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REVIEW ARTICLE

Crop Simulation Models for Precision Farming of Vegetable Crops : A Review

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ABSTRACT
Vegetables are an essential supplement to the human diet, being the abundant source of essential minerals, vitamins and fibre. Larger part of the land found across the world is unfit for food production due to natural and man-made environmental stresses. New research-based agricultural practices are required to render information to farmers and decision makers on the way to attain sustainable agriculture fighting the climate change. In this context, the use of crop simulation models is being encouraged. A crop simulation model is described as a quantitative scheme for predicting the growth, development, and yield of a crop. Crop Simulation Models (CSM) are computerized algorithms and systems of crop growth, development and yield, simulated using relevant mathematical equations as functions of soil parameters, weather and management practices. Many crops models in the vegetable growth and development assessment, benchmarking of production operation, nutrient and water management, greenhouse management, quality practices, climate change adaptation and research and education services were validated and published.
Key words: *Crop simulation models, Growth and development, Irrigation scheduling, Fertigation, Nitrogen dynamics, Product quality*

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INTRODUCTION

The predominant source of nutrients and minerals of Indian diet is the vegetables. The demand for vegetables is ever-increasing since the population is ever-growing. By the ceaseless innovations through researches in vegetable improvement and smart production technologies, the demand is being met [14]. However, the shrinking land area availability is a constraint for research experiments, given that the natural as well as the man-made disturbances reduces the land available for crop cultivation and plant research [23]. Moreover, the obligation of transferring the new technologies to the farmers lies with the researchers and scientist. In this context, the crops models shortcuts the plant research through its ability to simulate the plant growth, development, yield, economic traits of the crops in response to various research objectives with which the shortage in land availability and time can be contended [13].
The Crop Simulation Models (CSMs) are the computerized programs that can represent the crop development and yield, simulated through mathematical functions of soil and environmental condition along with the management practices [21]. They simulate/imitates the real crop behavior to predict the growth of every plant parts. Therefore, a CSM not only predicts the yield, but also provide quantitative knowledge about major plant processes of growth and development [5]. They are efficient instruments to

realize critical research priorities and complex plant-atmosphere systems thereby help to identify and fill the gaps in knowledge and enable more targeted research. This review focuses on the potential applications of CSMs in the vegetable crops.

Significance of CSMs

1. CSMs provide distinct understanding, prediction, control, coherent and holistic view of a system in a methodological manner as it contains quantitative information's.
2. They help in identifying research areas where cognition is deficient and new areas of research.
3. Models can complement the real-time experiments with improved elucidation of experimental results.
4. In the real-time experiments that involve high costs, long duration, high risks and technical blank, the CSMs can replace the actual experiments.
5. Agriculture/Horticulture cannot grow by itself. The CSMs integrate various research fields to bring novel advancement in crop cultivation.

Types of CSMs

Dourado-Neto and coworkers [5] classified crop models into two types.

a) Empirical models/ regression models/ black-box models: these are simplified mathematical models containing few variables. Most of the weather forecasting models operated at the governmental organizations are empirical models. Despite the analytic usefulness, they lack reality. The resulting equations are exclusively empirical and do not carry on physiological meaning.
b) Dynamic simulators/ mechanistic model/ physiological models/ models of processes/ crop simulation models: these models are developed to adjust and meet the reply of the crop in line with the meteorological, climatic, edaphic and biological factors.
    - Meteorological factors – light, temperature, humidity
    - Edaphic factors – nutrients, water status, toxic elements, soil properties
    - Biological factors – insects, diseases, weeds

This review has its prime focus on the crop simulation models.

TECHNIQUE OF CROP MODELLING

The regression analysis is the most basic statistical technique employed to adjust the mathematical models to the experimental data [22]. The CSMs are the computer programs that predict the yield and plant processes through integrating the mathematical models with the soil, environment and other experimental data fed into its database. Their prediction and interpretations go in line with the actual plant physiology and prediction and results are almost similar in most cases [5].

Protocol for developing CSMs

Given is the example of a CSM modeled for climate change simulation.

1. Crop model parameterization: crop models will be parameterized with available field and experimental data. Based on the crop-specific characteristics, the accumulated temperature requirement of a model for the baseline will be set
2. Climate data: the daily weather data over historical period including weather parameter for a baseline period are fed to the software base.
3. CO2 fertilization effect: it is accepted that the higher future atmospheric CO2 concentration will stimulate the plant growth. However, the magnitude of the effect is subject to uncertainty. The dynamic atmospheric CO2 concentration of the baseline period and future period is derived. These annual CO2 concentrations will be used when simulating the baseline and future scenarios
4. Simulation of climate change impact and adaptation: the simulation is processed with the above input data and the climate change and adaptation scenario will be obtained from the model output. The planting dates for the baseline period and future (with and without adaptation) scenario will be supplied by the model
5. Output file naming: once simulation is completed, the results will be saved into the provided template.

CSMs for specific objectives - case studies in vegetable crops

The crop simulation models are being beneficial in various domains namely simulation of growth and development of plants, precision irrigation, fertigation, fertilizer dynamics, precision fertilization, crop rotation and land use pattern; and product quality management. The various applications of CSMs in vegetable crops are illustrated in Fig. 1. Different CSMs designed for these purposes are furnished in Table 1.

Table 1. Different CSMs developed for vegetable crops

Sl. No.	Objective	CSM	Utility	Reference
1	Plant growth and development	DSSAT-CROPGRO - Tomato	Simulation of biomass accumulation and fruit yield, with respect to different air temperature regimes	[1]
2		VegSyst	Nitrogen and irrigation management	[9]
3			Dry matter production simulation	[8]
4	Precision irrigation and fertilization		Irrigation scheduling	[6]
5			Determination of N demands in fertigation nutrient solution	[7]
6		Fertigation model	Calculation of nutrient uptake in greenhouse crops	[24]
7		FERTIRRIGERE	Simulation of nutrient and water stauts in root zone; determination of routine macronutrient and irrigation requirements	[2]
8		GesCon	Simulation of water; N balances for open field grown crops	[5]
9	Fertilizer dynamics and precision fertilization	EU_Rotate_N	Assessment of N fertilizer dynamics; optimization of N use	[10]
10		WHCNS_Veg (soil Water Heat Carbon Nitrogen Simulator for vegetables)	Simulation of water and N fates in greenhouse condition	[17]
11	Crop rotation and land use planning	APEX - AGROTOOL	Integrated system for land use and environment sustainability	[19]
12	Quality management	GREENLAB	Simulation of kinetic potential growth rate of sink organs, distribution of fresh biomass to sink organs and thus fruit maturity	[12]

CSMs for growth and development

VegSyst is another CSM developed to aid the N and irrigation management in polyhouses. It simulates the dry matter production, plant N uptake and evapotranspiration (ETc) on day basis. It have been calibrated for three vegetable crops namely tomato, Californian pepper and melon [6-9]. Gallardo *et al*. [6] calculated and simulated DMP from daily fraction of intercepted PAR and radiation use efficiency (RUE). The proportion of intercepted PAR was determined from the thermal time. The plant N uptake, a power function of DMP, was derived as the product of DMP and N content. The combined use of VegSyst and sensor techniques for irrigation and N management would enable prescriptive-corrective management of both in polyhouse environments.

VegSyst was calibrated and validated for muskmelon by Gallardo and coworkers [7]. The model accurately simulated crop biomass production as well as the crop N uptake. The DMP simulation performance was better using a double RUE approach. The simulation of ETc over time was accurate. It offers an effective simulation platform for DMP, N uptake and ETc for different vegetable crops across different seasons.

Ayankojo and Morgan [1] employed the simulation model CROPGRO-Tomato of DSSAT (Decision Support System for Agricultural Transfer) to study the effect of temperature regimes on biomass build-up and yield in tomato. They stated that the tomato fruit yield reduced by 52-85% at higher air temperature. The reduction in yield was reported to be attributed to lower fruit production. Their results also suggested that in contrast to decrease in yield at high temperature, the biomass accumulation and leaf area index increased. They concluded that the planting date could be modified in the time of autumn from July-September to dates between November and December helps eliminating adverse outcome of heat stress under South Florida conditions.

A simple DSS for potato was designed by Manorama and others [18]. Their system was validated to simulate the yield at different days after planting (100 and 120 days after planting). This was developed for crop scheduling purpose that would enable growers to take appropriate decisions on planting dates and harvesting events of the potato crop.

CSMs for precision irrigation and fertigation

Water is the input that needs the most crucial and precise application. The right scheduling of irrigation/fertigation not only eliminates water wastage but also enables improved water and nutrient use efficiencies.

VegSyst offers day-to-day programme of N requirements and irrigation volume, daily plans of the recommended irrigation volume and recommended N concentration, minding the planting date, course of cropping season and the climatic factors of the given location. It was developed to determine daily irrigation requirements, N demands and N concentration of nutrient solution for fertigated vegetable crops [7]. It calculates daily values of the crop through biomass production, crop N uptake and evapotranspiration [7]. The model have been calibrated and found fit for vegetables namely tomato, sweet pepper, musk melon, cucumber, zucchini, eggplant and watermelon [8].

Voogt and others [24] developed a model named as "Fertigation model" that couples a crop evapotranspiration model with an empirical nutrient uptake model. The model was designed for greenhouse crops and calculates on-going nutrient uptake concentration, on the basis of parameters that are specific to the individual crops like cropping phase, leaf area index, plant height and real-time greenhouse microclimate data. The model is used for irrigation scheduling in the Netherlands.

FERTIRRIGERE is a high-powered model that stimulates nutrient and water status in the root zone of the plants. It provides routine scheduling of irrigation and macronutrient recommendations for optimal fertigation, through drip irrigation system. The model reduced 46% N application, without significant reduction in fruit production and quality [2].

Conversa and coworkers [4] developed a model, GesCon, which was designed to simulate water and N balances for optimal fertigation for open field grown vegetable crops. The model was validated for open field tomatoes [4].

CSMs for fertilizer dynamics and precision fertilization

Efficient nutrient and irrigation management is crucial for sustainable production of vegetables inside the greenhouse. Intensive greenhouse production is associated with high inputs of nutrients and water, particularly the combined use of irrigation and high N use, which tends to become a great risk of N losses to the environment, particularly nitrate-N leaching and consequent contamination of ground water [15].

EU-Rotate_N is a CSM developed to optimize nitrogen use, widely used across Europe. Guo *et al*. [9] employed EU-Rotate_N to assess N dynamics in greenhouse production of cucumber. The model was calibrated in contrast with the plant dry matter and soil moisture. The plant N uptake, soil N contents, N mineralization and N losses were predicted. The prediction results were of match the actual N mineralization rates and leaching losses.

Liang and others [17] designed a vegetable growth component to the CSM WHCNS (soil Water Heat Carbon Nitrogen Simulator), named as WHCNS_Veg and used in a vegetable greenhouse production unit. They conducted sensitivity analysis by conglomerating the model with the model-independent parameter estimation program. They reported that the soil hydraulic parameter and vegetable genetic parameters showed higher sensitivity than the N transformation characteristics. The automatic optimization algorithm showed good performance in adjusting the soil hydraulic parameters, vegetable crops' genetic parameters and N transformation parameters. This model proved a great potential to simulate water and N fates, and vegetable growth for intensive greenhouse application.

CSMs for crop rotation planning and land use

Maintaining and increasing the soil fertility during the active agricultural use is key factor to achieve the ever-increasing yields. A successful vegetable farming requires right choice of proper cultures, crop rotation scheme and crop allocation in different spatial scales. The economic demands and cultivation practices should be bridged for the sustained land use. The CSMs are widely used in agroecology and crop production system for forecasting and decision support. The advantages of CSMs over regression models are listed below.

i. Improved accuracy
ii. Multiple results based on wider range of environments
iii. Reduced uncertainty of calculations
iv. Unlimited number of monitored indicators of agroecosystem model

Medvedev and others [19] developed an improved integrated system of crop simulation model APEX-AGROTOOL for land use environment sustainability, which provided an ability to simulate the agro-landscape dynamics with respect to crop rotation effects. This model has been developed with versatile algorithms and has been calibrated for potato, root vegetables and legume vegetables.

Kharisma and Perdana [16] developed a linear programming model for crop production planning. Their model included crop rotation of four vegetables, aiming for crop diversification in the market. Their decision implied weekly planning for the entire year with three combinations of crop rotation system, which are as follows.

a) Combination of tomato and baby Kenya bean
b) Combination of carrot and baby Kenya bean
c) Combination of potato and baby Kenya bean

The model proved optimization of land utilization and right profits for Indonesian farmers, with maximized yield.

CSMs for quality management

A strong emphasis has been given in modelling the product quality of vegetable crops. The quality defines the degree to which a product meets the expectations of the consumer [20]. The models meant for quality prediction targeting the forecast dry matter production, attributed to photosynthesis, respiration, biomass partitioning, all being influenced by the environmental factors.

GREENLAB is a dynamic simulator, which acts more than a morphological model, simulating the interaction between the plant and environmental functions. It can simulate the plant organogenesis from seed germination to fruit maturity, considering the organogenic growth cycles of the individual crop. In this model, the fresh biomass production is computed from the transpiration. The fresh biomass is then distributed among the growing organs, based on the sink-demand. The demand of the sink organs is determined from the allometric relationships of source and kinetics of potential growth rate of each organ. The model proved accurate dynamics of plant growth, architecture and geometry. Added advantage is the production of 3D visualization [12].

CONCLUSION AND FUTURE PROSPECTS

The CSMs are capable of simulating many intricate processes and networkings that ascertain the crop yield undergoing the changing climate. Owing to the merit of the simulators, the significance of scale and geography in deciding the crop productivity is justified as well as the stability of generality and particularity in region and scale could be understood. This lays emphasis on the fact that the climate impacts research needs high integration and specialization. However, levelling up of these simulators requires synergistic approaches, as suggested by Challinor and others [3].

i. Staunch calibration of ambivalence
ii. Instrumentalities for integrating different modelling approaches
iii. Judicious calibration of models

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