Building Energy Simulation Model Application to Greenhouse Microclimate, Covering Material and Thermal Blanket Modelling: A Review

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ABSTRACT: This review documents the present knowledge and knowledge gap in applying building energy simulation (BES) dynamic models to greenhouses. The focus of this review is to compile the literature on the BES dynamic model of greenhouse microclimate, covering materials, energy requirements and thermal blankets using the Transient System Simulation version 18 (TRNSYS 18) software. Fifty-two journal articles, mostly Science Citation Index (SCI) and Scopus index journals, on BES development and simulation of greenhouse microclimate, greenhouse energy requirement, covering materials and thermal blankets were reviewed. These researchers sought to optimise greenhouse crop production. The main features of the TRNSYS 18 software for BES development are outlined; each research consulted for this review successfully developed, simulated and validated its BES. However, none of these developed models included the vapour pressure deficit (VPD) as a greenhouse microclimate factor, an essential climate parameter. In conclusion, this study demonstrates that applying a BES developed using TRNSYS has excellent potential to optimise greenhouse crop production and help adapt appropriate climate control strategies and energy-saving techniques. However, it is recommended to include VPD in future BES model development.

KEYWORDS: BES, TRNSYS, Simulation, Optimisation, Software, Greenhouse

I. INTRODUCTION

The demand for food has skyrocketed with the increase in human and animal populations (Hou *et al*., 2021). Continuous growth in the global human population has led to a rapidly rising demand for food. Due to climate change, open-field agriculture is significantly impacted by global warming, resulting in food shortage. The negative impact of global warming on open-field agriculture has affected food availability for both human and animal consumption. Therefore, the need to increase food production by expanding the land area under open-field cultivation and finding alternatives to open-field crop production are necessary to meet the growing demand for available food (AbdulAziz, 2002). Revamping crop production and producing high-quality agricultural products are essential for ensuring global food security under the threat of climate change. Greenhouse agriculture is an alternative to open field crop cultivation. In other words, the enormous demand for food can be met by adopting controlled environmental agriculture, i.e., greenhouse agriculture, which provides an atmosphere for crops to thrive throughout the year. Greenhouse farming is a common approach to creating a suitable enclosed microclimate for crop growth and development (Gorjian *et al*., 2020). Greenhouses are extensively utilised owing to their high output, approximately 10–20 times higher than outdoor yield and low-cost production (Akpenpuun and Mijinyawa, 2018; Chen *et al*., 2020; Hou *et al*., 2021). Greenhouses can also decrease the negative impacts of adverse external environments, such as dramatic changes in temperature and lighting or other severe weather events, including excessive or inadequate precipitation (Li *et al*., 2020).

A greenhouse, irrespective of its type, can provide appropriate growth conditions, ensure stable and continuous crop production, and improve quality (Shamshiri *et al*., 2018; Li *et al*., 2020; Akpenpuun and Mijinyawa, 2020). Greenhouses also extend the cultivation period to achieve a high yield, protect plants from severe outdoor weather, reduce production costs and offer the possibility of off-season cropping (Lee *et al*., 2012; Akpenpuun and Mijinyawa, 2018; Ghoulem *et al*., 2019). Although greenhouse agriculture is cost-effective, as it reduces the number of agrochemicals and water required for the production processes of crops, greenhouse crop production is one of the high-energy-

consuming sectors in large-scale agricultural production (Zhang *et al*., 2020; Rasheed *et al*., 2020a; Rabiu *et al*., 2022). This high energy consumption associated with large-scale greenhouse agriculture has caused an increase in research aimed at innovations and technological advancements. Recent reports include developing building energy simulation (BES) to optimise greenhouse crop production and the design and manufacture of different thermal screens and cladding materials to conserve energy or shield crops from adverse climates. These methods promote energy savings without compromising crop growth, development and yield (Yano and Cossu, 2019; Rabiu *et al*., 2022).

Greenhouses are usually cladded with transparent or semi-transparent materials, such as glass, horticultural glass (HG), polyethylene (PE), polyolefin (PO) and polycarbonate (PC). The transparent roof transmits solar radiation (SR), which heats the plants, greenhouse soil or floor, greenhouse structural components and other elements within the greenhouse environment. The generation of longwave radiation within the greenhouse environment, as a result of the trapped SR, is faster than its removal because of the impermeability of sidewalls and roofs to longwave radiation and hence the indoor air temperature is higher than the ambient temperature (Owolabi *et al*., 2017; Chen *et al*., 2020). Therefore, greenhouses are equipped with either natural or mechanical ventilation systems to control temperature and other environmental parameters for obtaining a favourable microclimate for crop production (Shamshiri *et al*., 2018). The ability to manipulate the greenhouse atmosphere makes it possible to produce crops, boost productivity, control quality, cultivate crops that would ordinarily be impossible and lengthen the cultivation period. However, the greenhouse environment requires energy for heating during the cold season or for cooling during the hot season (Akpenpuun and Mijinyawa, 2020; Sim *et al*., 2020; Tang *et al*., 2020).

The internal environmental elements of greenhouses include light, temperature, relative humidity (RH), vapour pressure deficit (VPD), carbon dioxide (CO_2) concentration, physical, chemical and biological characteristics of the soil and soil moisture, along with irrigation, fertilisation and cultivation methods (Shamshiri *et al*., 2018; Li *et al*., 2020). The growth, output and production quality in greenhouses depend mainly on the internal microclimate conditions. Therefore, many studies, such as Zhao *et al*. (2001), Bradford *et al*. (2010) , Yoshida *et al*. (2016), Cayli (2020), Sim *et al*. (2020) and Hou *et al*. (2021), have been conducted to improve the orientation, control of the microenvironment, structure covering materials and shading of the greenhouse, as well as the management of crops grown in greenhouses. Furthermore, the gradual establishment and improvement of various greenhouse microclimate simulation models also increase our understanding of the microclimate formation mechanisms of greenhouses (Li *et al*., 2020).

Greenhouse atmosphere simulation models describe the relationships and interactions between photosynthesis, transpiration, microclimate parameters (temperature, RH, VPD, solar irradiance and CO_2), greenhouse structural members, cover materials, outdoor conditions and the action of controllers on indoor microclimate. Therefore, greenhouse climate simulation models are helpful for the optimisation of greenhouse design, climate control and crop management (Rasheed *et al*., 2018b). Luo *et al*. (2005) reported that energy balance and process-based climate simulation models and applications to greenhouse climate control were carried out in the 1980s. Since then, greenhouse climate simulations conducted by various researchers have contributed to the knowledge base on greenhouse climate, light transmission, ventilation, crop transpiration, photosynthesis, energy demand, thermal screening and cladding materials (Luo *et al*., 2005; Ahmad *et al*., 2017; Rasheed *et al*., 2018a; Rasheed *et al*., 2020b; Ahamed *et al*., 2020; Akpenpuun *et al*., 2021b; Akpenpuun *et al*., 2021a; Rabiu *et al*., 2022).

Crop cultivation in greenhouses increases from high-altitude and temperate regions to low-altitude and tropical and subtropical regions due to global warming (Kumar *et al*., 2009; Ogunlowo *et al*., 2021). Hence, manipulating or regulating the greenhouse air temperature to be the same as or very close to the outdoor air temperature in the hot season is required for successful crop production in the greenhouse (Akpenpuun *et al*., 2021b; Rabiu *et al*., 2022).

Transient System Simulation (TRNSYS) is a BES program, a multifaceted component-based software capable of dynamically simulating simple and complex energy systems in buildings (Klein, 2012; Rasheed *et al*., 2018a).TRNSYS is a product of the University of Wisconsin's Solar Energy Laboratory. TRNSYS was developed, released and commercialised in 1975. The TRNSYS software consists of an engine that processes input files and a component library. Since its release, TRNSYS has continuously been upgraded to the status of a hybrid simulator. As a result, it is capable of performing several energy building simulations comprising energy load and energy system performance of commercial or residential buildings, technology assessment, solar thermal processes, renewable energy sources, airflow modelling, system calibration, use of wind and hydrogen fuel cells and electric power plant simulations (Chargui *et al*., 2012; Klein, 2012; Rasheed *et al*., 2019). Although TRNSYS is a robust building simulation application software extensively utilised for the transitory simulation of residential and commercial building thermal systems, it is yet to be fully deployed in greenhouse technology and management (Ahamed *et al*., 2020; Rasheed *et al*., 2020a). Recently, Choab *et al*. (2019) reviewed the available greenhouse thermal environment modelling application software and concluded that the most extensively utilised simulation application software products for greenhouse thermal environment modelling were TRNSYS and Design-Builder.

On the other hand, Baglivo *et al*. (2020) considered TRNSYS more convenient than Design-Builder because its flexibility makes it compatible with ANSYS Fluent, MATLAB and Excel. In this context, TRNSYS can be regarded as versatile and, as a result, very effective software for conducting energy simulations. Furthermore, TRNSYS software has demonstrated very high flexibility in the few cases where it has been used to study various scenarios of the climate and energy of greenhouse systems (Carlini *et al*., 2010). However, the peculiarity and complexity of greenhouse structures, such as their transitory moisture production rate, indoor microclimate

monitoring devices, and control equipment, make TRNSYS utilisation in greenhouse energy design and management quite challenging (Ahamed *et al*., 2020).

BES is an instantaneous energy demand technique based on various dynamic simulation procedures that forecast and analyse energy (Rasheed *et al*., 2020a; Ahamed *et al*., 2020). BES models complex efficiently analysed agricultural buildings by considering the building structural parameters and on-site weather conditions (Sethi, 2009; Rasheed *et al*., 2020a). A BES provides a platform on which the thermal behaviour of buildings can be investigated in real-time (Rasheed *et al*., 2015). Lee *et al*. (2012) noted that a reliable estimation of greenhouse energy load and selecting appropriate cooling and heating facilities are significant considerations for saving energy, initial investment, maintenance and operating costs (Lee *et al*., 2012).

This review aims to present the knowledge base of TRNSYS-based BES dynamic models and BES application to greenhouse technology and management. In addition, the specific applications of BES models to investigate greenhouse microclimates, covering materials, thermal screens, and the heating cooling load requirements of greenhouses were reviewed. This review will provide knowledge and a database of present innovations and applications of BES, highlight the current research gaps and recommend further studies.

II.   BUILDING ENERGY SIMULATION (BES)

A.   *Pre-processing*

Model pre-processing refers to determining the material properties and 3D design preparation of an experimental greenhouse or building before a simulation to enhance the model's performance. Pre-processing is an essential aspect of BES model development because pre-processing reduces the level of errors and increases the accuracy and sensitivity of the model. Table 1 and Figure 1 present the pre-process add-ons and programs with their respective functions, output file and BES flowchart.

B.   *Modelling*

Simulation Studio, the graphical user interface of the TRNSYS application software, displays model-building components and runs the simulation. Simulation Studio houses various model components for energy and microclimate simulations. The typical components of the simulation are listed in Table 2.

C.   *Simulation*

The simulation is performed in the TRNSYS Simulation Studio after completing the modelling processes in TRNBUILD. The IDF file containing all model conditions is imported into the TRNSYS simulation studio and the simulation is run. The simulation is performed using the weather data obtained at the experimental site to validate the model. Model accuracy is measured through model validation or verification. To validate the model, the following indices have been used over the years: coefficient of determination (R2), mean absolute error (MAE), root square mean error (RSME) and Nash–Sutcliffe efficiency (NSE) (Rasheed *et al*., 2020a). R2 measures how well two datasets fit each other. In contrast, RSME and MAE measure the deviation in the datasets and the robustness of the data around the line of best fit, respectively (Asa'd *et al*., 2019; Villagrán *et al*., 2019). According to Glen (2019), model evaluation techniques must answer the following vital questions: How well does the model match observed data? In other words, what is the goodness of fit? Assuming that multiple models are created, which is the best? And how accurate can the developed model predict new observations/data?

After validating the model, several other simulations are performed according to the set objectives of the study. For example, a study may want to investigated the influence of different thermal screens, the configuration of thermal screens in terms of the number of layers (multi-layer or single layer) and the type of material the thermal screen is made of (polyester, Luxous, or Tempa) on the heating or cooling energy requirement of a greenhouse (Rasheed *et al*., 2018c; Rasheed *et al*., 2020a; Rabiu *et al*., 2022). Figure 2 shows a typical BES model in the TRNSYS Simulation Studio.

D.   *Validation of BES Model*

The performance of a BES model is based on the RMSE, R^2, MAE and NSE coefficient of validation (see Section II *C .Simulation* for more details). The NSE coefficient quantitatively describes the accuracy of the model results. The value of NSE ranges from −1 to 1 and values closer to 1 indicate better predictive power of the model. The mathematical expression for NSE is presented in Eqn. (1) (Adesanya *et al,* 2022):

$$NSE = 1 - \left[\frac{\sum_{i=0}^{n}\left(T_i^{exp} - T_i^{sim}\right)^2}{\sum_{i=0}^{n}\left(T_i^{exp} - T_i^{mean}\right)^2} \right] \qquad (1)$$

where T_i^{exp}, T_i^{sim} and T_i^{mean} are the experimental and simulated temperatures of the greenhouse and mean temperature of the field experiment, respectively and *n* is the size of the observations.

E.   *Sensitivity Analysis*

To further increase the acceptability of the developed model, a sensitivity analysis is conducted to measure the impacts of varying the input variables, such as the thermal conductivity and thickness of the covering materials/thermal screen, on the output parameters. For example, to validate the reliability of a developed greenhouse thermal environment model, the opening-closing control strategy scenarios are such that the opening and closing of the vent openings are time-, ambient SR- and ambient temperature-dependent. The method that provides the best response to greenhouse climate is adopted. The sensitivity coefficient expressed in Eqn. (2) is the most appropriate for thermal systems and BES (Lam and Hui, 1996; Rasheed *et al*., 2020b).

$$\text{Sensitivity coefficient} = \left[\frac{\Delta OP}{\Delta IP} \right] \qquad (2)$$

where *IP* and *OP* are the input (temperature, thermal conductivity) and output (heating/cooling energy demand, yield) variables respectively.

Table 1: Results of the tensile properties.

S/No	Add-ons/ Programs	Function	File created
1	TRNFLOW	Coupling of airflow between the thermal zones and the ambient environment	
2	Transys3d	Sketchup add-on	.IDF
3	TRNBuild	Used to define input and output data parameters of a model	.BUI
4	Berkeley Lab Window 7.4 software	Allows the definition of the thermophysical properties of new material	.DOE-2
5	SoilNoding program	Calculates greenhouse soil/floor temperature	.txt file
6	TRNSYS 18	Simulation studio	
7	Google SketchUp™	3D design	IDF
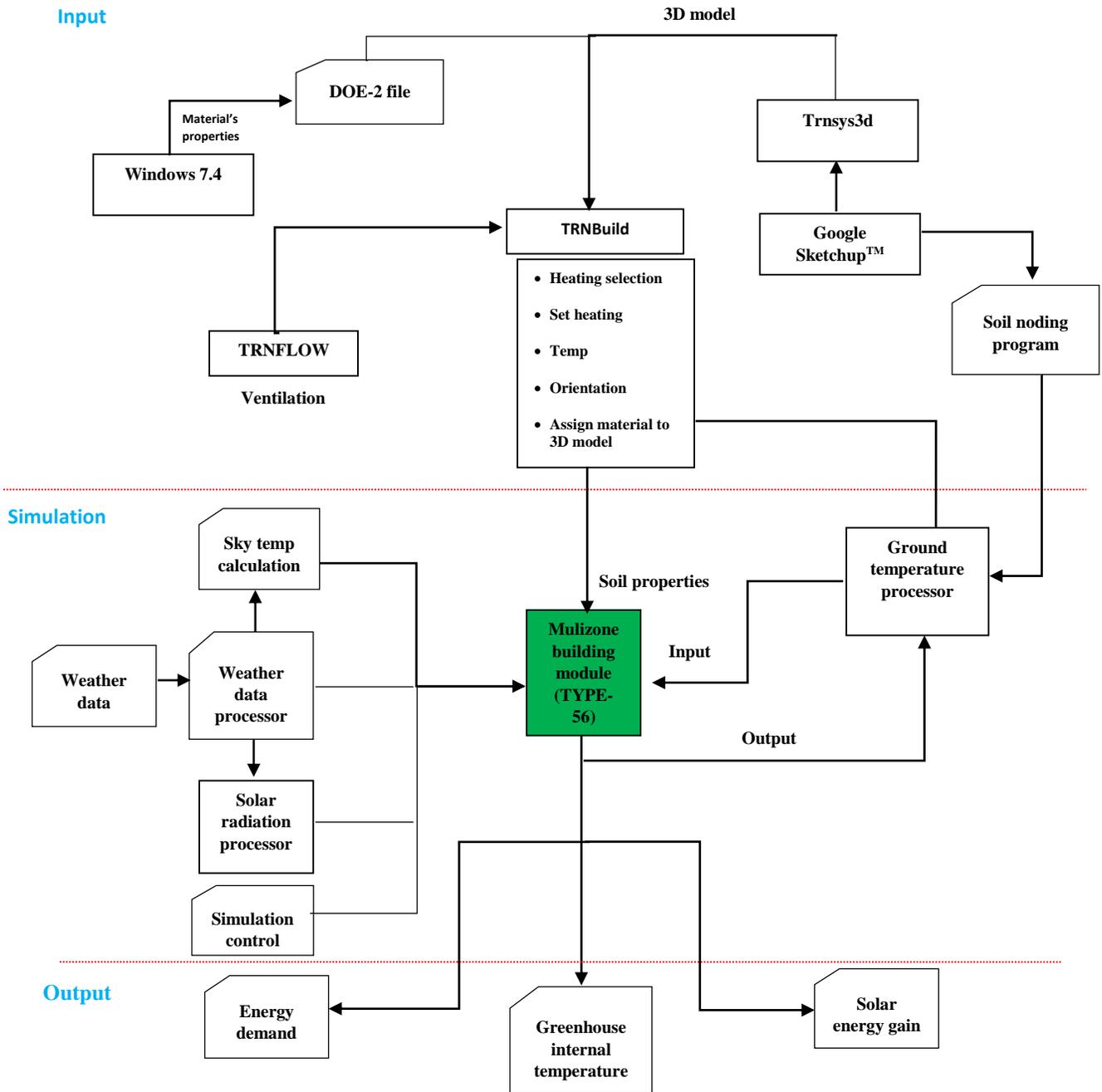
Figure 1: BES Flow chart in TRNSYS18.

Table 2: Components and functions of a typical BES model.

S/No.	Component/Type	Component/Type name	Function
1	Type-9	Weather data reader	Reads the .text file of the experimental site weather data
2	Type-56	Multi-zone	Describes the 3D model of the greenhouse/building.
3	Type-16	Solar radiation processor	Processes total horizontal solar radiation from the weather data reader.
4	Psychrometric chart	"Type-33"	Calculates dew point temperature using dry bulb temperature and humidity ratio from the weather data
5	Sky temperature calculator	"Type 69"	Calculates sky temperature using dew point temperature and diffuse and beam radiation data on a horizontal surface
6	Ground coupling module	"Type 49"	Couples the greenhouse floor and internal thermal environment
7	SoilNoding module		Determines the greenhouse floor temperature using the greenhouse floor file and convective heat transfer coefficient of Type-56.
8	Differential controller	"Type 911"	Controls the opening and closing of vents for natural ventilation
9	Controller	"Type 165"	Controls the opening or closing signals of the thermal screen and vent openings for natural ventilation
10	Monthly Function Scheduler	"Type 518"	Provides the daily and monthly control signals to "Type 165"
	Online plotter	"Type-65"	Displays the outputs
	Printer	"Type-25"	Prints the results in a text file format

Source: Klein (2012)

Figure 2: Typical BES model of a multi-span greenhouse in TRNSYS Simulation Studio (Rasheed *et al*., 2020b).

III. BES MODELS FOR GREENHOUSE THERMAL ENVIRONMENT AND ENERGY DEMAND

The greenhouse environment is a complex entity with many influencing factors; as a result, it is challenging to simulate changes in greenhouse air temperature. The climate also varies with different crops or the same crop at different times of the day. Therefore, it is difficult to control the greenhouse temperature accurately, but it can be maintained within a reasonable characteristic climate value to meet the requirements (Fei *et al*., 2021). Various scholars have conducted relevant studies to control greenhouse environments. Rasheed *et al*. (2019) studied the influence of selected thermal blankets and control strategies on greenhouse heating energy requirements. They reported that the heating requirements of greenhouses with polyester, Luxous and Tempa screens were 20%, 5.4% and 13.5% higher than the heating requirements of greenhouses with multilayer thermal blankets at night, respectively. Rasheed *et al*. (2019) also found that screen control significantly affects a greenhouse's energy conservation capacity at a setpoint of 60 $W.m^{-2}$ SR. The developed models from these studies allowed dynamic simulation of greenhouse systems.

To determine the energy expended in cooling and heating an experimental multi-span greenhouse in summer and winter, respectively, Rasheed *et al*. (2020a) developed a BES model to evaluate its performance under various structural design parameters, such as orientation, diurnal and seasonal control of thermal blanket(s), natural ventilation, heating and cooling temperature set points, type of cladding, thickness of cladding, cladding configuration, north-wall insulation and roof design. Rasheed *et al*. (2020a) concluded that using three layers of thermal screens saves as much as 70% and 40% of heating energy compared to using a single and double layer of thermal blankets, respectively, and also reduces the cooling demand by approximately 25%. The maximum heating loads were 0.65, 0.46, 0.41 and 0.34 $MJ.h^{-1}.m^{-2}$ for the multi-span greenhouse without a thermal blanket and with one-layer, two-layer and three-layer screens, respectively. Simultaneously, the maximum cooling load with the shading screens was 1.18 $MJ.h^{-1}.m^{-2}$, whereas the maximum cooling load without them was 1.5 $MJ.h^{-1}.m^{-2}$. In conclusion, the total annual energy demand of the greenhouse in the east–west orientation was lower than the total annual energy demand in the north-south orientations. On comparison, the simulated and experimental data resulted in R^2 and RMSE values of 0.63 and 1.3 ºC, respectively, with a thermal blanket and 0.84 and 1.8 ºC without a thermal blanket. R^2 and RMSE reported in this research showed a correlation between the simulated and experimental data.

Rasheed *et al*. (2019) simulated the indoor temperature of greenhouses. They compared these data with experimental temperature data obtained using natural ventilation, night-time heating setpoint and thermal curtain (scenario 1) and using ventilation without night-time heating setpoint and thermal blanket (scenario 2) for temperature control. They concluded that the simulated and experimental greenhouse indoor temperature had NSE values of 0.84 and 0.79 for scenario 1 and scenario 2, respectively. These NSE values indicated the goodness of fit between the experimental and simulated data and validated the developed model.

Lee *et al*. (2012) designed four types of naturally ventilated greenhouses using TRNSYS and then compared and analysed their energy load properties by applying meteorological data collected from six regions (Chuncheon, Suwon, Cheongju, Daegu, Cheonju, and Jeju) in Korea. Lee *et al* (2012), thereafter, reported that the heating load per year at Chuncheon was approximately in the range 9% to 49% higher than the heating load recorded in the other five regions. In contrast, the annual cooling load of 1-2 W greenhouse type at Chuncheon was the lowest compared with 1-2 W greenhouse type at Suwon, Cheongju, Daegu, Cheonju and Jeju. However, the 1-2 W greenhouse type at Chuncheon, Suwon, Cheongju, Daegu, Cheonju, and Jeju needed 23%, 20%, 17%, 16%, 18%, and 20%, respectively, more cooling energy than the widespan greenhouse type sited in all the six regions.

Ahamed *et al*. (2020) presented a detailed TRNSYS model that could predict the "transient heating requirement of a conceptual Chinese-style solar greenhouse (CSG) for Canadian Prairies at high northern latitudes." The TRNSYS simulated heating requirements were compared with those of a novel CSG developed and validated using a heating simulation model with a dynamic rate of evapotranspiration, air exchange and heating sub-models based on the heat balance of greenhouse air. The results showed that the difference in the monthly mean heating load excluding thermal blankets and plants in the two models was approximately 5.0%. Although Ahamed *et al*. (2020) succeeded in developing a BES model, they recommended complex modifications or sub-models for the building simulations in TRNSYS to reduce uncertainty in predicting greenhouse microclimates.

Rasheed *et al*. (2018a) investigated the effect of greenhouse roof shapes on the annual energy requirement and successfully created, calibrated and validated a BES model for three different greenhouse roof shapes. They calculated the annual energy demand required to maintain the desired temperature inside the test greenhouses. The results indicated that the annual energy requirements of the even- and round-shaped roof greenhouses were 2% and 8% higher than the energy requirements of a gothic-shaped roof greenhouse, respectively. In the same research, Rasheed *et al*. (2018a) described the influence of greenhouse structural design parameters, natural ventilation and type and thickness of cladding on energy consumption. They concluded that the correlation between the simulated and experimental data, described by NSE values of 0.761, 0.972, 0.878, 0.793 and 0.812, showed that the model had high accuracy. Gupta and Chandra (2002) developed a mathematical model to simulate the internal thermal greenhouse environment in a similar study. They compared the internal temperatures of conventional round-, even-, and gothic-shaped roof greenhouses. The results showed that the gothic-shaped roof greenhouse had a higher internal temperature than the round- and even-shaped roof greenhouses, resulting in less heating energy demand. As a result, it received more SR in winter.

Goto *et al*. (2017) developed an integrated model to simulate greenhouse environments under a given meteorological and plant data using TRNSYS. The model

considered ventilation, shading, heating, evaporation, cooling, evapotranspiration and the heat energy balance necessary to predict greenhouse air temperature and RH. The developed model was evaluated and validated using an experimental greenhouse and the model was applied to greenhouses located in Asian countries using local meteorological data. In addition, energy demand for heating and cooling the greenhouse microclimate under the prevalent ambient conditions at the experimental sites were also estimated. Goto *et al*. (2017) concluded that the developed model is an effective tool for making strategic energy and resource management decisions.

To evaluate the environmental controls in a tomato greenhouse in East Asia,Ishigami *et al*. (2014) developed a simulation model using TRNSYS. Greenhouse ventilation and heat balance were incorporated into the model to predict the greenhouse microclimate temperature and RH. A fog cooling system module with a maximum fogging rate of 0.36 kg.m^{-2}.h^{-1}, was activated when the air temperature and RH were greater than 28 °C and less than 90%, respectively and an evapotranspiration module was added during summer production to predict evapotranspiration. The ambient data used in this study were the hourly mean SR, temperature and RH values. The results showed that the simulation output for the indoor air temperature correlated with the measured values with reasonable accuracy and an error difference of 0.9 °C. The simulation model combined with the fog cooling and evapotranspiration modules accurately simulated the environmental conditions in the experimental greenhouse.

To investigate the effect of whitening on the optical properties of a greenhouse covering material of a naturally ventilated Zimbabwean greenhouse containing a rose crop Mashonjowa *et al* (2010) adapted and modified the gembloux dynamic greenhouse climate model (GDGCM) to simulate the effect of the whitening on maximum air temperature, vapour pressure deficit, canopy-to-air temperature difference and transpiration rate. These researchers reported that there was a significant reduction in greenhouse maximum air temperature, VPD, canopy-to-air temperature difference and transpiration rate. The differences in maximum air temperature, VPD, canopy-to-air temperature and transpiration rate were 1.6 °C, 2 kPa, +0.8 °C and 20%. The simulated results showed the same trend as the experimental data for all the parameters investigated. In addition, Mashonjowa *et al* (2010) concluded that the model adequately simulated the internal greenhouse microclimate using outdoor incident SR, cover transmittance and greenhouse structural configuration as inputs with R^2 = 0.95. Thus, the model can predict indoor climate and as a design tool for ventilation and cover material.

IV. BES MODEL FOR GREENHOUSE HEATING AND COOLING DEMANDS

To reduce greenhouse gas emissions and increase the profit margin by reducing heating and cooling costs in winter and summer, respectively, a shift from fossil fuel to non-fossil fuel energy sources is necessary (Semple *et al,* 2017). It has been estimated that heating and cooling account for approximately 40% of greenhouse operating costs (Semple *et al*., 2017; Akpenpuun *et al*., 2021a; Rabiu *et al*., 2022). Therefore, some researchers have developed BES models to

optimise greenhouse heating and cooling costs to reduce operating costs and their findings are documented in this following paragraphs.

Agrebi *et al*. (2021) numerically and experimentally investigated a 10 kW water-to-water heat pump (WTWHP) heating system with and without a solar collector using a glass covered greenhouse, respectively, under the meteorological conditions of Tunis. The WTWHP heating systems performances were evaluated and the result showed that the mean coefficient of performance (COP) of the WTWHP and solar-assisted WTWHP were 2.8 and 3.2, respectively. The proposed SAHP had a higher COP than the GCHP system, implying that the SAHP had the most significant heating capacity. Finally, the incorporation of solar energy in the heat pump system significantly improved the greenhouse temperature and energy efficiency of the solar-assisted heat pump system. The experimental results validated the TRNSYS simulation results.

Semple *et al*. (2017) explored the potential of closed greenhouses in the cold climate of Canada using natural ventilation for cooling and dehumidification and also the reuse of the removed thermal energy to heat the greenhouses on cold days or nights. To achieve this objective, Semple *et al*. (2017) developed a transient greenhouse model validated using natural gas consumption data from a reference greenhouse. The annual heating and cooling demands, the effect of varying the cover materials and the potential for heat recovery ventilation were determined. Semple *et al*. (2017) concluded that a surplus energy ratio (SER) ranging from 1.5 to 3.4 was observed for the Southern Ontario location for a single glass, double PE and double glass greenhouses, respectively. In contrast, the SER for Montreal and Vancouver ranged between 1.0 and 3.1. The optimisation result showed that a fully closed greenhouse is possible in cold regions like Canada. The annual heating demand was either equal to or less than the cooling demand for all locations.

Rasheed *et al*. (2021) proposed a BES model for an air-to-water heat pump (AWHP) system integrated into a multi-span greenhouse with three compartments, 1, 2 and 3, using the TRNSYS-18 program. The proposed BES model was validated using an experimental AWHP and a multi-span greenhouse with 391.6 m^2 of floor area installed at Kyungpook National University, Daegu, South Korea. The simulated results were validated with the experimental results of internal greenhouse temperature, heating load, heat supply from the water reservoir to the greenhouse, the outlet water temperature of the heat pumps, heat pump electricity consumption, coefficient of performance (COP) and temperature of the water reservoir. The mean simulated COP of the AWHP was 2.2 at 13 °C ambient temperature. In addition, this study concluded that the RMSE and NSE values for indoor air temperatures for the three compartments were 1.9 °C, 1.8 °C and 2.0 °C and 0.71, 0.70 and 0.65, respectively. In contrast, RMSE and NSE values of the energy load for greenhouse compartments 1, 2 and 3 were 5140 Kcal.h^{-1}, 3674 Kcal.h^{-1} and 5141 Kcal.h^{-1} and 0.73, 0.81 and 0.67, respectively. Overall, the simulated results correlated well with the experimental results.

Choab *et al*. (2021) developed a greenhouse thermal model using TRNSYS to investigate the effects of design

parameters, crop evapotranspiration and air change rate on the thermal behaviour and heating/cooling energy requirements of a greenhouse situated in Agadir, Morocco. The model considered the presence of plants by adding heat and humidity gain to the heat and water balance of the greenhouse using an evapotranspiration sub-model. The BES model was validated using previous studies from the literature and the comparison showed fair agreement. The relative error of the annual heating demand was 1.66% and the evapotranspiration model showed a relative deviation of 6.5%. Choab et al. (2021) concluded that the optimum orientation was east–west, which resulted in a 9.28% reduction in the annual cost of microclimate control. In contrast, the Quonset-shaped greenhouse saved 14.44% of the annual cost of microclimate control. Furthermore, the heating demand decreased by 20.5% when the single PE covering was replaced by a double PE (3 mm gap thickness).

V. BES MODELS FOR GREENHOUSE COVERING MATERIAL AND THERMAL SCREEN

Greenhouse covering materials and thermal blankets are used to screen the greenhouse environment from the ambient environment. The greenhouse microenvironment can be monitored and controlled with the covering material in place. A thermal blanket is used to screen out the quantity of SR entering the greenhouse environment in hot regions or to conserve heat energy within the greenhouse environment in cold regions (Akpenpuun et al., 2021a). The choice of covering material and the thermal screen is dependent on the desired location and microenvironment. However, the BES model can be used to select these materials even before going to the field. In this context, the BES models for greenhouse covering and thermal screens are reviewed in this section.

Rasheed et al. (2018c) developed a TRNSYS-based BES to investigate the overall heat transfer coefficient (U-value) of some cladding materials of interest: PE, PC, polyvinyl chloride (PVC) and HG, to determine the effects of inside-to-outside temperature differences, wind speed and night sky radiation on the U-values of these materials. The study showed significant changes in the U-value in response to variations in the ambient weather parameters and the number of layers of the covering materials. They also reported that the U-values of PC, PVC and HG were 9%, 4% and 15%, respectively, lower than that of PE because of their larger thickness. They also noted that the U-values of all materials increased with the wind speed at a given temperature. The overall BES model allowed the analysis of different cladding materials regarding their behaviour upon exposure to ambient weather conditions. This model can assist in decision-making when planning energy conservation techniques for greenhouses.

Rasheed et al. (2020b) investigated the influence of selected thermal curtains, natural ventilation and heating setpoint controls on a multi-span greenhouse's annual and maximum heating requirements in the winter months of November, December, January and February in Taean Gun Chungcheongnam-do, South Korea. A BES model was developed to predict the heating load without thermal curtains (scenario 1) and with single- (scenario 2), double- (scenario 3) and triple-layered (scenario 4) thermal curtains and to estimate the air temperature below and above each thermal curtain layer. The model heating temperature setpoint was 18 °C and the ventilation and thermal screen opening–closing setpoints were time-based. The model predicted the maximum heating load based on scenario 1, 2, 3 and 4, the heating load when using a combination of different thermal curtains and the monthly heating load with day and night temperature setpoints.
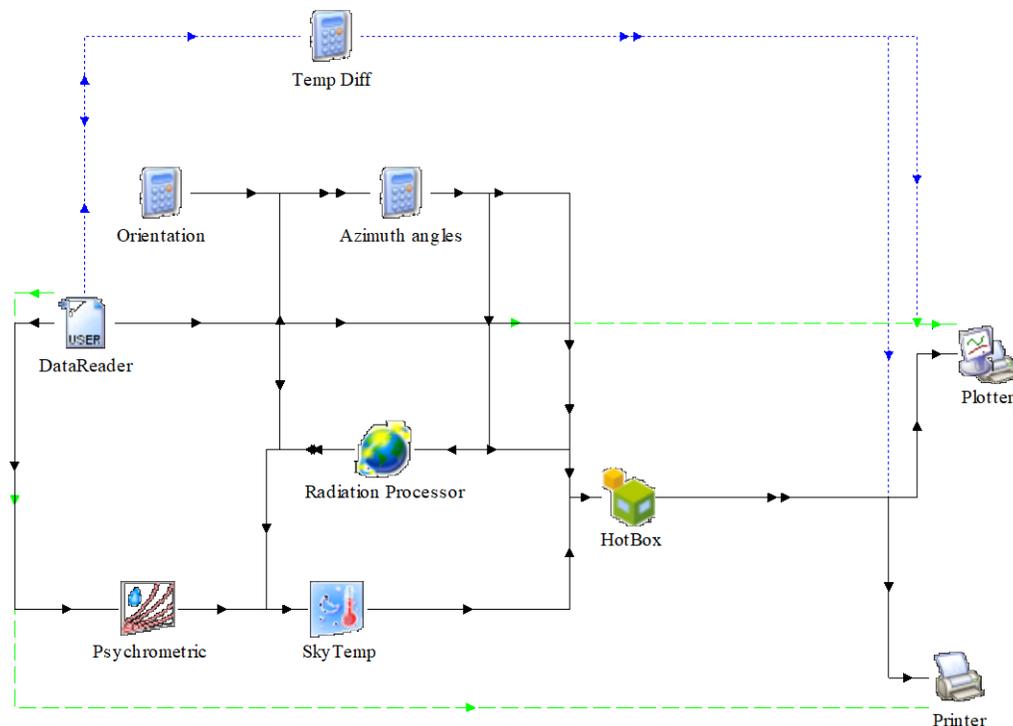
Figure 3. TRNSYS simulation for the determination of the U-value of greenhouse cover materials (Rabiu et al, 2022).

Rasheed *et al.* (2020b) concluded that the heating loads of the single- and double-layered thermal curtain greenhouses were 60% and 40% higher than that of a triple-layered thermal curtain greenhouse. The developed BES also predicted that using day- and night-time heating control setpoints in winter could reduce the heating requirement by 3%, 15%, 14%, 15% and 40% in November, December, January, February and March, respectively.

In addition, Rabiu *et al.* (2022) determined the thermophysical, radiative and aerodynamic properties of selected potential greenhouse thermal screen materials (M1, M2, M3, white polyester, Luxous, PH-55, PH-super, PH-66, M2, M3, Clima45 (0) and New-Lux) using a BES model shown in Figure 3 and experimental hotbox. The effect of the permeability of the thermal screen materials on the U-value was also investigated using the BES model with airflow through the material pores. Thermophysical, radiative and aerodynamic properties were used to evaluate the overall U-values. The BES model simulated the heat flux and derived the thermal retention qualities of the thermal screens based on their measured properties. The simulated and experimental U-values were compared to validate the model and there was an agreement between both.

Rabiu *et al* (2022) recorded that the overall U-values for White polyester 300/600, luxous, PH-55 (open), PH-super, PH-66 (al), M1, M2, M3, Climax45 and New-lux were 8.0, 9.0, 72.1, 11.5, 9.8, 4.4, 6.2, 4.4, 8.9 and 9.6 W m-2 K-1 and 8.2, 9.5, 38.9, 10.8, 9.1, 3.9, 5.8, 4.6, 8.7 and 9.8 W m-2 K-1, respectively. Then on comparing these results concluded that there was a correlation and there was no significant difference between the simulated and experimental data U-value. Rabiu *et al* (2022) also concluded that the U-value is valuable in estimating energy load and performance of energy-saving screens.

VI. CONCLUSION

TRNSYS-based BES models are being increasingly used owing to their flexibility and versatility. TRNSYS is a wise choice for agricultural building analysis, as BES models can enhance our understanding of greenhouse thermal and climatic environments. BES models are also valuable for designing climate management strategies.

All the reviewed studies successfully developed and simulated the thermal greenhouse environment, energy demand and properties of greenhouse cladding materials and thermal blankets. However, VPD, one of the most critical greenhouse microclimate parameters, has been ignored in the literature reviewed. Therefore, the recommendation of this review is to include VPD in future greenhouse BES models.

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