International Journal of Innovation and Scientific Research
ISSN 2351-8014 Vol. 13 No. 1 Jan. 2015, pp. 286-297
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http://www.ijisr.issr-journals.org/

Effect of greenhouse fixed ventilation opening on rose yield for Ethiopia highland

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ABSTRACT: In Ethiopia almost most greenhouses are equipped with fixed ventilation owing to the fact that its influence on CO_2 concentration, indoor temperature and RH% which affects plant growth is not clearly understood or due to lack of capacity. Particularly, relative humidity in the greenhouse not only affects plant growth but also major factor for pest-disease which should be maintained at the required range. In this study, the influences of fixed ventilation opening on indoor CO_2 concentration, temperature and relative humidity which consequently affect yield were investigated. To execute simulation and examine the influence of ventilation opening on indoor climate and yield a generic tool or a model set up in Matlab software was employed. For the existing ventilation configuration, simulation of indoor climate was conducted and the result illustrated that low CO_2 particularly during day time and high and low temperatures are major problems in the greenhouse. The observed indoor climate beyond the required range inhibits growth.
The result of the sensitivity analysis for summer period showed that one percent increase in ventilation opening increases the CO_2 concentration by 0.013%, decreases canopy temperature and vapor concentration by 0.065% and 0.114% respectively and increases yield by 0.328%. During winter period, a percent increase in ventilation area resulted in 0.036% and 0.075% reduction in canopy temperature and vapor concentration respectively, 0.012% increased indoor CO_2 concentration and 0.03% increment in dry matter harvest. A yearly base sensitivity analysis illustrated that, a percent increase in ventilation opening area increases the dry matter harvest and interior CO_2 by 0.231% and 0.012% respectively and decreases the canopy temperature and vapor concentration by 0.057% and 0.102% respectively.
Thus, production in Ethiopian highland can be improved by providing better ventilation so as to increase the CO_2 concentration and reducing extreme high temperature and vapor concentration in the greenhouse which influence the rate of photosynthesis. However, increased ventilation opening should be taken into consideration in relation to evapo-transpiration as a consequence of outdoor wind effect and the cost of insect screen to cover the larger ventilation opening.

KEYWORDS: ventilation, sensitivty analysis, simulation, dry matter harvest.

1 BACKGROUND

In Ethiopia greenhouse horticulture for flower production is assumed to be a young industry and started in 1999 in the highland part of the country near the capital Addis Ababa, and exporting started in 2000 [2],[10]

The capital Addis Ababa, place for some growers is found in the highland part of the country where its latitude 8.9^0N of equator, longitude 38.8^0E of Greenwich.

The measured data obtained from one of floriculture company, Lafto Rose farm PLC, depicted that undesirable indoor climate, specifically temperature and relative humidity are major problems.

Undesirable greenhouse indoor climate, pest-disease and environmental problems are major concern. Thus, reduction in yield could occur owing to the fact that pest-disease infestation and undesirable indoor climate. Danse et al., [6] pointed out that downy mildew and botrytis are the major problems in Ethiopian greenhouse horticulture particularly during the rainy season and mainly induced by low temperature.

Growers in this part of the country are still profitable despite the aforementioned problems in the greenhouse. However, maintaining the indoor climate at the required range such as CO_2, temperature and RH% can result better production and even reduces cost and environmental load due to chemical application.

Maintaining the indoor climate as per plant requirement can be achieved through applying knowledge of climate control techniques, which includes the use of appropriate cladding material, best possible ventilation area, passive heating or cooling and ventilation control strategies.

One of the vital process which affects greenhouse micro-climate is ventilation. It strongly helps to heat and mass exchange between the outdoor and indoor environment. Thus, climate control and energy efficiency can be improved with best design of ventilation features. Specifically, ventilation can be considered as one factor for optimum control of temperature, humidity and CO_2 concentration. A greenhouse design which permits a large range of values for the ventilation flux supports well-managed passive air exchange with the environment. In this regard, it provides improved opportunity for boosting up crop production, improving product quality and minimizes use of chemical for plant protection [13].

Mistriotis et al., [13] also depicted that, when the provision of mechanical ventilation is not possible due to energy and maintenance, natural ventilation is the cheapest way to regulate greenhouse indoor microclimate.

In Ethiopia, currently most growers are making use of natural ventilation for air exchange and to maintain the indoor climate.

To scrutinize and improve the indoor climate of the greenhouses and increase the yield per unit area, a tool or model which takes into account the influence of all the important design parameters on crop yield will be crucial.

According to Abdel-Ghany and Kozai [1] predicting state variables such as temperatures of air, plant, cover and soil, relative humidity, transpiration and evaporation based on either conducting experiments or simulation models essentially can help greenhouse designers to improve the greenhouse design to obtain an environment suitable for plant growth. In contrast to conducting experiments, simulation methods provide a quick, less expensive and more flexible and repeatable way provided that the model is reliable. In the past there have been various simulation or mathematical models developed that depend on the energy balance analysis. Principally, these simulation models were used to predict the greenhouse indoor climate as function of outdoor climate and parameters of the greenhouse elements.

Frausto and Pieters [8], Ganguly and Ghosh [9] explained that, greenhouse climate simulation models with high degree of complexity and lots of parameters that should be determined by calibration have been built in the past ten years.

Specifically concerning ventilation, some theoretical models were built to describe the air exchange in greenhouse. According to Mistriotis et al., [13], Okada and Takakura (1973) were the first to derive equation for the air exchange in the greenhouses, where, the ventilation rate is the sum of two terms; a term proportional to the outdoor wind speed and a term proportional to the square root of the temperature difference. Mistriotis et al., [13] also depicted that another model or approach was presented by Kozai et al., (1973), where natural ventilation in multi-span greenhouses was estimated on the basis of flow rate and pressure difference due to buoyancy or wind effect for one opening.

According to Bot, 1983; de Jong 1990; Boulard et al., 1996 as cited by Coelho et al. [5], knowledge of the physical principles of natrual ventialtion is very essenstial for the control of ventilation. Baptista et al., (1999, 2001) as cited by Coelho et al. [5], there are two main forces which are responsibe for pressure difference in natural ventilation. The first is wind, which causes an alteration of the pressure field around the buidling or obstacle, resulting positive or negative pressure differences. The second is thermal bouyancy or stack effect owing to the variation in indoor and outdoor temperatures and the consequential density gradient. Thus, movemtnt of air by natural convection can occur when the abovementioned two process combined.

A generic tool or a model built as an integral approach in Matlab software designed by Wageningen University and Plant Research International (PRI) was used in this study. The tool encompasses heat and mass balance equations which would enable to analyze greenhouse design parameters (cover properties, passive heating and cooling, ventilation area, soil properties). The model helps to execute sensitivity analysis of design parameter and simulation of indoor climate and dry matter harvest.

OBJECTIVE

The purpose of this study is to determine the effect of ventilation area on indoor climate, consequently on yield for the existing greenhouse configuration in the highland part of Ethiopia.

2 MATERIALS AND METHOD

2.1 ROSE VARIETY

The response of major rose varieties grown in Ethiopian highland to indoor climate such as temperature, RH%, light and CO_2 was reviewed so as to make set point. Accordingly, PAR requirement 700-900µmol/m^2/s [15], temperature requirement 17-25^{0}C [16] and relative humidity requirement 60-80% [12] were taken as best possible range at which the rose performs better.

2.2 THE MODEL

The body of model consists of three major components; state variables that vary with time (greenhouse air temperature, canopy temperature, soil temperature, vapor concentration of greenhouse air, greenhouse CO_2 concentration and total biomass), control inputs (shade screen, white wash and ventilation opening control) and external inputs (solar radiation, wind speed, outdoor temperature, outdoor air vapor concentration and outdoor air CO_2 concentration). The model output, particularly the state variables are in hourly values and thus the external inputs were in hourly basis. Consequently, hourly sky global radiation value was calculated and other external inputs except CO_2 were collected from Ethiopian meteorological agency. Outdoor CO_2 concentration was assumed to be constant that is 340ppm.

Matlab ode(15) was used to compute the energy and mass balance equations discussed below.

(A) ENERGY BALANCE IN GENERIC TOOL

According to Bot, (1983) as cited by El Ghoumari et al., [7] the dynamic behavior of state variables (temperature, humidity and CO_2) inside the greenhouse is governed by the energy and mass balances. Specifically, the energy balance which influences greenhouse temperature is affected by the energy input of the heating system, the energy losses caused by the energy exchange between the cover and the outside environment as well as through the natural ventilation provided by the windows, and finally the energy which comes out of the solar radiation.

The heat fluxes among different components within the greenhouse (cover, soil, crop and air) were introduced in the generic tool indicated in the equations below. Radiative and convective heat exchanges which occur among the components were described in the energy balances of the states.

ENERGY BALANCE FOR THE GREENHOUSE AIR TEMPERATURE

Greenhouse air temperature at different time instant has been computed on the basis of various equations which contain different convective heat fluxes as shown in eq.1.

$$Cap_{Air}\frac{dT_{Air}}{dt} = H_{canair} - H_{AirOut} - H_{Airflr} - H_{air\,cov} ....[Wm^{-2}] \quad (1)$$

ENERGY BALANCE FOR THE COVER TEMPERATURE

To compute the differential cover temperature at different time instant, near infrared and PAR components of the solar radiation, longwave radiation fluxes and convective heat fluxes among different bodies were listed out in the equation stated below (eq.2):

$$Cap_{\mathrm{cov}}\frac{dT_{\mathrm{cov}}}{dt} = R_{sun\,\mathrm{cov}} + H_{air\,\mathrm{cov}} + L_{air\,\mathrm{cov}} + R\_TIR_{can\,\mathrm{cov}} + R\_TIR_{flr\,\mathrm{cov}} - H_{\mathrm{cov}\,out} - R\_TIR_{\mathrm{cov}\,Ssy} ....[Wm^{-2}] \quad (2)$$

ENERGY BALANCE FOR THE CANOPY TEMPERATURE

Similar to cover temperature computation, the differential equation of canopy temperature comprises near infrared and PAR portion of solar radiation, longwave heat fluxes and convective heat fluxes among various greenhouse components indicated in the equation below (eq.3).

$$Cap_{can}\frac{dT_{can}}{dt} = R\_PAR_{suncan} + R\_NIR_{suncan} - H_{canair} - L_{canair} - R\_TIR_{can\cov} - R\_TIR_{canflr} - R\_TIR_{cansky} \ldots\ldots\ldots\ldots[Wm^{-2}] \quad (3)$$

ENERGY BALANCE FOR GREENHOUSE FLOOR TEMPERATURE

To calculate the greenhouse soil temperature at different time instant, in the same manner, near infrared and PAR portion of solar radiation, longwave heat fluxes and convective heat fluxes among greenhouse components were taken into account, described in the equation below (eq.4):

$$Cap_{flr}\frac{dT_{flr}}{dt} = R\_PAR_{sunflr} + R\_NIR_{sunflr} + H_{airflr} + R\_TIR_{canflr} - R\_TIR_{flr\cov} - H_{flrso1} - R\_TIR_{flrsky} \ldots\ldots\ldots[Wm^{-2}] \quad (4)$$

(B) VENTILATION FLUX

As discussed earlier, pressure difference between the external and internal air as consequence of wind action and buoyancy or stack effect are the main cause of natural ventilation [3], [4].

VENTILATION FLUX FOR ROOF OR SIDE OPENING ONLY

If a greenhouse is equipped with either roof or side opening only, ventilation fluxes is calculated making use of a mathematical equation stated below [14].

$$f_{vent} = \frac{A}{2}C_d\sqrt{2g(h/4)\frac{(T_{air} - T_{out})}{T_m} + C_w * V_{speed}^2} \ldots\ldots\ldots[m^3 m^{-2} s^{-1}] \quad (5)$$

(C) VAPOR BALANCE AND TRANSPIRATION

Vapor balance in the greenhouse should take into account crop transpiration, vapor loss due to ventilation and condensation on the cover. The, equation stated below (eq.6) was used to compute the vapor pressure in the greenhouse at different instant of time.

$$con\_VP_{air}\frac{dVP_{air}}{dt} = MV_{canair} - MV_{air\cov} - MV_{airout} \ldots\ldots\ldots\ldots[kg.m^{-3} s^{-1}] \quad (6)$$

Transpiration from the canopy is calculated based on the vapour pressure difference between the canopy and greenhouse air as stated below (eq.7):

$$MV_{canair} = VEC_{canair}(VP_{can} - VP_{air}) \ldots\ldots\ldots\ldots[kg.s^{-1}.m^{-2}] \quad (7)$$

(D) CARBON DIOXIDE BALANCE

Regarding carbon dioxide balance within the greenhouse, plants respiration and air exchange due to window ventilation affect carbon dioxide equilibrium [7].

Consequently, the following relationship was used to compute the greenhouse carbon dioxide concentration. In the generic tool, the carbon dioxide balance depends on the crop assimilation rate, respiration rate and flux through ventilation opening as stated in eq.8 below.

$$Gh\_h*\frac{dCO_{2air}}{dt}=MC_{crpair\_m}+MC_{crpair\_g}-MC_{aircrp}-MC_{airout}..[kgm^{-2}s^{-2}] \quad (8)$$

(E) GROSS PHOTOSYNTHESIS RATE FOR ROSE OR GROWTH MODEL

Obtaining a growth model which can fit the generic tool was investigated.

GENERIC TOOL GROWTH RATE CALCULATION APPROACH

The approach in generic tool to compute photosynthesis was performed by introducing inhibition factors for light and carbon dioxide. Here, the inhibition factors are introduced based on parameters p1 and p2 respectively as illustrated below. For each factor, these parameters are crop specific which would enable to fit the response of photosynthesis calculated by this approach with respect to response of rose to these factors obtained from literature, particularly the result of Kim and Leith [11]. That means the trend of the inhibition factors should at least be similar to the trend of photosynthesis versus these factors.

$$MC_{aircrp}=h\_R_{can}*h\_CO_{2air}*MC_{aircrp\_pot}.........[g(CO_2)m^{-2}hr^{-1}] \quad (9)$$

$$h\_R_{can}=\frac{R_{can}}{p1+R_{can}}..................................[-] \quad (10)$$

$$h\_CO_{2air}=\frac{CO_{2air}}{p2+CO_{2air}}.............................[-] \quad (11)$$

$$MC_{aircrp\_h}=h\_Tcan*h\_Tcan24*MC_{aircrp}............[g(CO_2)m^{-2}hr^{-1}] \quad (12)$$

$$\frac{dYield}{dt}=HI*\beta\_CO_2\_CH_2O*\beta\_CH_2O\_DM*(MCaircrp-MCcrpair)...........................[kg(DM)m^{-2}s^{-1}] \quad (13)$$

For temperature, a trapezoidal temperature filter was used for mean and instantaneous temperature of the canopy. The generic tool has these temperature inhibition factors based on the crop response to temperature, thus rose response to mean temperature and instantaneous temperature were considered as indicated in the figure 1**Erreur ! Source du renvoi introuvable.**. The inhibition factor ranges between one and zero, and when the temperature is in the optimal range, then the inhibition factor becomes one or there is no punishment. Otherwise there is a punishment when the temperature is out of the optimal range in both cases.

By taking into consideration MCaircrp_pot as canopy photosynthesis, it is possible to use this approach for this research work to compute net photosynthesis. And finally yield was calculated as harvested number of stems (eq.13).

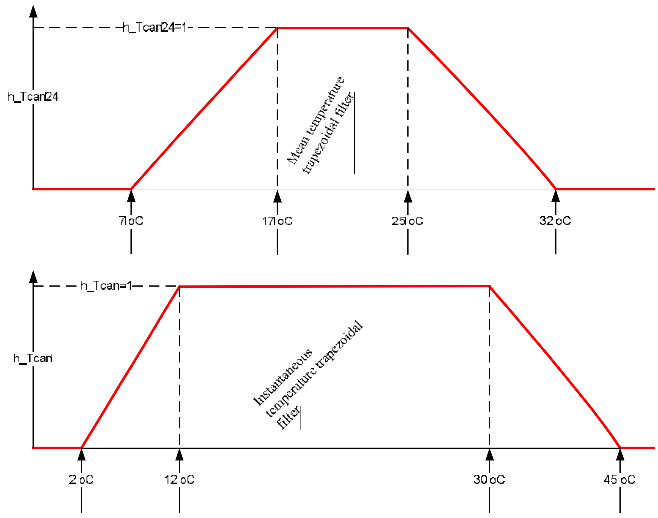

Fig. 1. Temperature growth inhibition factor computation method

(F) SENSITIVITY ANALYSIS FOR GREENHOUSE COVER PROPERTIES

In the sensitivity analysis, the extent of influence of ventilation area on rose yield was calculated. That is, small change in ventilation area and the resulting change in the state variables could be calculated.

In this analysis, the ventilation area of the existing Ethiopian greenhouse which is 60m^2 per 960m^2 was considered as nominal value, then the percent change in dry matter production when this design parameter increased by 1% was calculated.

According to van Henten (1994) as qouted by Vanthoor et al., [17], the relative sensitivity of dry yeil for a given design parameters is calculated as described below.

$$S_r(t) = \frac{Yield_{Pnom+\Delta p}(t) - Yield_{Pnom}(t)}{Yield_{Pnom}(t)} * \frac{P_{nom}}{\Delta P} \qquad (14)$$

$$\Delta P = h * P_{nom} \qquad (15)$$

Where, h is perturbation factor (0.01), $Yield_{Pnom}$ is the yield at nominal value of the design parameters, $Yield_{Pnom+\Delta P}$ is the increase in yield when the design parameter increased by 1 percent (h) and P_{nom} is the nominal value of the design parameters.

3 RESULT AND DISCUSSION

Before using the model for simulation and sensitivity analysis primarily validation was carried out. In the execution of model validation, as illustrated in figure 2, the difference between simulated and measured greenhouse air temperature is less significant.

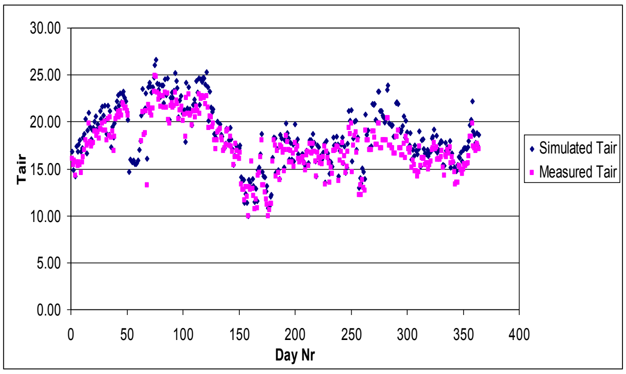

Fig. 2. Comparison of simulated and measured mean daily greenhouse temperature

3.1 SENSITIVITY ANALYSIS

According to the sensitivity analysis carried out, the influence of the parameter (ventilation area) on dry matter production during summer and winter is somehow different. As illustrated in the table 1 for summer season, a percent increment in ventilation area has negative influence or reduction on canopy (0.065%) and greenhouse air temperature (0.058%). However, greenhouse CO_2 concentration increased by 0.013% when the ventilation area increased by 1%. This due to the fact that since there is no external supply of CO_2, the greenhouse CO_2 concentration can be lowered as a result of photosynthesis during day time, even less than the outdoor CO_2 concentration, specifically for smaller ventilation opening area. As compared to the above climatic factors, ventilation opening area increment by 1% drastically reduces indoor vapor concentration by 0.114%. This could show that indoor vapor concentration is significantly higher than outdoor vapor concentration. Regarding yield, a percent increase in ventilation opening area resulted in 0.328% increment in dry matter harvest. This is owing to the fact that, higher ventilation opening area can alleviate higher temperature during day time and increases interior CO_2 concentration consequently the photosynthesis would become relatively better.

Similarly, sensitivity analysis for winter season showed that (table 2), increased ventilation opening by 1% reduces both canopy and indoor temperature and vapor concentration. On the contrary, indoor CO_2 concentration and dry matter harvest increased by 0.012% and 0.03% respectively.

Here, it is possible to see the significant difference between dry matter harvest increment during summer and winter. During summer season (dry season for almost 9-10 months), the increment in yield larger than winter season, this is due to the fact that high temperature problem during day time in summer season is noticeable and can be minimized by increased ventilation to enhance photosynthesis. Consider CO_2 increment and enhanced photosynthesis in both seasons is same, again concerning indoor temperature, since winter season (rainy season) is characterized by relatively lower outdoor temperature, increment in ventilation area can contribute to cooler indoor temperature which can inhibit photosynthesis, however, as seen in figure 3, 4 and 5, the influence of ventilation opening area on interior CO_2 concentration more considerable than on canopy and air temperature. Thus, it is justifiable to expect increment in dry matter harvest in winter which is mainly due to increased CO_2 concentration.

According to sensitivity analysis executed on yearly base or for one year (table 3), likewise winter and summer season, increased ventilation opening area by 1% resulted 0.057% and 0.054% lower in both canopy and indoor temperature respectively. However, dry matter harvest and indoor CO_2 concentration increased by 0.231% and 0.012% respectively for same reason as discussed above. Similarly, indoor vapor concentration significantly reduced by 0.102% as the opening area increased by 1% as compared to above interior climatic factors.

As discussed earlier, in the highland part of Ethiopia, botrytis is major problem in greenhouse cultivation due to high RH%, thus better ventilation can be an option to inhibit the reproduction of this disease.

3.2 SIMULATION OF STATE VARIABLES

Simulation of greenhouse indoor climate (Figure 3) showed that when the existing ventilation area three times higher, the influence on indoor temperature is somehow insignificant, nevertheless, extreme high temperature slightly can be reduced as consequence of the increased ventilation area. This is due to the fact that higher ventilation area allows better heat and mass exchange as explained by Mistriotis et al., [13]. To contrary, higher ventilation opening area exacerbates low temperature during night time very slightly.

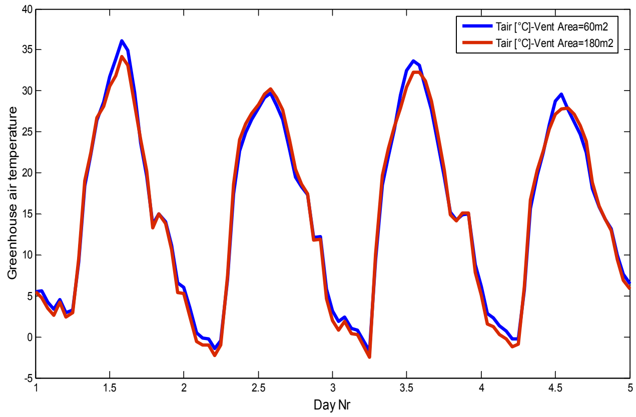

Fig. 3. The effect of ventilation area on greenhouse air temperature

Moreover, the simulation result for canopy temperature (Figure 4) showed that as compared to during night time extreme low temperature, day time high temperature can possibly be reduced when the ventilation area increase from the existing value 60m^{2}per span to 180m^2 per span.

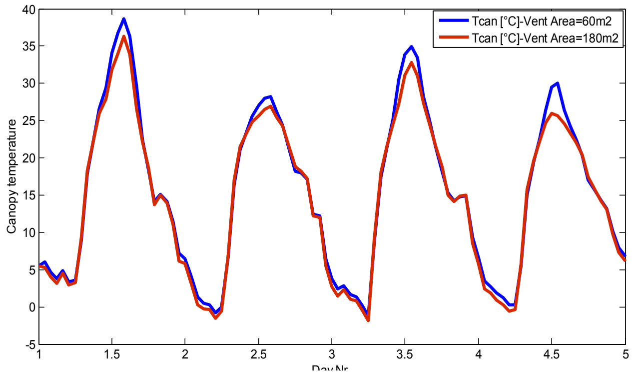

Fig. 4. The effect of ventilation area on canopy temperature

According to simulation output for indoor CO_2 concentration (Figure 5), when the ventilation area is tripled it has significant impact on the CO_2 greenhouse concentration particularly during day time. During day time, due to photosynthesis the indoor CO_2 gets very low as compared to the outdoor CO_2 concentration, thus, higher ventilation area would enable more CO_2 flux from outside to inside. To the contrary, during night time, owing to maintenance respiration, the CO_2 inside the greenhouse becomes higher provided that the ventilation opening is very small so that less possibility for the gas to escape to the environment. Hence as the graph illustrates, when the ventilation is relatively higher, night time indoor CO_2 concentration gets lower. It is possible to draw inference that for greenhouse with no external CO_2 supply or dependent on natural ventilation, it possible to maximize the production by closing the opening during night time to increase indoor CO_2 for photosynthesis for the subsequent day, however, care also should be taken to control RH% inside the greenhouse simultaneously.

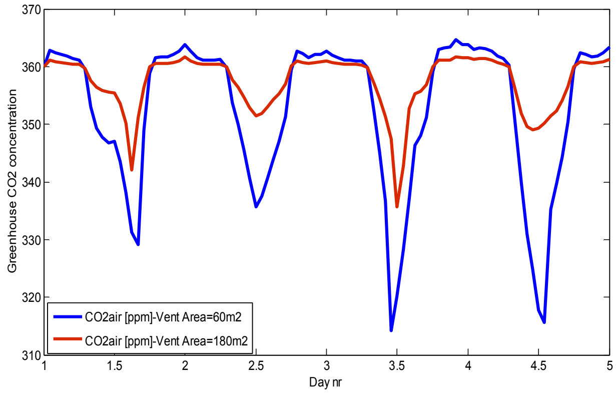

Fig. 5. The effect of ventilation area on greenhouse CO_2 concentration

Table 1. Integrated relative mean sensitivity analysis for summer season

States	Parameter
	Ventilation Area
Tcov	-0.034
Tair	-0.058
Tcan	-0.065
Tflr	-0.051
VPair	-0.114
CO_{2air}	0.013
DM_{harv}	0.328

Table 2. Integrated relative mean sensitivity analysis for winter season

States	Parameter
	Ventilation Area
Tcov	-0.021
Tair	-0.036
Tcan	-0.036
Tflr	-0.029
VPair	-0.075
CO2air	0.012
DM_{harv}	0.03

Table 3. Integrated relative mean sensitivity analysis for one year

States	Parameter
	Ventilation area
Tcov	-0.031
Tair	-0.054
Tcan	-0.057
Tflr	-0.045
VPair	-0.102
CO2air	0.012
DM_{harv}	0.231

4 CONCLUSION

The study revealed that increased ventilation opening area for Ethiopian highland greenhouse floriculture can contribute to the increased in yield due to the fact that significant improvement of indoor CO_2 concentration and minimizing higher day temperature particularly during the longer summer season.

However, increasing ventilation area should be associated with the rate of evapo-transpiration and cost of insect screen for larger openings.

Moreover, increase ventilation opening area can exacerbate low temperature during night time, specifically during winter season. Thus, rose growth model which takes into consideration night time temperature influence on yield is very crucial.

ACKNOWLEDGEMENT

I would like to thank Mr.Mesfin Benti, Mr.Mulugeta Kebede and Mr. Frew Abeba for their support, advice and courage during this work. Also I would like to extend my heartfelt gratitude to Dr. Mengistu Sime (PhD) and Dr.Boja Mekonen (PhD) for their valuable comments and support.

SYMBOLS AND ACRONYMS

Abbreviation/ symbol	*Description*	*Value*	*Unit*
β_CO_2_CH2O	Conversion factor from CO_2 to CH_2O	30/44	-
β_CH_2O_DM	Conversion factor from CH_2O to Dry matter	0.8	-
MCaircrp_h	Photosynthesis rate	-	kg(CO_2) m^{-2} s^{-1}
MCcrpair_m	Maintenance respiration rate		kg(CO_2) m^{-2} s^{-1}
tau_NIR	Cover near infrared transmissivity	0.87	-
tau_PAR	Cover PAR transmissivity	0.83	-
epsilon-covup	Cover long-wave emission coefficient	0.67	
A	Roof ventilation opening area	60	m^2
Cap_{Air}	Heat capacity of the air	10^3	J m^{-2} K^{-1}
Cap_{can}	Heat capacity of the canopy	$1.2*10^3$	J $m^{-2}K^{-1}$
Cap_{cov}	Heat capacity of the cover	$2.5*10^3$	J m^{-2} K^{-1}
Cd	Discharge coefficient	0.705	-
con_VP_{air}	Vapor pressure constant	-	kg.m^{-3}.J^{-1}
Cw	Global wind coefficient		-
DM_{harv}	Percent dry matter harvest	-	%
fvent	Ventilation flux	-	$m^3m^{-2}s^{-1}$
g	Acceleration due to gravity	9.8	m s^{-2}
h_CO_2air	Inhibition factor for CO2	-	-
h_Rcan	Inhibition factor for radiation	-	-
h_Tcan	Inhibition factor for temperature	-	-
h	vertical height of ventilation opening	6.2	m
Haircov	Sensible heat greenhouse air to cover	-	W m^{-2}
Hairflr	Sensible heat greenhouse air to the floor	-	W m^{-2}
Hairout	Sensible heat greenhouse air to the surrounding due to ventilation	-	W m^{-2}
Hcanair	Sensible heat canopy to air	-	W m^{-2}
Hcovout	Sensible heat cover to the surrounding	-	W m^{-2}
HEC	Convective heat exchange	-	$Wm^{-2}K^{-1}$
HECaircov	Convective heat exchange air to cover	-	$Wm^{-2}K^{-1}$
HECairflr	Convective heat exchange air to floor	-	$Wm^{-2}K^{-1}$
HECcanair	Convective heat exchange canopy to air	-	$Wm^{-2}K^{-1}$
Hflrsol	Sensible heat floor to soil	-	W m^{-2}
HI	Harvest Index	65	%
Laircov	Latent heat greenhouse air to cover	-	W m^{-2}

Mcaircrp	Crop CO_2 assimilation rate	-	kg (CO_2) $m^{-2}s^{-1}$
MCcrpair	Maintenance respiration		kg (CO_2) m^{-2} s^{-1}
Mcaircrp_pot	Potential crop CO_2 assimilation rate	-	kg $m^{-2}s^{-1}$
MVcanair	Vapor flux from canopy to air	-	kg.s^{-1}.m^{-2}
MVaircov	Vapor flux air to cover	-	g m^{-2} s^{-1}
PAR	Photosynthetic active radiation	-	µmole $m^{-2}s^{-1}$
NIR	Near Infrared	-	µmole $m^{-2}s^{-1}$
P1	Crop parameter for radiation inhibition	-	-
P2	Crop parameter for CO_2 inhibition	-	-
R_PARsunflr	PAR radiation sun to floor	-	Wm^{-2}
R_PARsuncan	PAR radiation sun to canopy	-	Wm^{-2}
R_NIRsunflr	Near infrared radiation sun to floor	-	Wm^{-2}
R_NIRsuncan	Near infrared radiation sun to canopy	-	Wm^{-2}
R_TIRcancov	Longwave radiation canopy to cover	-	W m^{-2}
R_TIRcanflr	Longwave radiation canopy to the soli	-	W m^{-2}
R_TIRcansky	Longwave radiation canopy to sky	-	W m^{-2}
R_TIRcovsky	Longwave radiation cover to sky	-	W m^{-2}
R_TIRflrcov	Longwave radiation the soil to the cover	-	W m^{-2}
R_TIRflrsky	Longwave radiation floor to sky	-	W m^{-2}
Tair	Greenhouse air temperature	-	^{o}C
Tcan	Canopy temperature	-	^{o}C
Tcov	Greenhouse cover temperature	-	^{o}C
Tflr	Floor temperature	-	^{o}C
Tm	Mean temperature	293	^{o}K
Tout	Surrounding temperature	-	^{o}C
Vspeed	Wind speed	-	m s^{-1}
VP_{can}	Vapor pressure on canpy	-	Pa
VP_{air}	Vapor pressure of greenhouse air	-	Pa
VEC_{canair}	Vapor exchange coefficient	-	kg.s^{-1}.Pa^{-1}.m^{-2}

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