016/J.JHER.2018.10.003>
- Yan X, Jiang D, Fu J, Hao M (2018) Assessment of sweet sorghum-based ethanol potential in China within the water–energy–food nexus framework. *Sustainability*:10. <https://doi.org/10.3390/su10041046>
- Zhang WJ, John MG, Bassi AM et al (2018) Systems thinking: an approach for understanding eco-Agri-food systems. In: *TEEB for Agriculture & Food: Scientific and Economic Foundations*. Geneva: UN Environment Ch 2:17–55
- Zhou J bin, Wang C yang, Zhang H et al (2011), Effect of water saving management practices and nitrogen fertilizer rate on crop yield and water use efficiency in a winter wheat–summer maize cropping system. *Field Crops Res* 122:157–163. <https://doi.org/10.1016/J.FCR.2011.03.009>

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