# Evapotranspiration Models in Greenhouse

M.Sc. Thesis by Wan Fazilah Fazlil Ilahi

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# Preface

After completing this report, I could say that I had gained new knowledge and better understanding in the subject area. It is worthwhile spending the time to search for information and learn the topics related to the studied area.

Heartfelt thanks to Harm Boesveld for his invaluable guidance, steadfast support and encouragement. I would like to give special thanks to Dr. C. Stanghellini for the knowledge and help in understanding the subject area.

Finally and not less important, I would like to thank my family and friends for supporting me during the ups and down completing this thesis. I hope this thesis can be, apart of the last step achieving my MSc degree, will give a contribution to the subject area.

Wageningen, August 2009

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# Abstract

The expansion of greenhouse cultivation all over the world had lead to the need for reliable crop evapotranspiration (ETc) estimation to encounter better yield and crop quality, water scarcity and environmental aspects. There are various methods available to determine the rate of evapotranspiration (ET) in greenhouses. These methods calculate for the total amount of water lost through transpiration and evaporation.

In a greenhouse environment, protected crop ET is influenced by the energy balance of the whole system in a greenhouse and depends strongly on the greenhouse characteristics and on the climate control equipment. For different type of greenhouses, from high technology as such closed and controlled greenhouses to traditional plastic rain shelter greenhouses will require a reliable method to determine ET.

There are a lot of studies been done for the development of ET models and comparisons on what models best suit the protected crops and different types of greenhouses. In this literature study, different kind of ET models which are widely used in both practical and research areas are gathered and a distinction is made for the types of greenhouse, crops and greenhouse climate data.

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# 1 Introduction

Greenhouse cultivation is a steadily growing agricultural sector all over the world (Souza et al., 2002). The utilization of greenhouses, mainly for cultivation of vegetables and ornamental is undergoing transformation for modernization that gives the opportunity to improve yield. Greenhouses may range from low cost such as plastic greenhouses to more sophisticated greenhouses for example the glass and controlled greenhouses. This type of modern agriculture has many advantages especially for reducing the climatic hazards.

It is known that water is a major issue almost all part of the world especially for countries which have insufficient water source. With this great expansion of greenhouse cultivation, the need of proper irrigation management is important. Accurate estimations on the crop water requirement is needed to avoid the excess or deficit water application, with consequent impacts on nutrient availability for plants, soil salinity and groundwater contamination (Blanco and Folegatti, 2004). This can be done by using appropriate method to determine the crop evapotranspiration (ET).

ET includes two processes of evaporation and transpiration. In FAO 56 (Allen et al., 1998), it is explained that evaporation and transpiration occur simultaneously and is difficult to distinguish them. Almost 100% of ET is form evaporation from the sowing stage (when the crop is small) where else for full crop cover more than 90% of ET comes from transpiration.

There are a lot of literatures on methods to estimate ET in greenhouses. ET can be measured or estimated by direct or indirect methods. Most common direct method estimate ET from measurements with weighing lysimeters (Baille et al., 1992). This also include the evaporation measuring equipment, class A pan, reduced evaporation pan, Piche atmometer and modified atmometer (Blanco and Folegatti, 2004; Fernandes et al., 2003; Souza et al., 2002). Indirect method includes the measurement of net radiation, crop surface temperature and water vapour deficit. A lot of models had developed from these measurements to determine ET especially for the transpiration model for example Okuya (1988) and De Graaf models (Graaf, 1988).

In greenhouse analysis, estimation of ET has predominantly been conducted by using the Penman-Monteith model (Takakura et al., 2009). The current use of Penman-Monteith equation is to calculate ET for outdoor climates. However, a lot of research used the Penman–Monteith model for ET estimation in greenhouses. For example, Boulard (1997) in his research used the Penman-Monteith formulation to validate a tomato crop transpiration model. Pollet (2000) also used the application of the Penman-Monteith model to calculate the ET of head lettuce in glasshouse conditions.

Due to the fast development of greenhouse culture all around the world, the needs of information on how it affects ET in greenhouses has to be known and summarized. The existing models for ET calculation has to be studied to know whether it is reliable or not for greenhouse climate (hereafter, microclimate). A literature based study will be carried out to gather this scattered information and discuss the effectiveness of each model in different type of greenhouse climates based on previous studies.

## 1.1 Problem definition

Each type of greenhouse provides different microclimate which affects the physical process of the ET rate of a greenhouse canopy. Estimation on how much energy to be absorb by the plant depend a lot on the greenhouse characteristics (cladding material) and on the climate control equipment (shading screen, for system, heating, and ventilation). Therefore, reliable estimations for plant requirements must take these factors into account and come up with methods that connect between crop ET and the greenhouse climate.

With the expansion of greenhouse culture all over the world, this had lead to various ET models for ET estimation. Consequently, this leads to the demand for ET models which are appropriate and reliable for greenhouse conditions. This study consist reviews of models available in literatures and models developed by experts to estimate reliable ET.

## 1.2 Research objectives

The objectives for this research are listed below:

i) Identification of the existing ET models being used to calculate ET in greenhouses.

ii) To study and have a review of ET models that establishes reliable ET rates in greenhouse.

iii) Personal objective: to gain knowledge of irrigation principles that is related to greenhouse.

iv) Social objective: Identify the most appropriate way to calculate crop ET for proper irrigation management that could improve farmers' income by saving water and fertilizers sources. Also to have a healthier environment where water can be conserved.

v) Scientific objective: Contributing a review of the best option for estimating ET in greenhouses.

## 1.3 Research questions

Main research questions:
How does greenhouse conditions affect crop ET rate and what ET models best predict ET rate?

Sub research questions:
i) What ET models exist to calculate ET in greenhouse from previous researches?
ii) How does the ET models being categorized, either by the type of crops, greenhouse or climate conditions?
iii) What kind of data is required to calculate ET from the existing models?
iv) How the Penman-Monteith model related in the ET calculation in greenhouse?
v) What are the best options to calculate ET in greenhouse?
vi) What criteria does the ET model must have to be practically reliable?

# 2 Theory

## 2.1 Evapotranspiration

Evapotranspiration (ET) is the process which returns water to the atmosphere from surfaces. The rate and amount of ET is the core information needed to design irrigation projects, and is also essential for managing water quality and other environmental concerns. ET can be divided into two sub-processes: evaporation and transpiration.

Evaporation occurs on the surfaces of open water such as reservoirs, puddles or from vegetation, soil and ground surfaces. Where else transpiration involves the removal of water from the soil by plant roots, transport of the water through the plant into the leaf, and evaporation of the water from the leaf's interior into the surface (Ward and Elliot, 1995).

### 2.1.1 Evapotranspiration from soil and plants

According to FAO 56, evaporation and transpiration occur simultaneously and there is no easy way of distinguishing between the two processes (Allen et al., 1998). The driving factor of evaporation from a crop soil is mainly determined by the fraction of the solar radiation reaching the soil surface besides temperature, wind velocity, and vapour pressure gradients. As crop start to develop, the fraction of solar radiation will decrease as the canopy shades the soil surface. Allen et al. (1998) explained that when the crop is small, water is predominately lost by soil evaporation, but once the crop is well developed and covered the soil, transpiration is the main process. Therefore, ET process depend on the crop stages where early stages (sowing) ET comes from evaporation, and when crop develop both evaporation and especially transpiration has more influence in ET rate.

Transpiration is defined by Kramer (1983) as the loss of water from plants in the form of vapour. The removal of water occurs through stomata which are the small openings on the plant leaf. Vaporization occurs when water and some nutrients is taken up by roots and transported through the plant to the intercellular spaces in the leaf. Here the vapour exchange with the atmosphere is controlled by the stomata aperture. Once some water is evaporated from the stomata, more water moves in the cellular spaces to replace the loss. The evaporation process initiates the pull of water from the roots through the xylem (plant tissue that transport water to leaf) and out from the leaves.

Like evaporation, transpiration also depends on the solar radiation, temperature, wind and vapour pressure gradient. The transpiration rate is also influenced by crop characteristics, environmental aspects and cultivation practices. Different kinds of plants may have different transpiration rates.

### 2.1.2 Potential evapotranspiration

Potential evapotranspiration or PE is a measure of the ability of the atmosphere to remove water from the surface through the processes of evaporation and transpiration assuming no control on water supply (Pidwirny, 2006). ET are complex processes because the rate of water vapour loss depends on many factors such as the amount of solar radiation reaching the surface, amount of wind, the aperture of the stomata, soil water content, soil type and the type of plant. Realizing this, Ward and Elliot (1995) in their book mentioned that most researchers have attempted to remove all unknowns such as aperture of the stomata, soil water content, and focus only the climatic factors in order to simplify the situation. The simplified calculation was termed also as PE. The rate of PE depends primarily on atmospheric conditions including the sun radiation and wind.

One example of the simplified calculation was defined by Penman (1956) as the amount of water transpired in unit time by a short green crop, completely shading the ground, of uniform height and never short of water. The conditions defined by Penman theoretically provide the maximum EP rate based on the given climatic conditions only.

### 2.1.3 Reference evapotranspiration

Reference crop evapotranspiration, $ET_o$ is the ET rate from reference surface of a hypothetical grass reference crop with specific characteristics. The crop is assumed to be well watered with a full canopy cover. Moreover $ET_o$ is a climatic parameter expressing the evaporation power of the atmosphere. The Penman-Monteith (equation1) method is recommended to calculate $ET_o$.

$$\boxed{\lambda ET = \frac{\Delta(R_n - G) + \rho_a c_p \frac{(e_s - e_a)}{r_a}}{\Delta + \gamma\left(1 + \frac{r_s}{r_a}\right)}}$$

**Equation 1: Penman-Monteith equation**

In the equation, $\lambda$ is latent heat of vaporization, $\Delta$ is the slope of the vapour pressure temperature relationship, $R_n$ is net radiation, $\rho_a$ is air density, $C_p$ is the specific heat of dry air, $e_s$ is saturation vapor pressure, $e_a$ is actual vapor pressure of the air, $r_a$ is aerodynamic resistance, $r_s$ is bulk surface resistance and $\gamma$ is psychomotor constant.

### 2.1.4 Actual evapotranspiration

Actual evapotranspiration, AE is the quantity of water that is actually removed from a surface due to the process of evaporation and transpiration (Pidwirny, 2006). It is the rate of ET where its value has the interest of all researchers. AE is also known as crop evapotranspiration, $ET_c$. In FAO 56 (Allen et al., 1998), $ET_c$ is the ET from the normal well planted crops. The water loss from ET is the amount of water required to the crop. $ET_c$ can be found by multiplying $ET_o$ with crop coefficients ($K_c$). $K_c$ is crop specific ET values which incorporates crop characteristics and averaged effects of evaporation from the soil (Allen et al., 1998).

## 2.2 Evapotranspiration in greenhouse

In greenhouse cultivation, crop transpiration is the most important energy dissipation mechanisms that influence ET rate. ET in a greenhouse includes the energy balance of net radiation from the sun, transfer of heat and vapour from a canopy. Most physically-based models that are based on energy balances typically provide a more comprehensive estimate of transpiration (Prenger et al., 2001). Bot (1989) described that the important parts of the greenhouse which are effect the energy balances are the greenhouse cover, greenhouse air, crop and soil.

### 2.2.1 Greenhouse energy balance variables

**Solar radiation**

The solar radiation can be divided into direct radiation which is originating from the sun and diffuse radiation which is scattered in the atmosphere by the clouds. The solar energy flux at earth level is within the wavelength region between 300 and 2500 nm. For plant growth the wavelength of interest is between 400 and 700 nm. This region of spectrum is called photosynthetic active radiation (PAR). Only a small part of the PAR energy is absorbed by the crop and is directly converted into the photosynthesis process where else the remainder in converted into heat.

The interaction of the greenhouse cover with both direct and diffuse solar radiation determines how much radiation is transmitted and available at crop level. This can be determined by the optical laws of reflection, absorption and transmission of the greenhouse cover material. For this purpose, the optical properties of the cover and construction, the angle of incoming radiation and the geometry of the construction have to be known. For direct component of solar radiation, Bot (1989) distinguish the angle follows from the solar position determined by the time, date and the latitude of the observed greenhouse and by the orientation and geometry of the surfaces. For the diffuse radiation it follows from the distribution of the radiation intensity over the hemisphere which differs for various meteorological conditions especially for a clear and cloudy sky.

## Heat exchange

The transport of energy by a flow from one place to the other in the direction of flow and the transport from a surface to a flowing medium or vice-versa are called convection. Exchange of greenhouse air with the internal surfaces such as cover, crop, heating pipes and soil surface is by convection. The same mechanism holds for the exchange between the outer surface of the greenhouse and the ambient air. Convective heat transfers determine a large part of the micro climate inside a greenhouse (Tadj et al., 2007).

The greenhouse cover exchanges energy at the inner surface to the greenhouse air and to outside air. Natural convection is expected inside the greenhouse due to low local air velocities generated by the existing temperature differences while outside the greenhouse, forced convection is expected due to local air velocities generated by the wind field. The convective heat exchange is defined by:

$$\boxed{qcnv = \alpha_h A_s (T_a - T_s)}$$

**Equation 2: Convective heat exchange equation**

Where $T_a$ and $T_s$ are the ambient air and cover surface temperature (K), $A_s$ is the surface area and $\alpha_h$ is the heat transfer coefficient (W $m^{-2}$ $K^{-1}$). The heat transfer coefficient is dependent on fluid properties and system parameters for a particular geometry of the cover. Bot (1983) had measured the convective heat transfer to and from the greenhouse cover also the flow field over the cover which yielded to natural convection relations for the heat transfer at the inside and outside surfaces of the cover for low wind speeds up to 3 ms-1. At higher wind speeds forced convection has been found outside.

Crop is a major solar energy in greenhouse cultivation. The energy is later converted into latent and sensible heat. This latent and sensible heat is transported to the greenhouse by convection. Therefore, the energy balance of a crop is from the absorption of solar radiation particularly the photosynthetic active radiation (PAR), the exchanged sensible and latent heat and the thermal radiative exchange with the various greenhouse parts.

For controlled greenhouse with heating pipes, the heat transfer between pipes and the air is also by convection. The important criteria determining the convective exchange are the length and diameter of the pipe. In the energy balance of the various greenhouse parts, the exchange with the soil is of minor importance due to the relatively small measurement on daily basis (Allen et al., 1998). However, the soil surface exchanges thermal radiation with the other greenhouse components.

### Vapour balance

In the greenhouse environment, crop transpiration is the main source of vapour besides evaporation from a wet surface. Vapour removal takes place through both condensation and ventilation, so that the following balance equation holds:

$$\boxed{E - C - V = 0}$$

**Equation 3: Vapour balance equation**

Where E is the crop transpiration, C and V is the vapour removed by condensation and ventilation respectively. The amount of water vapour contained in a parcel of air depends a lot on the temperature of the greenhouse air. Relative humidity and vapour pressure deficit quantify the “drying power” of air that is the amount of vapour that air at a given temperature is able to absorb. The temperature when vapour starts to saturating is called dew point which is also a measurement of humidity.

## 2.3 Types of greenhouse

Greenhouse types depend much on the structure, construction method and material, facilities and equipment made for the greenhouse. In central and northern Europe most greenhouses are glass covered where else in warmer climates the majority of the greenhouses are covered with plastic film (Lin, 2001). Globally, the plastic film greenhouses are more than glass greenhouses which have been readily adopted on all five continents, especially in the Mediterranean region, China and Japan (Jensen and Malter, 1995).

The common greenhouse types are venlo-type, wide-span, plastic, and arched greenhouse. The shape of the greenhouse structure influences the internal climate of the greenhouse environment especially on temperature, humidity and light transmission. The shapes that appear most frequently are gable roof or pitched roof, saw tooth or shed roof, round arched tunnel, round arch with vertical side wall, pointed arch wit sloping side wall and pointed arch with vertical side wall.

Construction materials used for greenhouse are wood, steel, aluminium and some even have combinations of these materials. For cladding materials, the common used are glass, synthetic panes which is also called rigid plastics and plastic film.

The facilities and equipments used inside a greenhouse can classify the greenhouse as a controlled environment greenhouse or not. These equipments include heating equipment, ventilation and cooling, screens, carbon dioxide ($CO_2$) enrichment and supplementary lighting. Heating equipment is required in a greenhouse when low temperatures inside the greenhouse are too low for crop production (Evans, 2005). The heating system will provide heat energy to maintain optimal temperatures within the greenhouse. Ventilation and cooling are most needed when the temperature and humidity inside the greenhouse is high.

Two types of ventilation are exist either through natural or forced ventilation (Breuer and Knies, 1995). The natural ventilation is by wind effects through ventilation window openings where else force ventilation uses fans as a source for wind. Cooling systems are provided either by direct evaporative cooling or indirect evaporative cooling. Direct evaporative cooling systems are based on the principle of cooling greenhouse by the evaporation of water. The common equipments are fan and pad cooling, fog cooling and roof cooling. A system which combines the evaporative cooling and mechanical cooling (removal of sensible and latent heat) is called indirect evaporative cooling. Screens are used to black out and shading for energy saving and environmental control. Depending on the screen materials, it can give large impact on the energy balance of the greenhouse through the reduction of ventilation, infra-red radiation and convection.

Supply of extra $CO_2$ is applied to increase the yield of greenhouse crops. This extra supply can be achieved by supplying pure liquid $CO_2$ or combustion of fossil fuel with small burners in the greenhouse. On the other hand, supplementary lighting in greenhouse is use for supplementing daylight in greenhouse to increase the irradiance level for photosynthesis. This application can also increase day length for the growth of the crops especially for the first phase growing young plants (example roses and cut chrysanthemums).

Greenhouses are a technology based investment. The higher the level of technology used the greater potential for achieving controlled growing conditions. To find the best estimation of ET method or model in a greenhouse, three categories of greenhouse types are define here according to their technology.

### 2.3.1 Low technology greenhouses

Greenhouses under this category use simple and low technology structure. These greenhouses may be less than 3 meters in total height especially for tunnel or igloos type of greenhouse (Annon., 2005). The tunnel greenhouses generally consist of bent trusses (hoops) which are screwed to the ground by means of screw anchors or cast in concrete (Bakker et al., 1995). The frame structure is made from wood, bamboo sticks or steel. They do not have vertical walls and have poor ventilation, mainly passive ventilation. This type of structure is relatively inexpensive and easy to build. Automation equipments are rarely used in this greenhouse.

According to Togani and Pardossi (1999), the internal climate of the low technology greenhouse is strongly dependent on external conditions. Plastic greenhouses with low technology of the structure are likely susceptible to damage which mainly cause by wind. Moreover, the crop production is limited by the growing environment which restricts yields and does little to reduce the incidence of pests and diseases (Annon., 2005).

### 2.3.2 Medium technology greenhouses

Medium technology greenhouses are better in structure as compared to the low technology greenhouses where the supporting structure is galvanized iron and aluminium (Togani and Pardossi, 1999). They are typically characterized by vertical walls more than 2m but les than 4 meters tall and a total height usually less than 5.5 meters (Annon., 2005). Medium level greenhouses are usually clad with either single or double skin plastic film or glass and use varying degrees of automation.

This type of greenhouse is closer to the low technology greenhouse in terms of the internal technology, but closer to the high technology greenhouse in terms of internal climate control (Togani and Pardossi, 1999). This may be due to the use of facilities and equipments for better growth environment. Production in medium level greenhouses can be more efficient than field production.

### 2.3.3 High technology greenhouses

The most sophisticated structures belong to this category. They contain galvanized iron support structures, aluminium glass supports, and almost always use glass as a covering material (Togani and Pardossi, 1999). The wall construction height is at least 4 meters, with the roof peak being up to 8 meters above ground level (Annon., 2005). These high technology structures can provide optimum growth environment through climate control. Air movement (ventilation), temperature and incident light in the greenhouse can be controlled by various facilities and equipments. These equipments are normally controlled and regulated by an information system.

Due to the sophisticated structures and facilities, the greenhouse cultivation is only profitable under high productivity. They are normally limited to industrial areas where production is high. However, with the use of high level technology greenhouses, the dependency on labour work can be reduce, thus reduce the cost for production.

# 3 Evapotranspiration models in greenhouse

Accurate estimation of ET rate in greenhouse is a key parameter in the water management for greenhouse cultivation. Indirect measurement of ET in greenhouse is a method of calculating ET using microclimate data. Despite the abundance of transpiration models available in the literatures (Graaf, 1988; Hamer, 1998; Jolliet, 1994; Okuya and Okuya, 1988), it was found more reasonable to study the ET models as it accounts both evaporation and transpiration processes in a greenhouse environment. Moreover, distinguishing both the process is difficult as their occur simultaneously (Allen et al., 1998). Realizing this, the most widely used ET models in greenhouse will be studied. Table 1 lists ten ET models that arise most in literatures and relevant to be applied for the greenhouse condition.

**Table 1: Different types of ET models used in the study**

| ET models | Classification | |
|---|---|---|
| FAO Penman | Combination method based on energy balance | Physical model |
| FAO Penman-Monteith | Combination method based on energy balance | Physical model |
| Stanghellini | Combination method based on energy balance | Physical model |
| Fynn | Combination method based on energy balance | Physical model |
| Penman-Monteith Screen-house | Simplified model from Penman-Monteith | Physical model |
| Energy Balance equation | Energy balance | Physical model |
| FAO Radiation | Radiation based | Empirical model |
| Priestley Taylor | Radiation based | Empirical model |
| Hargreaves | Radiation-temperature based | Empirical model |
| Simplified model | Simplified model from Penman-Monteith | Empirical model |

There are two approaches to estimate ET indirectly from either empirical models or physically based models. ET models listed in table 1 are some physically based models that are based on energy balances and combination of different theories. Others are empirical based models which primarily account for solar radiation, temperature and relative humidity only (Kashyap and Panda, 2001). According to Prenger et al. (2001) empirical models are usually developed for a specific region during a specific time period which may not always be accurately for other time periods and regions.

In order to have correct calculations of the actual ET rate, the reference ET ($ET_o$) calculated from the models must be multiplied with the crop coefficient ($K_c$).

## 3.1 FAO Penman model

Penman in 1948 was the first to develop the combination method for computing evaporation (Singh and Yadava, 2003). He combined the components to account for the energy required to sustain evaporation and a mechanism required to remove the vapour. The FAO Penman model is an improved Penman model in which the wind function is more sensitive than that used originally by Penman in 1948 (Kashyap and Panda, 2001). The Penman equation is given as:

$$ET_o = \frac{1}{\lambda}\left[\left[\frac{\Delta}{\Delta+\gamma}\right](R_n - G) + \left[\frac{\gamma}{\Delta+\gamma}\right](6.43)(W_f)(VPD)\right]$$

$$W_f = 1 + 0.0536\, u_z$$

**Equation 4: FAO Penman equation**

Where,

| | |
|---|---|
| $\lambda$ | Latent heat of vaporization (MJ $kg^{-1}$) |
| $R_n$ | Net radiation at the crop surface (MJ $m^{-2}$ $day^{-1}$) |
| G | Soil heat flux density (MJ $m^{-2}$ $day^{-1}$) |
| $\Delta$ | Slope vapour pressure curve (kPa °$C^{-1}$) |
| $\gamma$ | Psychrometric constant (kPa °$C^{-1}$) |
| $W_f$ | Wind function |
| VPD | Vapour pressure deficit (kPa) |
| $u_z$ | Wind speed at z (m )height |

## 3.2 FAO Penman-Monteith model

FAO Penman-Monteith (Allen et al., 1998) simulates a reference crop of 0.12 meter in height, with a surface resistance of 70 $sm^{-1}$ and an albedo of 0.23. This method estimates evaporation from an extensive surface of green grass cover of uniform height, actively growing, completely shading the ground and under non-limited soil water. The Penman-Monteith equation for the calculation of daily $ET_o$ (mm $day^{-1}$) is as follow:

$$ET_o = \frac{0.408\,\Delta\,(R_n - G) + \gamma\,\frac{900}{T+273}\,u_2\,(e_s - e_a)}{\Delta + \gamma\,(1+0.34\,u_2)}$$

**Equation 5: Penman-Monteith equation**

Where,

| | |
|---|---|
| $ET_o$ | Reference evapotranspiration (mm day$^{-1}$) |
| $R_n$ | Net radiation at the crop surface (MJ m$^{-2}$ day$^{-1}$) |
| G | Soil heat flux density (MJ m$^{-2}$ day$^{-1}$) |
| T | Mean daily air temperature at 2 meter height (°C) |
| $u_2$ | Wind speed at 2 meter height (m s$^{-1}$) |
| $e_s$ | Saturation vapour pressure (kPa) |
| $e_a$ | Actual vapour pressure (kPa) |
| $e_s - e_a$ | Saturation vapour pressure deficit, VPD (kPa) |
| $\Delta$ | Slope vapour pressure curve (kPa °C$^{-1}$) |
| $\gamma$ | Psychrometric constant (kPa °C$^{-1}$) |

## 3.3 FAO Radiation model

The FAO radiation model (Doorenboss and Pruitt, 1975) is based on solar radiation. Equation 5 below was taken from Liu et al. (2008):

$$ET_o = b \left[ \frac{R_s}{\lambda} \frac{\Delta}{\Delta + \gamma} \right] - 0.3$$

$$b = 1.066 - 0.13 \times 10^{-2}\, RH + 0.045\, U_d - 0.20 \times 10^{-3}\, RH \times U_d - 0.315 \times 10^{-4}\, RH^2 - 0.11 \times 10^{-2}\, U_d^2$$

**Equation 6: FAO - Radiation equation**

Where,

| | |
|---|---|
| $R_s$ | Solar radiation (cal cm$^{-2}$ day$^{-1}$) |
| $\lambda$ | Latent heat of vaporization (MJ kg$^{-1}$) |
| $\Delta$ | Slope vapour pressure curve (kPa °C$^{-1}$) |
| $\gamma$ | Psychrometric constant (kPa °C$^{-1}$) |
| b | Dimensionless parameter |
| RH | Relative humidity |
| $U_d$ | Mean daytime wind speed (ms$^{-1}$) |

In the greenhouse, wind speed is relatively small based on the air speed measurements inside a greenhouse measured by Teitel et al. (2008). The measured wind speed was below 5 ms$^{-1}$.

## 3.4 Priestley Taylor model

Priestley and Taylor (1972) developed a model to calculate ET using net radiation and soil heat flux. He assumed that there is no or low advection which is the transport of energy and mass by a flow from one place to the other in the direction of flow. The equation is given as:

$$ET_o = \frac{1}{\lambda} \alpha \frac{\Delta}{\Delta + \gamma} (R_n - G)$$

**Equation 7: Priestley Taylor equation**

Where,

| | |
|---|---|
| $\lambda$ | Latent heat of vaporization ($MJ\ kg^{-1}$) |
| $R_n$ | Net radiation at the crop surface ($MJ\ m^{-2}\ day^{-1}$) |
| $G$ | Soil heat flux density ($MJ\ m^{-2}\ day^{-1}$) |
| $\Delta$ | Slope vapour pressure curve ($kPa\ °C^{-1}$) |
| $\gamma$ | Psychrometric constant ($kPa\ °C^{-1}$) |
| $\alpha$ | Empirical coefficient of 1.26 (Kashyap and Panda, 2001; Liu et al., 2008) |

## 3.5 Hargreaves model

The 1985 Hargreaves $ET_o$ (Hargreaves et al., 1985) model requires only measured temperature data which is simple and less impact than other models (Hargreaves et al., 2003). This model can be used as an alternative when solar radiation data, relative humidity data or wind speed data are unavailable (Allen et al., 1998). The Hargreaves temperature based method is given by the following equation:

$$ET_o = \frac{1}{\lambda}(0.0023)(T_{mean} + 17.8)(T_{max} - T_{min})^{0.5} R_a$$

**Equation 8: Hargreaves equation**

Where,

| | |
|---|---|
| $\lambda$ | Latent heat of vaporization ($MJ\ kg^{-1}$) |
| $R_a$ | Extra-terrestrial solar radiation ($MJ\ m^{-2}\ day^{-1}$) |
| $T_{max}$ | Maximum daily air temperature (°C) |
| $T_{min}$ | Minimum daily air temperature (°C) |
| $T_{mean}$ | Mean daily air temperature (°C) |

## 3.6 Stanghellini model

Stanghellini model (1987) is a revised model of Penman-Monteith which represent conditions in a greenhouse where air velocities are typically low (less than 1 m $s^{-1}$). The combination equation of Stanghellini model includes the internal and external resistance terms as well as a more complex calculation of the solar radiation heat flux derived from the empirical characteristics of short wave and long wave radiation absorption in a multi layer canopy.

The estimation of $ET_o$ was done using a well developed tomato crop which was grown in a single glass, Venlo-type greenhouse with hot water pipe heating. The calculation of the solar radiation flux included the contribution of radiation from the greenhouse components: heating pipes, soil covering and cladding. These were combined into the "temperature of ambient air" ($T_h$) as described by Stanghellini (1987). Furthermore Stanghellini used the leaf are index (LAI) to account for energy exchange from multiple layers of leaves on greenhouse plants. The equation for hourly $ET_o$ (mm $h^{-1}$) is derived from the form published in Donatelli et al. (2006) and Prenger et al. (2002).

$$ET = 2\,LAI\,\frac{1}{\lambda}\left(\frac{s\,(R_n - G) + K_t\left(\dfrac{VPD\,\rho\,C_p}{r_R}\right)}{s + \gamma\left(1 + r_c / r_a\right)}\right)$$

$$Rn = \frac{0.07\,R_{ns} - 252\,\rho\,C_p\,(T - T_o)}{r_R}\quad,\ R_{ns} = 0.77\,R_s$$

$$r_R = \frac{\rho\,C_p}{4\,\sigma\,(T + 273.15)^3}$$

**Equation 9: Stanghellini equation**

Where,

| | |
|---|---|
| $ET_o$ | Reference evapotranspiration (mm $day^{-1}$) |
| $R_n$ | Net radiation at the crop surface (MJ $m^{-2}$ $day^{-1}$) |
| G | Soil heat flux density (MJ $m^{-2}$ $day^{-1}$) |
| $K_t$ | Unit conversion factor equal to 3600 s $h^{-1}$ |
| VPD | Daily or hourly vapour pressure deficit (kPa) |
| $\rho$ | Mean atmospheric density (kg $m^{-3}$) |
| $C_p$ | Specific heat of the air (MJ $kg^{-1}$ °$C^{-1}$) |
| $r_R$ | Radiative resistance (s $m^{-1}$) |
| $r_c$ | Canopy resistance (s $m^{-1}$) |

| | |
|---|---|
| $r_a$ | Aerodynamic resistance (s $m^{-1}$) |
| $\lambda$ | Latent heat of vaporization (MJ $kg^{-1}$) |
| s | Slope of the saturation vapour pressure curve (kPa °$C^{-1}$) |
| $\gamma$ | Psychrometric constant (kPa °$C^{-1}$) |
| $R_{ns}$ | Net short wave radiation (MJ $m^2$ $day^{-1}$) |
| $R_s$ | Ground level solar radiation (MJ $m^2$ $day^{-1}$ |
| T | Hourly or daily mean air temperature (°C) |
| $T_o$ | Leaf temperature (°C) |
| $\sigma$ | Stefan-Boltzman constant (MJ $m^{-2}$ $K^{-4}$ $day^{-1}$) |
| LAI | Leaf area index ($m^2$ $m^{-2}$) |

## 3.7 Fynn model

Another ET model was derived by Fynn (1993) to achieve a combination equation for ET in a greenhouse. His derivation was similar to Stanghellini's, however he did not include Stanghellini's solar radiation heat flux calculation. Fynn (1993) assumed that the air and leaf temperatures were equal, thus simplifying the measurements required. The Fynn equation is also different because it modifies only the vapour pressure term with the LAI since water vapour exchange occurs at all layers of the canopy, while the irradiative energy only occurs in the top most layer. The equation as published in Fynn (1993) and Kirnak et al. (2002) is as follow:

$$ET = \frac{2\ LAI\ \rho\ C_p\ (e_a^* - e_a) / r_e + \delta\ (R_n - G)}{\lambda\ \gamma\ r_i}$$

**Equation 10: Fynn equation**

Where,

| | |
|---|---|
| $R_n$ | Net radiation at the crop surface (J $m^{-2}$ $s^{-1}$) |
| G | Soil heat flux density (J $m^{-2}$ $s^{-1}$) |
| $\rho$ | Mean atmospheric density (kg $m^{-3}$) |
| $C_p$ | Specific heat of the air (J $kg^{-1}$ °$C^{-1}$) |
| $e_a^*$ | Saturation vapour pressure at mean air temperature (Pa) |
| $e_a$ | Vapour pressure of the air (Pa) |
| $\lambda$ | Latent heat of vaporization (J $kg^{-1}$) |
| $\gamma$ | Psychrometric constant (Pa °$C^{-1}$) |
| $r_e$ | External resistance of canopy to sensible heat (s $m^{-1}$) |
| $r_i$ | Internal resistance of canopy to vapour transfer (s $m^{-1}$) |
| LAI | Leaf area index ($m^2$ $m^{-2}$) |

## 3.8 Energy balance equation

Takakura et al. (2005) first derived a simple heat balance equation for the plant canopy model from the Penman-Monteith equation to estimate ET from a plant canopy. Incoming radiation downward and upward, air temperature and wind speed above the canopy are the only four factors to be measured by the equation. Takakura et al. (2009) later used this energy balance equation to estimate ET in a greenhouse condition and developed an instrument for the measurement of the ET. The method used by Takakura is simpler than Penman-Monteith equation. Thus, ET rate per unit greenhouse floor area can be calculated from the following equation (Takakura et al., 2009):

$$\boxed{E = \frac{R_n - h\,(T - T_w) - G}{l}}$$

**Equation 11: Energy balance equation**

Where,

| | |
|---|---|
| $E$ | Evapotranspiration (kg $m^{-2}$ $h^{-1}$) |
| $R_n$ | Net radiation over the canopy (kJ $m^{-2}$ $h^{-1}$) |
| $h$ | Coefficient of the convective heat transfer (kJ $m^{-2}$ $h^{-1}$ $K^{-1}$) |
| $T$ | Air temperature (°C) |
| $T_w$ | Surface temperature (°C ) |
| $G$ | Heat flux to the ground ( kJ $m^{-2}$ $h^{-1}$) |
| $l$ | Heat due to vaporization (kJ $kg^{-1}$) |

The heat transfer coefficient in equation 11 is the sensible heat transfer term. According to Takakura and Fang (2002), the heat transfer coefficient for outside conditions was a function of wind speed, but inside the greenhouse, it was shown that a constant of 7 W m $m^{-2}$ $°C^{-1}$ can be used as an average value.

## 3.9 Simplified model

Baille et al. (1994) did a simplified model for predicting ET rate for nine greenhouse ornamental species with the use of indoor climate (solar radiation and vapour pressure deficit) and leaf area index. He proposed a correlation to these factors based on the formalism of the Penman-Monteith equation. The proposed equation is as follow:

$$E = A f_1(L)\,G + B f_2(L)\,D$$

$$f_1 = 1 - \exp(-\alpha L)$$
$$f_2 = L$$

$$A = \frac{\Delta}{\Delta + \gamma^*} \qquad B = \frac{1}{\lambda}\left[\frac{3.6 \times 10^3 \rho C_p / r_a}{\Delta + \gamma^*}\right]$$

**Equation 12: Proposed simplified model by Baille et. al (1994)**

Where,

| | |
|---|---|
| E | Crop evapotranspiration rate (kg $m^{-2}$ $h^{-1}$) |
| G | Inside solar radiation (kg $m^{-2}$ $h^{-1}$) |
| D | Inside air vapour pressure deficit (kPa) |
| L | Leaf area index |
| $f_1$, $f_2$ | Dimensionless functions of L |
| A | Values of model parameter (dimensionless) |
| B | Values of model parameter (kg $m^{-2}$ $h^{-1}$ $kPa^{-1}$) |
| $\alpha$ | Leaf angle distribution (0.64 from Stanghellini (1987)) |
| $\Delta$ | Slope of the saturated vapour pressure-temperature curve (kPa $K^{-1}$) |
| $\gamma^*$ | $\gamma^* = (1 + r_s/r_b)$, $\gamma$ is the psychometric constant (kPa $K^{-1}$), $r_b$ is canopy boundary layer resistance ($sm^{-1}$), $r_s$ is canopy surface resistance ($sm^{-1}$) |
| $\lambda$ | Latent heat of vaporization (J $kg^{-1}$) |
| $\rho$ | Density of air (kg $m^{-3}$) |
| $C_p$ | Specific heat of air (J $kg^{-1}$ $K^{-1}$) |
| $r_a$ | Leaf aerodynamic resistance ($sm^{-1}$) |

Baile et. al (1994) reported that the values of A ranged from 0.12 to 0.67, while B ranged from $14 \times 10^{-3}$ to $37 \times 10^{-3}$ kg $m^{-2}$ $h^{-1}$ $kPa^{-1}$ (for daytime ET) which had shown wide range of response of crop transpiration to solar radiation and vapour pressure deficit. A reasonable estimation of leaf aerodynamic resistance ($r_a$) was also obtained from the study.

## 3.10 Penman-Monteith screen-house model

A one-dimensional screen-house model was derived by Möller et al. (2004), based on a modified equation incorporating an additional boundary layer resistance. The approach considers the screen-house air to be continuous with the lower atmosphere. This model is based on the partial similarity between the screen-house environment and open filed condition (Möller et al., 2004).

The Penman-Monteith screen-house model uses ambient climate data of temperature, humidity, wind speed and short wave radiation to predict crop climate and transpiration inside the screen-house. ET from the canopy within the screen-house can be calculated from the following equation:

$$LE = \frac{\Delta^{*} (R_n - G)}{\gamma^{*} + \Delta^{*}} + \frac{\rho C_p [ (e_s(T_a) - e_a ]}{r_a [ \gamma^{*} + \Delta^{*} ]}$$

$$\Delta^{*} = \Delta (1 + r_b/r_a)$$

$$\gamma^{*} = \gamma [1 + (r_c + r_b)/r_a ]$$

$$r_a = \ln [(z_m - d)/z_{om}] \ln [(z_h - d)/z_{oh}] k^{-2} u^{-1}$$

$$r_b = 220 (D^{0.2}/u_{in}^{0.8})$$

**Equation 13: Penman-Monteith screen-house equation**

Where,

| | |
|---|---|
| LE | Canopy latent heat flux (W $m^{-2}$) |
| $R_n$ | Canopy net radiation (W $m^{-2}$) |
| G | Soil heat flux (W $m^{-2}$) |
| $\rho$ | Density of air (kg $m^{-3}$) |
| $C_p$ | Specific heat of air (J $kg^{-1}$ $K^{-1}$) |
| $T_a$ | Ambient air temperature (°C) |
| $e_s$ | Saturation vapour pressure (kPa) |
| $e_a$ | Actual vapour pressure (kPa) |
| $\Delta$ | Slope of the saturated vapour pressure-temperature curve (kPa $K^{-1}$) |
| $\gamma$ | Psychrometric constant (kPa $°C^{-1}$) |
| $r_a$ | Leaf aerodynamic resistance ($sm^{-1}$) |
| $r_b$ | Leaf boundary layer resistance ($sm^{-1}$) |
| $r_c$ | Canopy resistance |
| $z_m$ | Sensor heights of momentum (m) |
| $z_{om}$ | Roughness lengths for momentum (m) |
| d | Canopy zero plane displacement (m) |
| $z_h$ | Sensor heights of humidity measurements (m) |
| $z_{0h}$ | Roughness lengths for heat and water vapour (m) |
| u | Horizontal wind speed ($ms^{-1}$) |
| D | Mean leaf diameter (m) |
| $u_{in}$ | Internal air speed ($ms^{-1}$) |

# 4 Overview of evapotranspiration models in greenhouse

Previous studies on greenhouse ET models were done for different greenhouse types which gave indication on reliable ET models that can be applied in greenhouses. Based from the literatures, an overview of ET models that had been used in each type of greenhouse will be presented. Furthermore the ET models are also summarized here based on their accuracy and available data in greenhouse.

## 4.1 Application based on greenhouse type

Three groups of greenhouse type were distinguished earlier in section 2.3 which can be used to determine the ET models that best calculated the ET rate. The three groups are greenhouses from low, medium and high technology. The technology of the greenhouse here counts for the structure, material, equipment and facilities of the greenhouse.

### 4.1.1 ET model for low technology greenhouses

Low technology greenhouses have low cost structures covered with plastic film, without active climatic control systems and normally crops are grown on soil. The typical greenhouses are plastic greenhouse tunnel, screen-houses or insect netting structures which simply have structures covered with nets. Natural ventilation is the common practice for this type of greenhouse (Baille et al., 2001; Fernández et al., 2009).

Recently Fernández et al. (2009) did a study to evaluate several ET models which were FAO Penman-Monteith, FAO Penman, FAO Radiation and Hargreaves model in a low cost structure, plastic film (0.2 mm thick thermal polyethylene sheet) greenhouse. The plastic greenhouse has a symmetrical roof of 12.5% slope, without heating equipment and passively ventilated by opening side panels and roof vents. Perennial grass crop was grown in the greenhouse. Calculated ET with models was compared with the measured ET from a weighing lysimeter located in the greenhouse. Calculated ET was checked for both conditions without and with whitening (whitening with calcium carbonate on the external plastic cover for cooling purpose) Fernández et al. (2009).

Fernández et al. (2009) reported that calculated ET in a plastic greenhouse without whitening was best with FAO Penman and FAO Radiation as most data were closely distributed around the 1:1 line of the measured ET. The FAO Penman and FAO Radiation had a correlation coefficient ($r^2$) of 0.98 and 0.97 respectively. For Hargreaves model, the calculated ET was largely overestimated when calculated using the original equation (Hargreaves et al., 1985). However, Fernández et al. (2009) recalculated it by multiplying the extraterrestrial radiation term with the greenhouse radiation transmissivity and the result accurately agreed with measured ET with a small relative error of 3.7% and $r^2$ equal to 0.97. By contrast, the FAO Penman-Monteith model underestimated the measured ET when the aerodynamic resistance ($r_a$) term in the calculations used higher values. For the greenhouse perennial crop Fernández et al. (2009) assumed a constant and lower value of $r_a$ (150 s $m^{-1}$) which resulted to a better estimation of ET with the FAO Penman-Monteith model as compared to the measured ET with relative error of 2.7% and $r^2$ equal to 0.97.

When whitening was applied to the greenhouse cover, ET calculated with Hargreaves model incorporating greenhouse radiation transmissivity showed the best agreement with the measured ET (as most calculated data are closely distributed around the 1:1 line, $r^2$ = 0.97 and slightly underestimated by 2.6% only) (Fernández et al., 2009). Other models by contrast underestimated the measured ET by the FAO Radiation (12%), FAO Penman (13%) and overestimated FAO Penman-Monteith model (adjusted with $r_a$ = 150 s $m^{-1}$) by 8.5%.

It is can be seen that the performance of the ET models differ in both conditions with and without whitening. Measured greenhouse ET values were accurately predicted without whitening, but they under and overestimated with whitening. Whitening reduced the radiation transmission and air temperature, but slightly increased the relative humidity inside the greenhouse. In a practical point of view, Fernández et al. (2009) recommended to use the Hargreaves model to estimate ET in a plastic greenhouse which require values of greenhouse transmissivity and daily temperature under standard management practice.

A study by Möller and Assouline (2007) in a flat-roof screen-house made of a black shading screen had shown that the ET rate calculated with FAO Penman-Monteith model accurately predicted ET with the measured ET from a lysimeter ($r^2$=0.93). The greenhouse crop was sweet pepper grown on a seedbed of sandy loam soil.

The same finding was achieved by Tanny et al. (2006) for the ET of a banana plantation grown in a light shading flat-roof screen-house. Measurements were conducted using an eddy covariance (EC) system and modelling was with the FAO Penman-Monteith. Good agreement was obtained between measured and calculated ET values with an average ratio between both values of 1.06. The FAO Penman-Monteith model succeed to predict ET in the screen-house environment (Tanny et al., 2006).

A screen-house model was derived by Möller et al. (2004) which was called the Penman-Monteith screen-house model. The model was based on a modified Penman_Monteith equation incorporating an additional boundary layer resistance (equation 13). The model was developed from energy balance components of microclimate and physiological parameters in a 50-mesh insect-proof screen-house cultivated with sweet pepper (Möller et al., 2004). ET calculated from the model was compared with the measured ET from a lysimeter-calibrated sap flow system. Half hourly average ET calculated from the model showed good agreement with sap flow, correlation coefficient $r^2$ equal to 0.94. For daily total ET values, calculated and measured ET also showed good agreement with difference in daily ET ranging from 0.3 to 6 %. The Penman-Monteith screen-house model was also checked for the sensitiveness of the model towards climatic data. It was found that the model was most sensitive to the level of incoming radiation, followed by air temperature, vapour pressure deficit and wind speed (Möller et al., 2004). The study of screen-house model adds the current lack of accurate measurement and predictions of ET under screening materials.

### 4.1.2 ET model for medium technology greenhouse

As defined in section 2.3.2, medium technology greenhouses have better structure than low technology greenhouses and use some of the facilities and equipments as those in high technology greenhouses for climate control. However, the usage of the equipment are somehow limited and not as advance as being used in the high technology greenhouse. This type of greenhouses mostly uses natural ventilation from the roof openings.

A study by Liu et al. (2008) found that the ET rate was best estimated using the FAO Penman model in a naturally ventilated greenhouse for banana crop. The study was to compare five widely used ET models of Priestly Taylor, FAO Radiation, Hargreaves, FAO Penman and FAO Penman-Monteith. The greenhouse was 20 meter long and consist two spans, each 10 meter wide. The mean height was about 6 meter and the roof glazing was corrugated double-paned polycarbonate. The greenhouse had two fans which were only operated when temperature inside the greenhouse exceeded 30 °C. However during the experiment, ventilation with fans was not used. Liu et al. (2008) reported that the five models yielded from the highest correlation coefficient ($r^2$) were FAO Penman ($r^2$=0.67), followed by FAO Penman-Monteith ($r^2$=0.67), FAO Radiation ($r^2$=0.63), Hargreaves ($r^2$=0.52) and Priestley Taylor ($r^2$=0.47) model.

From the study of Liu et al. (2008) it can be seen that FAO Penman model and FAO Penman-Monteith gave higher correlation coefficient than others. In both of the models, wind speed was considered in the $ET_o$ calculation process while the other three models of FAO Radiation, Hargreaves and Priestley Taylor model, calculations were based on radiation. These radiation based models are suitable for no or low advective conditions under no or low wind speed. Moreover, this study had found that the ET rate was largely depended on the vapour pressure deficit and air temperature in the greenhouse. Liu et al. (2008) concluded that for ventilated greenhouse, ET equations based on temperature and humidity gave better results than equations based on solar radiation only.

Another study for a naturally ventilated greenhouse was done by López-Cruz et al. (2008) which compared two theoretical models of FAO Penman-Monteith and Stanghellini model for a tomato crop. The measured ET was done by a weighing lysimeter. The greenhouse had plastic cover of calibre 700 with UV treatment and ventilated naturally with two side vents and two roof vents, which can be operated automatically and covered with anti-insects screens. Results of the study showed that due to a more detailed estimation of net radiation, leaf area index (LAI) and a better estimation of the stomatal resistance of the tomato crop, had gave the Stanghellini model ($r^2$=0.72) performed better than FAO Penman-Monteith ($r^2$=0.62) (López-Cruz et al., 2008). The FAO Penman-Monteith overestimates the ET rate as the model was developed for outdoor conditions. Stanghellini model which include the input parameter for LAI was the reason for better ET estimation especially for the greenhouse crop.

Although Liu et al. (2008) found that ET rate calculated with Priestley Taylor model was least accurate from the other models, Valdés-Gómez et al. (2007) alternatively proved that the ET estimation can be calculated with the model by using internal measurements of air temperature and relative humidity, and external measurements of solar radiation. In this case, the Priestley Taylor model predicted the ET rate with an error of 6.1% from the measured ET by water balance method (Valdés-Gómez et al., 2007). The experiment was conducted in a chapel plastic greenhouse type with zenithal ventilation set up in the roof, lateral and frontal ventilation on the greenhouse side which was operated manually. The greenhouse crop was tomato and used drip irrigation for water supply. It is known that the Priestley Taylor model is a radiation based model, therefore Valdés-Gómez et al. (2007) used an expression (equation 14) to calculate net radiation ($R_n$) which incorporated the input parameter of the greenhouse microclimate:

$$\boxed{R_n = [(1-\xi)\, R_{gi} + \varepsilon_a\, \sigma\, T_a^4 - \varepsilon_{cv}\, \sigma\, T_{cv}^4]\, FC^{-1}}$$

**Equation 14: Calculation for daily net radiation $R_n$**

Where $R_n$ is expressed in mm $d^{-1}$, $R_{gi}$ is the coming shortwave radiation inside the greenhouse (MJ $m^{-2}$ $d^{-1}$), $\xi$ is surface albedo, $\varepsilon_a$ is atmospheric emissivity, $\varepsilon_{cv}$ is the crop emissivity, $T_a$ is the air temperature (°K), $T_{cv}$ is the canopy temperature (°K), $\sigma$ is the Stefan-Boltzman constant (4.903 $10^{-9}$ MJ $K^{-4}$ $m^{-2}$ $d^{-1}$) and FC is a conversion factor (2.45 MJ $mm^{-2}$ $d^{-1}$). Furthermore, the study proposed to estimate solar $R_{gi}$ as follow (Valdés-Gómez et al., 2007):

$$\boxed{R_{gi} = \tau\, R_{ge}}$$

**Equation 15: Proposed calculation for inside solar radiation**

Where $\tau$ is the coefficient of solar radiation transmission of the plastic cover and $R_{ge}$ is solar radiation measured outside the greenhouse (MJ $m^{-2}$ $d^{-1}$). Valdés-Gómez et al. (2007) assumed that the soil heat flux, which is one of the input parameter in the Priestley Taylor model equal to zero as supported by the data analysis and other publications (Allen et al., 1998; Stanghellini, 1987). The air temperature and canopy was also assumed to be equal. The original Priestley Taylor model uses empirical coefficient ($\alpha$) of 1.26 but in this case the value of $\alpha$ was integrated with the surface canopy resistance and aerodynamic resistance which gave a value of 1.12 (Pereira and Nova, 1992). It can be concluded that the approach done by Valdés-Gómez et al. (2007) to calculate net radiation using the microclimate data can be applied for the ET estimation of the greenhouse tomato crop. However, it is important to note that the transmission properties of the greenhouse cover and empirical coefficient depend on the greenhouse conditions. It can be said from this study that the Priestley Taylor model used in this study gave good result because of the incorporation of the microclimate data in the greenhouse.

A present study done by Takakura et al. (2009) measured the ET rate with a simple energy balance equation for a fully grown tomato crop in a single-span greenhouse with natural ventilation. The greenhouse had an arched shape roof covered with air-inflated double-polyethylene glazing. The values estimated by this method were in good agreement with the measured data using sap flow meters and water consumed by fog cooling which gave a correlation of $r^2$ equal to 0.677, and 0.725 when soil heat flux was neglected. Takakura et al. (2009) showed that the net solar radiation term was the largest and could not be neglected. Although the soil heat flux can be neglected, the sensible heat transfer term cannot be neglected since the maximum of the possible range of values is large and significant (Takakura et al., 2009).

### 4.1.3 ET model for high technology greenhouse

High technology greenhouses commonly are closed type greenhouse where the environment is controlled. This type of greenhouse is well equipped with various automation which links to a control system management.

Both Stanghellini (1987) and Fynn model (1993) represent the ET model for the condition of controlled environment greenhouse. Stanghellini developed a model which accounts the relationship between the microclimate and the transpiration of a greenhouse canopy in a single glass, Venlo-type greenhouse with water pipe heating. The research was done with tomato plants having many leaf layers. By using the energy balance method to deliver the appraisal of the relationship between the transpiration rate of a greenhouse crop and the microclimate, Stanghellini model had shown to be practically useful for ET estimation.

Fynn (1993) did an experiment for the ET of potted chrysanthemum crop in a controlled shading and energy conservation greenhouse. The greenhouse had an exhaust fan for ventilation and was operated continuously at constant flow rate. Fynn model considered the ET estimation for only the area of a greenhouse floor covered by the canopy. He derived an equation that assumes energy is exchanged adiabatically in the form of water vapour between the canopy and the surrounding environment as a result of vapour pressure and temperature differences. Both solar and long wave radiation were also assumed to exchange from the canopy. Fynn (1993) showed that his model can accurately predicted the water requirements and environmental responses of a potted chrysanthemum.

Four ET models of FAO Penman, FAO Penman-Monteith, Stanghellini and Fynn were evaluated for the ET rate of Red Sunset red maple tress in a climate control greenhouse (Prenger et al., 2001). The greenhouse was equipped with an evaporative pad and fan ventilation system. Among the models, Stanghellini model calculated the best ET rate as compared to the ET measured by a lysimeter with the highest correlation coefficient ($r^2$) of 0.958. Other models followed by Fynn ($r^2$=0.940), FAO Penman-Monteith ($r^2$=0.886) and FAO Penman ($r^2$=0.872). The calculations with FAO Penman-Monteith and Penman had overestimated the ET rate. Prenger et al. (2001) reported that both models were derived based on an open water surface and "big leaf" which assumed the calculation of ET rate per area from a single surface of unit area. However, this is not true for the condition in greenhouse where the crops often have multiple leaf layers. Therefore, such model that accounts for the multiple leaf areas had predicted more accurate ET rate which in this case the Stanghellini and Fynn models. Comparing Stanghellini model with Fynn, Stanghellini model provided a more accurate prediction with a close correlation as the model was adapted for the actual leaf surface area while in Fynn model, the canopy surface area proportional to the floor area was taken as an assumption for the energy exchange.

The study of Prenger et al. (2001) had showed that FAO Penman-Monteith overestimated the ET for red maple trees because the model was derived for the outdoor conditions. However a study by Baille et al. (1992) found that the use of Penman-Monteith model to estimate ET of pot ornamental crops in greenhouse conditions was possible if the crop resistance term ($r_c$) is estimated by analytical functions for radiation level and vapour pressure deficit. The experiment was done in glass greenhouse equipped with hot pipe heating system, roof aeration and aluminized screen. ET calculation with FAO Penman-Monteith has the advantage of simplicity and reliability if $r_c$ is correctly estimated and if measurement or calculation of canopy net radiation is available (Baille et al., 1992). From this study, the results were satisfactory as measured and calculated ET followed the same pattern in the graph shown by Baille et al. (1992).

Another study by Baille et al. (1994) had bring to a simplified model for predicting ET rate of nine greenhouse ornamental species. The species are Begonia, Cyclamen, Gardenia, Gloxinia, Hibiscus, Impatiens, Pelargonium, Poinsettia and Schefflera. The study was done in a single span glass greenhouse, equipped with natural roof ventilation (which was opened only when inside temperature was higher than 25°C), fog system, shading screen and heating pipes as heating system. The indoor greenhouse climate of solar radiation, vapour pressure deficit and leaf area index were surveyed and correlations were made based to the formalism of the Penman-Monteith equation (equation 12). Results of the study had shown that the ET rate for the nine ornamental species under the greenhouse conditions gave satisfactory results, especially ET calculated at day time with the measured ET with correlation coefficient ($r^2$) between 0.87 and 0.97. Baille et al. (1994) suggested that the simplified model could be easily implemented in algorithms for irrigation and climate control as two important parameters of solar radiation and vapour pressure deficit can be available in greenhouse.

## 4.2 Application based on accuracy of the model

**Table 2: Summary of ET models accuracies for each greenhouse types reviewed from the studied literatures. $r^2$: Coefficient of correlation, RE: relative error, RMSE: root mean square error. Level of accuracy defines as 1 being most accurate, and following after as less accurate.**

| Greenhouse type | Greenhouse description | Level of accuracy | ET model | Accuracy | Greenhouse crop | Reference |
|---|---|---|---|---|---|---|
| Low technology greenhouse | Plastic greenhouse (without whitening) | 1 | FAO Penman | $r^2$=0.98, RE=1.7% | Perennial grass | Fernández et al. (2009) |
| | | 2 | FAO Penman-Monteith (with $r_a$=150 $sm^{-1}$) | $r^2$=0.97, RE=2.7% | Perennial grass | Fernández et al. (2009) |
| | | 3 | FAO Radiation | $r^2$=0.97, RE= -3.7% | Perennial grass | Fernández et al. (2009) |
| | | 4 | Hargreaves (with greenhouse transmissivity) | $r^2$=0.97, RE=3.7% | Perennial grass | Fernández et al. (2009) |
| | Plastic greenhouse (with whitening) | 1 | Hargreaves (with greenhouse transmissivity) | $r^2$=0.97, RE= -2.6% | Perennial grass | Fernández et al. (2009) |
| | | 2 | FAO Penman-Monteith (with $r_a$=150 $sm^{-1}$) | $r^2$=0.98, RE=8.5% | Perennial grass | Fernández et al. (2009) |
| | | 3 | FAO Radiation | $r^2$=0.98, RE= -10.7% | Perennial grass | Fernández et al. (2009) |
| | | 4 | FAO Penman | $r^2$=0.98, RE= -11.6% | Perennial grass | Fernández et al. (2009) |
| | Screen-house | 1 | Penman-Monteith Screen-house | $r^2$=0.94, RE=3.8% | Sweet pepper | Möller et al. (2004) |
| | | 2 | FAO Penman-Monteith | $r^2$=0.93 | Sweet pepper, banana | Möller and Assouline (2007), Tanny et al. (2006) |

| Greenhouse type | Greenhouse description | Level of accuracy | ET model | Accuracy | Greenhouse crop | Reference |
|---|---|---|---|---|---|---|
| Medium technology greenhouse | Natural ventilation | 1 | Stanghellini | $r^2$=0.72, RMSE=2.4 | Tomato | López-Cruz et al. (2008) |
| | | 2 | Energy balance equation | $r^2$=0.68 | Tomato | Takakura et al. (2009) |
| | | 3 | FAO Penman | $r^2$=0.63 | Banana | Liu et al. (2008) |
| | | 4 | Priestley Taylor (with Rn incorporate greenhouse microclimate) | RE=6.1% | Tomato | Valdés-Gómez et al. (2007) |
| | | 5 | FAO Penman-Monteith | $r^2$=0.63, $r^2$=0.62, RMSE=17.1 | Banana, tomato | Liu et al. (2008), López-Cruz et al. (2008) |
| | | 6 | FAO Radiation | $r^2$=0.52 | Banana | Liu et al. (2008) |
| | | 7 | Hargreaves | $r^2$=0.49 | Banana | Liu et al. (2008) |
| | | 8 | Priestley Taylor | $r^2$=0.47 | Banana | Liu et al. (2008) |
| HIgh technology greenhouse | Controlled environment | 1 | Stanghellini | $r^2$=0.96, RMSE=0.006 | Tomato, red sunset red maple trees | Stanghellini (1987), Prenger et al. (2001) |
| | | 2 | Fynn | $r^2$=0.94, RMSE=0.021 | Chrysanthemum, red sunset red maple trees | Fynn (1993), Prenger et al. (2001) |
| | | 3 | FAO Penman-Monteith | $r^2$=0.89, RMSE=0.161 | Red sunset red maple trees | Prenger et al. (2001) |
| | | 4 | FAO Penman | $r^2$=0.87, RMSE=0.179 | Red sunset red maple trees | Prenger et al. (2001) |
| | | 5 | Simplified model | $r^2$=0.87-0.97 | Ornamental species | Baille et al. (1994) |

Table 2 shows the accuracies of ET models in each category. These accuracies were taken from the studied literatures of section 4.1.1. The accuracy of each model is made from comparisons with the measured ET in each study. Based on the available information in the literatures, each model were compared and arranged according to their accuracies.

For the low technology greenhouse type, as much as three categories of greenhouse were distinguished. These include low structure plastic greenhouse, with and without whitening and screen-houses. It can be seen that FAO Penman and FAO Penman-Monteith had been used most in this type of greenhouse. Moreover the use of a simpler, temperature-radiation based model such as Hargreaves model was used quite often also. Complex models such as Stanghellini and Fynn were not found in the literatures for calculation of ET in low structure greenhouse. This is because these models were developed mainly for the conditions of a controlled environment greenhouse. However, it is still interesting to know if these models might predict good ET estimations in low technology greenhouse. In order to use these complex models, more climatic parameters must be measured which might require expensive equipments. It can be said that the adoption of common and simple ET models was because it can measure quite accurately and less measurements need to be taken which can reduce the cost of management.

Contrary, the medium technology greenhouse had been using both simple and complex ET models. The best option for the ET estimation in a naturally ventilated, medium technology greenhouse was the Stanghellini model. Stanghellini model was developed for the conditions of a greenhouse which include the input parameter for leaf area index (LAI). LAI is an important parameter which influences the calculation of transpiration from a leaf surface area.  FAO Radiation and Hargreaves are two models which have the lowest accuracies when adopted in this type of greenhouse. These two models are radiation based models which incorporate less the input parameter of greenhouse microclimate.

In high technology greenhouses, most researches used the complex ET models. All five models listed in table 2 have high accuracies and can be applied in this type of greenhouse. Most of these models take into account the input parameter for the greenhouse microclimate especially LAI, vapour pressure deficit, leaf or canopy resistance and the correct amount of radiation received by the greenhouse canopy. If simpler models which based solely on temperature or radiation were used to calculate ET in this high technology greenhouse, the estimation might either under or overestimated the ET rate.

## 4.3 Application based on available data

In order for an ET model to be applied, available data must be adequate for the calculations. Not all data or parameters defined in a model can be measured in a greenhouse due to lack of measurement equipments, expertise and historical data or even budget. Table 3 list the main data or parameter that is needed for each ET models define from the equations list in section 3.

**Table 3: Measurement data for each ET models**

| ET models | Data needed | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Rn | u | $T_a$ | $T_o$ | $T_w$ | VPD | RH | LAI | Etc |
| FAO Penman | x | x | | | | | | | |
| FAO Penman-Monteith | x | x | x | | | x | | | |
| FAO Radiation | x | | | | | | x | | |
| Priestley Taylor | x | | | | | | | | |
| Priestley Taylor (with Rn incorporate greenhouse | x | | x | | x | x | | | x |
| Hargreaves | x | | x | | | | | | |
| Stanghellini | x | | x | x | | x | | x | |
| Fynn | x | | | | | x | | x | |
| Energy Balance equation | x | | x | | x | | | | |
| Simplified model | x | | | | | x | | x | |
| Penman-Monteith Screen-house | x | x | x | | | x | | | x |

Where the terms can be defined as follow,

Rn Net radiation
u Wind speed
$T_a$ Ambient air temperature
$T_o$ Leaf temperature
$T_w$ Surface temperature, which is the overall average temperature of plant canopy and ground surface
VPD Vapour pressure deficit
RH Relative humidity
LAI Leaf area index
Etc Other data such as greenhouse transmissivity and measurements for leaf boundary layer resistance in Penman-Monteith screen-house

For situations where limited data are made available for the ET calculation, a person has to use ET models that require less defined parameters in the equations. Table 4 list some of the possible available data and correspond ET models for ET estimations in a greenhouse.

**Table 4: Selection of ET models based on least available data**

| Data availabe | ET Models |
|---|---|
| Rn | Priestley Taylor |
| Rn, $T_a$ | Hargreaves |
| Rn, RH | FAO Radiation |
| Rn, u | FAO Penman |
| Rn, VPD, LAI | Fynn, Simplified model |

From table 4, the Priestley Taylor model only needs the measurement for net radiation. In the original equation of the model, data on soil heat flux is needed. However in most situation, soil heat flux is relatively small on daily basis and can be neglected (Allen et al., 1998; Stanghellini, 1987).

Hargreaves and FAO Radiation are radiation based models which also can be used when less data are available. Allen et al. (1998) also suggested in FAO 56 for minimum data requirements especially when weather data are missing, the use of Hargreaves ET model can be used. On the other hand when weather data are available, especially the wind speed and net radiation, FAO Penman will be a better option.

For models that include leaf area index or LAI in the equations, limited data such as net radiation and vapour pressure deficit can be encountered with models of Fynn and a simplified model by Baille et al. (Baille et al., 1994). Other models that are not listed in table 4 needs more detailed data and can not be simplified for the ET calculations. In FAO 56 (Allen et al., 1998), there is a chapter for simplifying the FAO Penman-Monteith equation for conditions of missing climatic data. Despite the option of ET models based on available data, some studies had chose the use of a model based on its simplicity, for example the Hargreaves model suggested by Fernández et al.(2009). However, one must note that the reliability of the ET estimation based on limited data and simplicity of the model may not be accurate. Allen et al. (1998) also less recommended to use an alternative ET calculation procedure which require only limited meteorological parameters.

# 5 Discussion

## 5.1 Accuracies of the ET models

The three types of greenhouse have different level of performance based on their correlation coefficient ($r^2$) from measured and calculated ET rates. This can be seen from table 2 where the accuracies of each model under each greenhouse type were listed. From observation, it can be seen that $r^2$ were high under low and high technology greenhouses, contrary in medium technology greenhouse $r^2$ were lower than others.

ET models used in low technology greenhouse were mainly FAO Penman, FAO Penman-Monteith, FAO Radiation and Hargreaves models. These models were developed principally for the condition of outdoor conditions. It can be said that the environment inside the low technology greenhouse reflect the outdoor conditions. This is because the internal climate is strongly dependent on external conditions (Togani and Pardossi, 1999). The structure of the greenhouse itself allows the influence of outdoor climate to internal climate as exchange of air occurs continuously through open doors, windows and screen-house material. Furthermore the greenhouse does not have controlled climate equipment which modifies the internal climate. Therefore, the relation of outdoor and indoor climate could be the reason of high $r^2$ determined by the models.

Higher $r^2$ was also found for ET models calculated in high technology greenhouse. For this type of greenhouse specific models such as Stanghellini and Fynn model were most used. These models were mainly developed for greenhouse conditions (Fynn et al., 1993; Stanghellini, 1987) where air velocities are typically low and has micro climate which differ from outside climate (controlled climate greenhouse). The application of these models had proven to be reliable for ET calculation in high technology greenhouse. When FAO Penman-Monteith and FAO Penman were used in this type of greenhouse, $r^2$ was quite high but still low as compared to the application in low technology greenhouse. This show that the models were better suited for low technology greenhouse.

Lower $r^2$ were obtained in medium technology greenhouse although both models developed for field and greenhouse conditions were applied. In this type of greenhouse, Stanghellini model gave most accurate ET estimation while the original equation of Priestley Taylor model gave the least accurate estimation. It can be seen that complex ET models gave higher $r^2$ than simple temperature or radiation based ET models. However neither complex nor simple ET models give higher $r^2$ than they did in low and high technology greenhouses. This shows that medium technology greenhouse have micro climate that represent both conditions in low and high technology greenhouses especially when the greenhouse use natural ventilation from opening roofs and windows. On the other hand, the structure of the greenhouse and equipment follow slightly as those in high technology greenhouse. The mixture of the characteristics of the greenhouse type can be one reason of lower $r^2$ determined in this type of greenhouse. Such models that incorporate the energy balance from all factors in greenhouse were found to be the best option to be used here.

## 5.2 ET concepts

ET models in greenhouses that were found in literatures and listed in table 1 mostly give the value for reference ET ($ET_o$). Allen et al. (1998) described that $ET_o$ is ET rate from a reference crop surface and not short of water, while crop ET ($ET_c$) is the real ET of a crop when the crop coefficient factor ($K_c$) is taken into consideration. $K_c$ is a coefficient expressing the difference in ET between the crop and the reference crop surface.

The only factors affecting $ET_o$ are climatic parameter, therefore $ET_o$ calculations are based on climatic data. $ET_o$ express the evaporating power of the atmosphere at a specific location and time of the year and does not consider the crop characteristics and soil factors while (Allen et al., 1998). On the other hand, $ET_c$ incorporates crop characteristics and soil factors as which is contributed by the $K_c$ value. $ET_c$ can also be derived directly from meteorological and crop data by incorporating the crop specific characteristics of albedo, aerodynamic and canopy resistances, and leaf area index (Allen et al., 1998). By defining $ET_o$ and $ET_c$, table 5 distinguish the ET concepts of the ten models studied.

**Table 5: ET concepts of the ten ET models**

| ET models | ET concept | Reference crop or based crop |
|---|---|---|
| FAO Penman | $ET_o$ | Alfalfa |
| FAO Penman-Monteith | $ET_o$ | Grass |
| FAO Radiation | $ET_o$ | Grass |
| Priestley Taylor | $ET_o$ | Grass |
| Hargreaves | $ET_o$ | Grass |
| Energy Balance equation | $ET_o$ | Tomato |
| Stanghellini | $ET_c$ | Tomato |
| Fynn | $ET_c$ | Chrysanthemum |
| Penman-Monteith Screen-house | $ET_c$ | Sweet pepper |
| Simplified model | $ET_c$ | *Ornamental species |

*Ornamental species: Begonia, Cyclamen, Gardenia, Gloxinia, Hibiscus, Impatiens, Pelargonium, Poinsettia and Schefflera

It was noticed that Donatelli et al. (2006) in his published paper define ET concept for Stanghellini model as $ET_o$. The model was implemented in software for calculating $ET_o$. Other literatures denoted Stanghellini model, Fynn and Penman-Monteith screen-house model as ET only without identifying the ET concepts they refer to. From this study point of view, ET concepts especially for models that give $ET_c$ are define according to Allen et al. (Allen et al., 1998) in FAO 56 which relate $ET_c$ by direct calculation from meteorological and crop data. Therefore, this reveal that Stanghelini, Fynn, Penman-Monteith screen-house and simplified model as an $ET_c$ models.

Comparing measured and calculated ET rate in literatures was done in various ways. Liu et al. (2008) in medium technology greenhouse for banana relate measured $ET_c$ with calculated $ET_o$ directly with a coefficient factor, $K_c$. They experimentally determined $K_c$ as ratios of $ET_c/ET_o$ and used the ratio to relate $ET_o$ to $ET_c$ as suggested by Allen et al. (1998). The $K_c$ values then refer to the specific crop of banana in the study.

Other literatures calculated $ET_c$ as a corresponding equation derived directly from meteorological and crop data (Baille et al., 1994; Fynn et al., 1993; Prenger et al., 2001). Valdés-Gómez et al. (2007) had applied a $K_c$ factor to the calculated ET rate obtained from Priestley Taylor model which then gave a value for $ET_c$. Therefore comparing directly measured $ET_c$ with calculated $ET_c$ in these literatures was reliable.

Tanny et al. (2006) and Takakura et al. (2009) compared measured $ET_c$ with calculated $ET_o$ directly without mentioning the effect or result of $K_c$ values in their publications. In another case, Fernández et al. (2009) define the measured ET rate by lysimeters as $ET_o$. Consequently they compared measured ET (refer to $ET_o$ here in the literature) with calculated $ET_o$ from reference ET models. In this way the comparisons were true as measured ET was denoted by $ET_o$. According to Allen et al. (1998), a requirement for perfect measurement with lysimeters is that the vegetation both inside and immediately outside the lysimeter must be perfectly matched (same height and leaf area index). This requirement has historically not been closely adhered to in a majority of lysimeter studies and has failed to predict real ET. Therefore, it might have been the reason Fernández et al. (2009) define measured ET by lysimeters as $ET_o$. This reflect the study done by Möller and Assouline (2007) where they used lysimeters as ET measurements inside a screen-house and applied the soil water balance approach to compute water use (WU). The soil water balance approach does not incorporate $K_c$ values thus; they compared WU directly with calculated $ET_o$.

It can be concluded that for comparing measured ET and calculated ET rate, the same concept or theory which the ET are base for must be identified closely. In this way only the accuracy of the model can be determined and reliable. Moreover, having the $ET_c$ available will give stronger correlation between measured and calculated ET.

## 5.3 ET measurement in greenhouse

**Table 6: Equipment used in literatures to measure ET in each greenhouse type**

| Greenhouse type | Greenhouse description | Reference | Equipment |
|---|---|---|---|
| Low technology greenhouse | Plastic greenhouse | Fernández et al. (2009) | Lysimeter |
| | Screen-house | Möller et al. (2004) | Lysimeter |
| | Screen-house | Möller and Assouline (2007) | Lysimeter |
| | Screen-house | Tanny et al. (2006) | Eddy covariance (EC) |
| Medium technology greenhouse | Natural ventilation | López-Cruz et al. (2008) | Lysimeter |
| | Natural ventilation | Takakura et al. (2009) | Sap flow meter |
| | Natural ventilation | Liu et al. (2008) | Load cells |
| | Natural ventilation | Valdés-Gómez et al. (2007) | Water balance method |
| HIgh technology greenhouse | Controlled environment | Prenger et al. (2001) | Electronic weighing balance |
| | Controlled environment | Fynn (1993) | Lysimeter |
| | Controlled environment | Baille et al. (1994) | Electronic weighing balance |

From table 6, it can be seen that most equipment being used in greenhouses are lysimeter. Lysimeter was used with a soil water balance approach to calculate measured $ET_o$ in plastic greenhouse and screen-house (Fernández et al., 2009; Möller and Assouline, 2007). Möller et al. (2004) used lysimeter calibrated with sap flow (SF) and eddy covariance (EC) system installed inside the screen-house to measure canopy transpiration and evapotranspiration. SF has a sensor that measures the heat flow, while EC sensors measures water vapour or heat fluxes from the crop canopy. The weight change of a weighing lysimeter represents the cumulative affects of both ET and plant growth which has been used by Fynn et al. (1993) and López-Cruz et al. (2008) in their studies.

Other equipments such as electronic weighing balance measures the amount of water lost by crop and substrate (Baille et al., 1994; Prenger et al., 2001). The balance supported a certain bench section with an independent system of water supply and drainage. The number of plants on the balance depends on the pot size and crop development stage (Baille et al., 1994). Load cells was used by Liu et al. (2008) to measure plant transpiration. Load cells with a resolution of 5 g were deployed under each crop buckets where the plants were cultivated in.

The use of lysimeter to measure ET rate has been a common practice in greenhouses which can be proven by the list of literatures listed in table 6 and others (Stanghellini, 1988; Yang et al., 1990). Although it has been mentioned earlier that real ET measurements by lysimeter are hardly adhere, Allen et al. (1998) in FAO 56 mentioned that precise weighing lysimeters, where water loss is directly measured by the change of mass can give accuracy of a few hundredths of millimetre.

Beside the equipments listed in table 6, few researches used atmometer, class A pan and reduced evaporation pan in estimating ET rate in greenhouses (Blanco and Folegatti, 2004; Fernandes et al., 2003). Fernandes et al. (2003) had found that the best equipment to use was reduced pan and atmometer, while Blanco and Folegatti (2004) has shown that atmometer had the best performance in estimating the crop ET rate in greenhouse. With these results it is can be said that atmometer might be another good option besides weighing lysimeter for estimating ET.

## 5.4 Greenhouse micro climate measurement

**Table 7: Climate equipment placement for greenhouse climate data**

| Greenhouse type | Greenhouse description | Reference | Placement of climate data equipment |
|---|---|---|---|
| Low technology greenhouse | Plastic greenhouse | Fernández et al. (2009) | Inside and outside |
| | Screen-house | Möller et al. (2004) | Inside and outside |
| | Screen-house | Möller and Assouline (2007) | Inside and outside |
| | Screen-house | Tanny et al. (2006) | Inside |
| Medium technology greenhouse | Natural ventilation | López-Cruz et al. (2008) | Inside and outside |
| | Natural ventilation | Takakura et al. (2009) | Inside |
| | Natural ventilation | Liu et al. (2008) | Inside |
| | Natural ventilation | Valdés-Gómez et al. (2007) | Inside and outside |
| HIgh technology greenhouse | Controlled environment | Prenger et al. (2001) | Inside |
| | Controlled environment | Fynn (1993) | Inside and outside |
| | Controlled environment | Baille et al. (1994) | Inside |

The accuracy and reliability of climate data are important for ET calculations with ET models. Table 7 lists the ways of placing the climate data equipment done by previous researches either inside or outside the greenhouses.

Climate data measured inside the greenhouse were done for all types of greenhouse. Measuring inside climate is essential as these data are closely related to the actual ET govern by the crop, soil and water surfaces. Baille et al. (1994), Prenger et al. (2001), Tanny et al.(2006), Liu et al. (2008) and Takakura et al. (2009) had only measured inside climate. Measured climate data using various equipments were done for solar radiation, net radiation, air temperature, leaf temperature and wind speed. The measurements were taken near the crops inside the greenhouse with some having approximately 30 cm above crop canopy (Baille et al., 1994; Liu et al., 2008; Prenger et al., 2001). The climate data obtained from inside climate was directly used to compute ET rate with ET models.

Despite having inside climate data, some literatures did measurement for outside climate, near the greenhouse. These were done mostly in low technology greenhouse followed by medium and high technology greenhouse. It is known that low technology greenhouse is more related to outside climate due to the structure and material of the greenhouse.

Fernández et al. (2009) in plastic greenhouse measured inside and outside climate data with an automatic agro-meteorological station. For air temperature and relative humidity measurements, aspirated psychcrometer was used. Wind velocity was measured by cup anemometer. The weather station placed outside, near the greenhouse was used to measure outside radiation to determine greenhouse transmissivity (greenhouse transmissivity is the ratio between inside and outside solar radiation). Moreover Fernández et al. (2009) did an evaluation of the greenhouse climate to know the temperature gradient, radiation transmission and relative humidity between outside and inside climate especially for the effect of whitening.

In a screen-house, climate data measured outside and inside were done by measuring solar radiation, wind speed, air temperature and humidity (Möller et al., 2004). Inside climate data was measured near the crop canopy while outside, a distance of 5 meter away from the side walls of the greenhouse was taken. Estimated crop ET ($ET_c$) for a hypothetical sweet pepper crop outside the screen-house was computed and related to the hourly sap flow values against $ET_o$. It was found by Möller et al. (2004) as much as 60% reduction of crop water use was found inside the screen-house as compared to the open filed. Outside solar radiation was used to determine net radiation below the screen which was derived from the radiative flux equations (Möller et al., 2004).

Further research by Möller and Assouline (2007) was done to see the effect of a shading screen on micro climate and crop water requirements. Measurements were done with an automatic weather station located in the centre of the screen-house and 5 meter away outside. Measured climate data were global radiation, wind speed and air temperatures. Outside global radiation was used to compute screen transmissivity by the ratio of global radiation inside and outside. Daily global radiation, air temperature and wind speed were compared between outside and inside the screen-house. Results had shown that gradient temperature between outside and inside the screen-house correlated highly. Wind speed measured inside and outside the screen-house also gave high correlation coefficient ($r^2$) of 0.80 which means wind speed had almost the same speed as outside. Comparison between inside $ET_o$ and outside $ET_o$ computed from measured climate data had resulted to 38% lower ET rate under the screen than those estimated outside. The main influence of this slightly low ET rate was caused by the reduced radiation inside the screen-house.

In medium technology greenhouse, López-Cruz et al. (2008) measured outside radiation for the purpose of calculating greenhouse transmissivity which needed both data of solar radiation inside and outside the greenhouse. In the same greenhouse type, a comparison was made by Valdés-Gómez et al. (2007) to compare $ET_c$ computed by Priestley Taylor method using solar radiation inside and outside the greenhouse. For this reason, an automatic weather station (AWS) was installed inside the greenhouse to measure solar radiation, net radiation, air temperature and relative humidity. Another AWS was installed over a grass cover to measure atmospheric conditions outside the greenhouse. The study had shown that $ET_c$ gave relatively low error of 6.1% using internal measurements of air temperature and relative humidity but outside measurement of solar radiation. For this condition, the possibility of using a solar radiation sensor outside the greenhouse will be reliable when considering the transmission properties of the covering material.

Fynn (1993) measured solar radiation and air temperature outside the controlled greenhouse (high technology greenhouse) for the purpose of comparing solar irradiance level and temperature gradient between inside and outside. Inside climate data is more crucial to be used for estimating ET rate in high technology greenhouse as done by Stanghellini (1987), Baille et al. (1994), and Prenger et al.(2001).

It can be concluded that the most important climate data for greenhouses are inside data. These data will reflect correctly for the condition of the greenhouse environment. Outside climate data was more related in low technology greenhouse as the condition of the greenhouse reflects outside field condition most. Moreover, outdoor climate was used most by these literatures to compare the weather condition between inside and outside, especially for solar radiation, temperature and wind speed. It was not found in the literatures for greenhouses that used available climate data from a weather station located a distance away from the greenhouse or historical weather data to compute ET rate. All of the researches had used own climate measurement to collect climate data either inside or outside, near the greenhouse. It might be possible if outside climate data obtained from weather station give error to the ET estimations as the data could not accurately reflect the micro climate of the greenhouse.

One method was found in the literatures which correlate outside solar radiation to inside solar radiation with a ratio that gives the value of greenhouse transmissivity. This method had found to be reliable when using outside solar radiation, together with internal temperature and relative humidity to compute $ET_c$ with Priestley Taylor model as recommended by Valdés-Gómez et al. (2007).

# 6 Conclusion

The greenhouse industry has expanded in many parts of the word and the need of information on a reliable ET method especially by indirect method is crucial. Each type of model might not be suitable for all conditions of greenhouse. This has been proven from the literatures studied which showed that the accuracy of each model depend a lot on the microclimate of the greenhouse type.

In this study, the type of greenhouses were first defined in order to classify the ET models which were most being used in previous studies. Based on the available materials, distinguished were made on the ET models which suited the greenhouse type. An overview is given on the accuracy of each model as the result of previous studies. Furthermore, a selection of ET models for limited climatic data was described.

It can be said that most researches preferably used the common and simple models for low technology greenhouse. Despite to its simplicity, these models had given good ET estimations for the greenhouse. Based on their accuracy the FAO Penman model is recommended to calculate ET in plastic greenhouse and Hargreaves model (incorporating the greenhouse transmissivity to the extraterrestrial radiation value) in screen-house.

For medium technology greenhouse, the stanghellini model was most accurate as compared to other ET models. The Stanghellini model was found highly accurate to measure the ET rate inside the high technology greenhouse.

For the purpose of comparing between measured and calculated ET rate, having calculated crop ET ($ET_c$) would be more reliable. $ET_c$ can be either computed by multiplying reference ET ($ET_o$) with crop coefficient ($K_c$) or modified the original equation and incorporate crop characteristic data.

Weighing lysimeter and atmometer were found to be good ET equipments in greenhouse which can give accurate measurement of $ET_c$. The most important climate data will are climate that are measured inside the greenhouse. Outside climate was used most to determine greenhouse transmissivity by the ratio between inside and outside solar radiation.

Although the use of an ET model for estimating ET rates in greenhouses is still an optional for one to choose which depend largely on greenhouse type and available climatic data, based on previous studies it can be said that the accuracy of the model in each type of greenhouse can be a factor for a model to be adopted.

# 7 Recommendations

This study is based on literatures of previous research done by researchers all over the world. The materials prepared for the study might not be enough and need to be added to draw more concrete results from it. It was found from the study that there are some literatures written in other languages which was difficult to be translated. Therefore, in order to compile different ET models being practiced in all type of greenhouses all over the region, these materials might be valuable to be translated carefully.

The accuracy of the models listed in this study is based on fixed conditions of the previous study. It is recommended for further analysis, to validate these ET models with real greenhouse microclimate data, especially for conditions in different type of greenhouses. With this respect, the accuracy of the model can be more reliable.

It was shown that inside climate has been dominated for the calculation of the ET rate. In certain salutation, it is not always possible to measure inside climate of the greenhouse due to lack of facilities and equipments, expertise and budget. Therefore, using available climate data especially from nearby weather station which give outside greenhouse climate data might be useful. In order to fully utilize outside data, an appropriate method through a correction factor which could lead to inside condition might be a solution. To achieve this, further research on the correlation between outside and inside climate of the greenhouse has to be done.

The inconsistency of the ET models accuracies estimated in the medium technology greenhouse has to be well thought also. The need of an ET models which can give high accuracy as those in low and high technology greenhouse is important in order to achieve better irrigation management in this type of greenhouse. Development of new models or having an adjustment factor for the condition of medium technology greenhouse will urge for further research on this subject area.

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