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Growth responses of green mustard (*Brassica juncea)* and water spinach (*Ipomoea aquatica*) in terms of water productivity and yield based on Cropwat 8.0 with limited data availability in a semi-arid developing nation

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Abstract

The crop water requirement (CWR) is one of the most important aspects to consider when studying food production under the types of water scarcity constraints that are widely encountered in semi-arid regions. Better CWR predictions lead to better irrigation applications when studies are hampered by inadequate data and expertise. The aim of this work is therefore to predict the irrigation requirements, variate the irrigation application, to determine and model the crop growth and production responses, and subsequently assess the crop water productivity. In this research, we input climate, crop and soil data and certain strong assumptions to FAO-Cropwat Version 8.0 to predict the CWR. Green mustard (*Brassica juncea*) and water spinach (*Ipomoea aquatica*) were cultivated in polybags with limited handling, and irrigated with variations in the predicted CWR. The crop height, number of leaves, and fresh weight were measured and used as input to a crop-water response model using the response surface methodology. The water productivity (WP) was then used to quantify the crop-water relationship. The results showed that these two small vegetables showed similar effects from irrigated water on the crop height, with a slightly different effect on the number of leaves, and different effects on the fresh weight. The models fitted the reduced quadratic model, and were considered to be valid. The most significant components of our model were the potential evapotranspiration (ETo), available water (AVW), and the interaction between ETo and AVW, which showed saddle responses with maximum and minimum effects. The WP for green mustard was higher than for water spinach. The highest WP for both crops was achieved when they were irrigated with a reduction of 50% from the predicted CWR. In these research conditions, we recommend taking advantage of FAO- Cropwat version 8.0 for a reduction in irrigation water application. We also suggest further experiments with crops cultivated in fields.

Keywords: Crop water requirement, FAO-Cropwat version 8.0, Response surface methodology, Water productivity, Semi-arid region, Small vegetables

1. Introduction

Interest in agricultural water management has gained momentum recently. Agriculture consumes more water than other sectors, and in semi-arid developing nations, food security is facing a considerable increase in pressure due to threats from water scarcity [1]. Water is a vital resource for agriculture and daily life, but is becoming scarce due to climate change. The adverse effects of this mean that arid and semi-arid areas are more vulnerable: these cover a third of the world, and typically have long dry seasons and erratic rainfall. Hence, sustainable agricultural water management needs to be studied in regard to these areas [2-4].

Many studies have attempted to address the trade-off needed between crop production and water scarcity by improving the management of irrigation water resources, with an emphasis on crop water allocation and water requirement, such as those by Gong et al. [5], Xie et al. [6], Pereira et al. [7] and Bao et al. [8]. The assessment of crop water requirement (CWR) is one of the key aspects of optimal agricultural water management, since it allows for better allocation of irrigation water in terms of appropriate timing, quantity, and quality [9, 10]. CWR is the amount of water in mm that is needed to replace the evapotranspiration (ET) from a given crop field [9, 11, 12]. There are two main methods of assessing the CWR: direct methods (or measurements in the field) and indirect methods [13, 14]. Indirect methods are preferred in order to tackle the limitations of the direct approach. Furthermore, indirect methods can account for effects from the climate, the characteristics of the crop, and the condition of the field or soil [11, 12].

FAO has developed software tools that are used worldwide to assist in CWR prediction, such as FAO-Cropwat version 8.0, which is an open-access platform. The majority of studies of arid and semiarid environments have taken advantage of this model, including research on seasonal water requirements for the major crops in the central highlands of Ethiopia [15]; irrigation management in Egypt [16]; and the water requirements of the major crops grown in the semi-arid zones of Turkey [17], the southern part of Iraq [18], and the arid environment of Saudi Arabia [19]. There are also several studies that have carried out an analysis of single crops, such as the irrigation requirements for potatoes in the Lower Gangetic Plains of India [20], the CWR for corn in the Middle Gujarat [21] and South

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Sulawesi Indonesia [22], the CWR for cabbage grown in Niamey, Ethiopia [23], and the CWR for jatropa grown in the semi-arid region of Botswana [24] and for tomatoes grown in the Serere district of Uganda [25].

Although this model is widely used, efficient, and effective, it has some limitations in terms of the quality, sufficiency, and uncertainty of the input data, and the expertise needed to operate the software and interpret the results [26-28]. Several researchers have proposed ways to tackle these drawbacks; for example, Zakari et al. [29] increased the accuracy of the CWR by conducting a sensitivity analysis of the input data, and Saeed et al. [30] conducted a spatiotemporal sensitivity analysis of CWR subject to climate change in Iraq's arid and semi-arid regions.

The ultimate effect of CWR on crop yield has been long discussed. Doorenbos and Kassam [31] pointed out that in particular, although the potential growth and yield of a crop are determined by the climate and crop genetics, water and other input factors should be managed in a way that meets the biological needs of the crop. If the full CWR is not met, this can affect crop growth and production, meaning that an understanding of the complex response of crops and yields to water is essential to pave the way for improvements in the efficiency and productivity of water use [31, 32]. Pasquale Studeto et al. [32] reported that in the late 1970s, FAO introduced a simple equation to explain crop yield and water use relations, which indicated that a relative reduction in ET caused a reduction in crop yield. Today, this approach has been developed further with the introduction of water production functions for estimating the complex interactions between water and crop yield response.

Following the rapid advancements in information technology and computation, various models and software have been developed to study the responses of independent variables to dependent variables, such as the response surface methodology (RSM). This was pioneered by Box and Wilson in 1951, and was developed based on combinations of statistical and mathematical techniques to assist in the analysis of responses [14, 33]. Research on agriculture water management has benefited from the RSM, including the establishment of an optimal combination of applied water and nitrogen for potatoes [34], and a study of the responses of water spinach biomass cultivated in a hydroponic environment to crop growth variables and water electrolysis [35]. Koehuan [14] explored the estimation and optimisation of the socio-economic-environmental response to staple food consumptive water use.

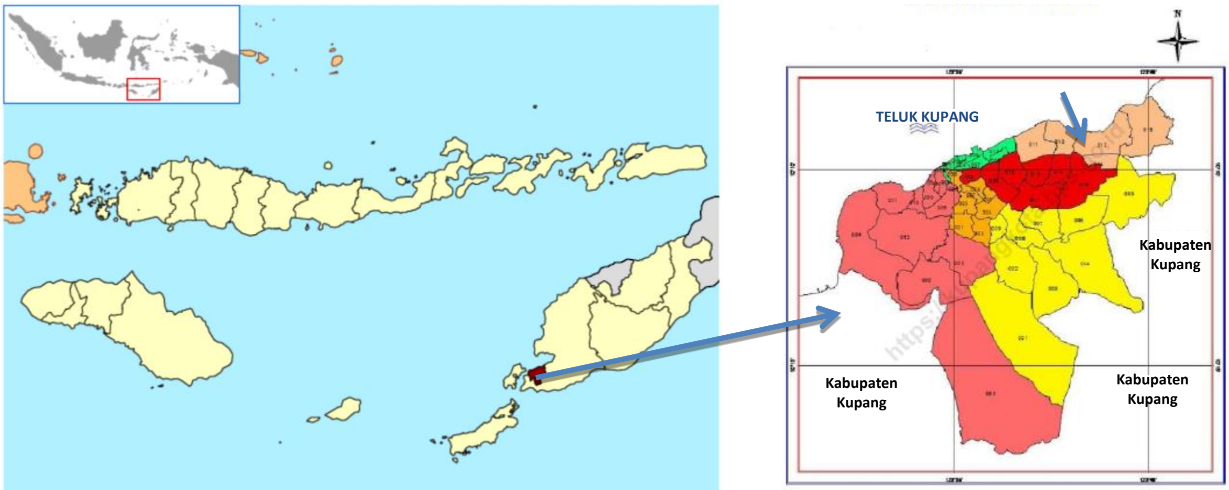
In a study of the efficiency and effectiveness of water use, Giordano et al. [36] reported that irrigation efficiency indicators were widely used in the past to describe the proportion of water used by plants compared to the amount of water supplied, or, in certain cases, to water obtained from a source. In 1996, a more robust water productivity indicator called the crop water productivity (CWP) was introduced by David Seckler; this heralded a new era in water management, as the CWP could be defined in physical or economic terms. In physical terms, the CWP is the units of production per volume of water utilised. This concept is used to increase agricultural output while using less water, which can be accomplished by increasing crop production while using the same amount of water, or by producing the same amount of food while using less water [36-38].

This study aims to enrich the applications of FAO-Cropwat 8.0 in semi-arid developing nations where insufficient data and expertise are available. We will explore the responses of the growth and production of two vegetables to the application of water, and will determine the CWP.

2. Materials and methods

2.1 Study location

The experiments were carried out in the Kelapa Lima District of Kupang Municipality in West Timor, Indonesia, at latitude 10°10'12.6" south and longitude 123°36'27.9" east [39, 40], between May and June of 2022. Figure 1 shows maps of the research location.



Source: Wikipedia [40] Source : BPS Kupang municipality [39]

Figure 1 Maps of the research location

2.2 Crop water requirement

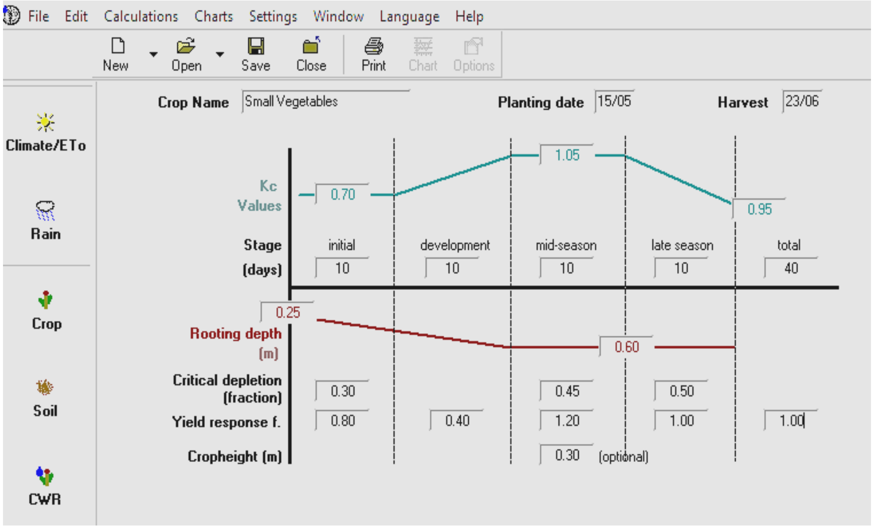
The CWR was estimated due to the difficulty of obtaining accurate field measurements. The prediction of CWR is based on the postulate of a relationship between crops and the atmosphere and soil conditions [31]. Smith [41] developed the FAO-Cropwat model to help with CWR prediction, and this software was subsequently revised, with the current edition being version 8.0. Cropwat estimates CWR based on potential evapotranspiration (ETo) prediction, and relies on the Penman-Monteith method (PMM), which takes into account four essential agro-climate parameters: air temperature, humidity, sunshine, and wind speed.

Climate and rainfall data from the period 2017–2021 was obtained from the Lasiana Climate station, located at latitude 10.14 south and longitude 123.70 east at an elevation of 20 m above mean sea level (MSL). In this paper, the CWR is used interchangeably with crop evapotranspiration (ETc), which is calculated based on the formula below:

$$CWR = ETc = ETo \times Kc \tag{1}$$

where CWR is crop water requirement (mm); ETc is crop evapotranspiration (mm); ETo is potential evapotranspiration (mm); and Kc is the crop coefficient.

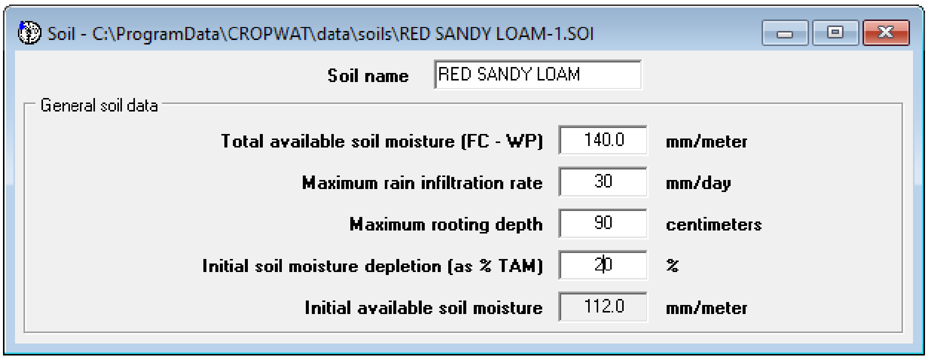
The crop coefficient (Kc) used to account for the characteristics of each crop was derived from the Cropwat software. Green mustard (*Brassica juncea*) and water spinach (*Ipomoea aquatica*) were assumed to fall into the category of small vegetables. We also made the assumption that each stage of crop growth lasted 10 days (1 decadal), and another strong assumption was the rooting depth. The assumptions made in the prediction of the crop coefficient (Kc) are presented in Figure 2. Due to limitations on data and expertise in soil characterisation, we also made assumptions for the soil properties, based on those reported by Vudhivanich [42], as shown in Figure 3.



Crop Name Small Vegetables
Planting date 15/05
Harvest 23/06

	initial	development	mid-season	late season	total
Kc Values	0.70		1.05	0.95	
Stage (days)	10	10	10	10	40
Rooting depth (m)	0.25		0.60		
Critical depletion (fraction)	0.30		0.45	0.50	
Yield response f.	0.80	0.40	1.20	1.00	1.00
Cropheight (m)			0.30 (optional)		

Figure 2 Assumptions made when estimating the crop coefficient


Soil - C:\ProgramData\CROPWAT\data\soils\RED SANDY LOAM-1.SOI

Soil name RED SANDY LOAM

General soil data

Total available soil moisture (FC - WP) 140.0 **mm/meter**
Maximum rain infiltration rate 30 **mm/day**
Maximum rooting depth 90 **centimeters**
Initial soil moisture depletion (as % TAM) 20 **%**
Initial available soil moisture 112.0 **mm/meter**

Figure 3 Assumptions made when calculating the soil properties

Effective rainfall (REff) was selected as a fixed percentage of 80% of monthly rainfall, which is a dependable level [42]. The net irrigation requirement (NIR) represents the amount of water required to ensure crop growth, and the irrigation water application (IRWA) is the NIR per unit cropping area, which in this study means compensating 100% of CWR. The available water (AVW) is the water stored in the soil that is available for crop growth. NIR, IRWA, and AVW were calculated as shown in the formulae below:

$$NIR = ETc - REff \tag{2}$$

$$IRWA = (NIR \times A)/1000 \tag{3}$$

$$AVW = IRWA - DRGW \tag{4}$$

where NIR is net irrigation requirement (mm/decadal); ETc is crop evapotranspiration (mm/decadal); REff is effective precipitation (mm/decadal); IRWA is irrigation water application (ml/unit); A is the irrigation area/unit (mm^2); AVW is the available water (ml/unit); and DRGW is drainage water (ml/unit).

2.3 Crop growth and production responses

Green mustard and water spinach were cultivated in polybags with soil medium supplemented with organic fertiliser, with minimal processing and handling, to imitate the simple growing method that is widely practiced by farmers within the study area. The experiment was conducted in the dry season, and the rainfall was monitored manually. The IWRA was applied manually twice a day, in the morning and afternoon, using a measuring cup. The drainage loss (DRGW) from each polybag was collected in a plastic tray, and measured daily with measuring cup in the morning before the next application of the IWRA.

A varying IWRA was used to compensate for a lack of data and expertise in NIR prediction. Five different values of IWRA were calculated based on the NIR as an output of Cropwat: P1 = NIR; P2 = NIR + (50% NIR); P3 = NIR + (25% NIR); P4 = NIR − (25% NIR); and P5 = NIR − (50% NIR). Each value was used three times. The crop growth response was measured based on crop height and number of leaves, and the crop production was measured in terms of crop fresh weight. Every decadal or 10 days after planting (DAPs), the crop height and leaf count were measured and the fresh crop weights were measured in the harvest (40 DAPs). The growing conditions are illustrated in Figure 4.

The crop growth response in terms of IWRA and AVW was predicted with the RSM using a historical data design (HDD) approach. In the modelling process, the RSM consisted of two main steps: the first was an analysis of the linear model, and if there was the possibility of curvature, a second step was applied to analyse the nonlinear model. To obtain a better prediction, the terms in the model were manually adjusted [14, 33]. The basic forms of the linear and nonlinear responses are formulated below.

$$y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \varepsilon \tag{5}$$

$$y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} x_i^2 + \sum\sum_{i<j} \beta_{ij} x_i x_j + \varepsilon \tag{6}$$

where y is the independent variable; x_i are the dependent variables, i = 1, 2, …, k; β is the model coefficient; and ε is an error term that is assumed to be independent and identically distributed (*iid*).

The response model was a multi-input/multi-output model with three input (independent) variables: ETo, IWRA, and AVW. These were used to obtain the simultaneous effects on the three output (dependent) variables of crop height, quantity of leaves, and crop fresh weight. The model was evaluated using indicators such as an analysis of variance (ANOVA), the determination coefficients of R^2, adjusted R^2, and predicted R^2, the adequate precision (Adeq Prec), and a residual analysis of prediction error of sum squares (PRESS). The responses were visualised using contour plots and three-dimensional (3D) plots.

a) Green mustard b) Water spinach

Figure 4 Photographs showing the growing conditions

2.4 Crop water productivity analysis

A CWP analysis was conducted to study the responses of crop production to water and to select the best level of water application based on the highest value of CWP. There are two CWP indicators, based on IWRA and AVW, as follows:

$$CWP_{Irrigation} = \text{Crop weight}/IWRA \tag{7}$$

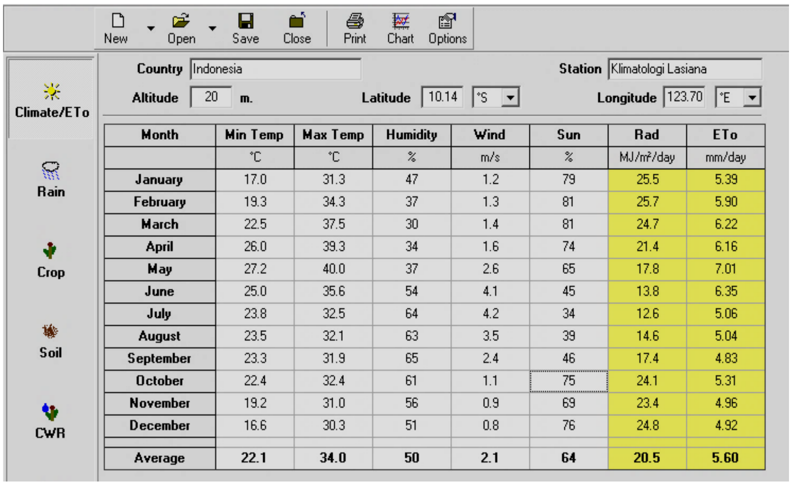
$$CWP_{Available} = \text{Crop weight}/AVW \tag{8}$$

where $CWP_{Irrigation}$ is the crop water productivity based on IWRA (kg/m^3), and $CWP_{Available}$ is the crop water productivity based on AVW (kg/m^3).

3. Results and discussion

3.1 Application and availability of irrigation water

The basis for calculating the application and availability of irrigation water was the prediction of potential ETo, calculated using the PMM. The results from FAO-Cropwat version 8.0 showed that the minimum value of ETo was in September (4.83 mm/day) and the maximum in May (7.01 mm/day), with an average value of 5.60 mm/day. The ETo on the growing activity in May and June (6.35 mm/day). The ETo results are presented in Figure 5.



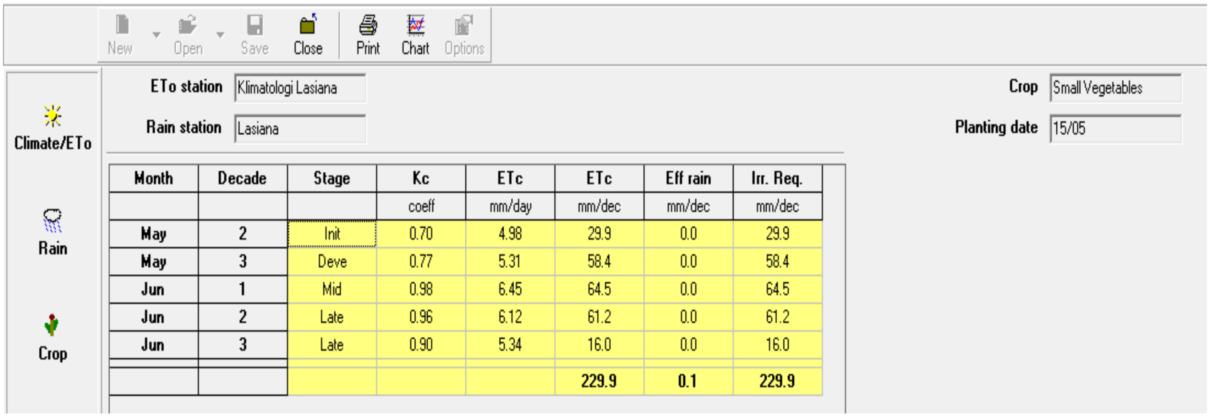
Country: Indonesia
Station: Klimatologi Lasiana
Altitude: 20 m.
Latitude: 10.14 °S
Longitude: 123.70 °E

Month	Min Temp	Max Temp	Humidity	Wind	Sun	Rad	ETo
	°C	°C	%	m/s	%	MJ/m²/day	mm/day
January	17.0	31.3	47	1.2	79	25.5	5.39
February	19.3	34.3	37	1.3	81	25.7	5.90
March	22.5	37.5	30	1.4	81	24.7	6.22
April	26.0	39.3	34	1.6	74	21.4	6.16
May	27.2	40.0	37	2.6	65	17.8	7.01
June	25.0	35.6	54	4.1	45	13.8	6.35
July	23.8	32.5	64	4.2	34	12.6	5.06
August	23.5	32.1	63	3.5	39	14.6	5.04
September	23.3	31.9	65	2.4	46	17.4	4.83
October	22.4	32.4	61	1.1	75	24.1	5.31
November	19.2	31.0	56	0.9	69	23.4	4.96
December	16.6	30.3	51	0.8	76	24.8	4.92
Average	22.1	34.0	50	2.1	64	20.5	5.60

Figure 5 Results for potential evapotranspiration (ETo)

The results for CWR were divided into five decadals. The minimum CWR was found in the initial growing phase (May–I) at 4.98 mm/day, and the maximum in the mid-phase of growing (June–I) at 6.45 mm/day. The total CWR during the growing period was 229.9 mm. These values were identical to the NIR, since there was effectively no rainfall during the growing period. The CWR predictions were slightly higher than those reported for cabbage growing in Ethiopia and tomatoes growing in Uganda, for which the minimum CWR values were 2.57 mm/day and 3.24 mm/day, respectively, in the initial phase, and the maximum values were 5.81 mm/day and 6.25 mm/day, respectively, in the mid-phase [23, 25]. The net irrigation requirements are shown in Figure 6.

The average IRWA varied according to the phase of crop growth and the variation of application from FAO-Cropwat 8.0 outputs. The minimum value of IRWA was 141 ml/unit during the late growing period, and the maximum value was 683 ml/unit. The average IRWA values are shown in Table 1.



ETo station: Klimatologi Lasiana
Rain station: Lasiana
Crop: Small Vegetables
Planting date: 15/05

Month	Decade	Stage	Kc	ETc	ETc	Eff rain	Irr. Req.
			coeff	mm/day	mm/dec	mm/dec	mm/dec
May	2	Init	0.70	4.98	29.9	0.0	29.9
May	3	Deve	0.77	5.31	58.4	0.0	58.4
Jun	1	Mid	0.98	6.45	64.5	0.0	64.5
Jun	2	Late	0.96	6.12	61.2	0.0	61.2
Jun	3	Late	0.90	5.34	16.0	0.0	16.0
					229.9	0.1	229.9

Figure 6 Results for net irrigation requirement

Table 1 Average values of irrigation water application in ml/unit

Components	NIR (Cropwat 8.0)	NIR + (50% NIR)	NIR + (25% NIR)	NIR − (25% NIR)	NIR − (50% NIR)
May–2	352	528	440	264	176
May–3	413	619	516	309	206
June–1	455	683	569	341	228
June–2	432	649	540	324	216
June–3	283	424	353	212	141

The values of DRGW showed a similar variation with IRWA depending on the stages of crop growth and the variation in IRWA. The minimum value of DRGW was 51.2 ml/unit in the development phase, and the maximum value was 472.1 ml/unit in the mid-phase. The results for the average DRGW are presented in Table 2.

Table 2 Average values of DRGW in ml/unit

Components	NIR	NIR + (50% NIR)	NIR + (25% NIR)	NIR − (25% NIR)	NIR − (50% NIR)
May–2	248.3	421.2	339.6	163.8	83.2
May–3	258.2	426.1	355.6	149.0	51.2
June–1	241.4	472.1	362.6	132.2	51.8
June–2	225.6	443.5	340.0	118.0	52.2
June–3	191.0	310.0	255.0	122.5	52.5

The minimum value of AVW was 88.5 ml/unit in the late phase, and the maximum value was 213.6 ml/unit in the mid-phase. Asgarzadeh et al. [43] have pointed out that in addition to controlling the physical state of the soil, soil water may also have an impact on its chemical and biological properties, which may affect how well plants absorb nutrients and the activity of soil organisms. Control of soil water status is therefore essential in agricultural systems. The results for the average AVW are presented in Table 3.

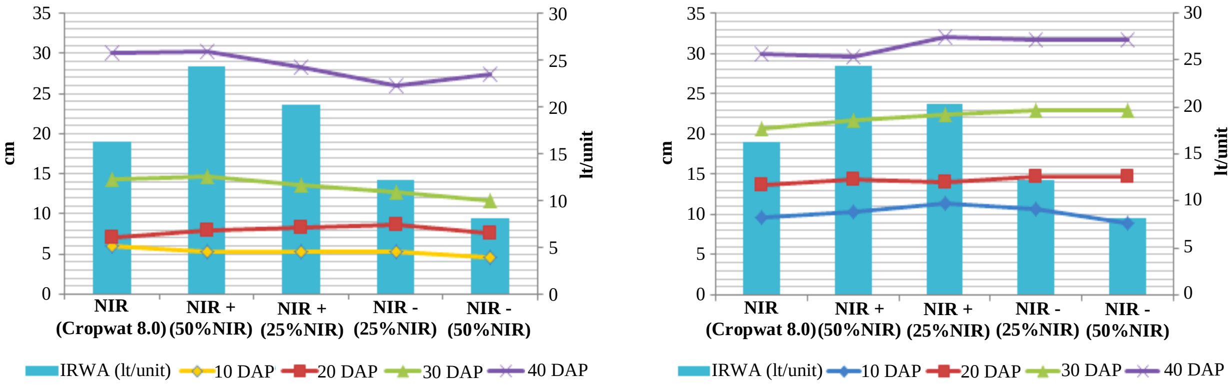
Table 3 Results for average AVW in ml/unit

Components	NIR	NIR + (50% NIR)	NIR + (25% NIR)	NIR − (25% NIR)	NIR − (50% NIR)
May–2	103.7	106.8	100.4	100.2	92.8
May–3	154.8	192.9	160.4	160.0	154.8
June–1	213.6	210.9	206.4	208.8	176.2
June–2	206.4	205.5	200.0	206.0	163.8
June–3	92.0	114.0	98.0	89.5	88.5

3.2 Crop growth and production responses

The response of plant growth and production to water use has been studied for a long time, and this research began with a curiosity about the relationship between plant growth and the environment. At the end of the eighteenth century, the study of plant physiology emerged, and by the nineteenth century, studies of the response of plant growth and production to water use had begun to be published [44]. Water influences the physiological and biochemical processes in plants, and these alterations in biochemical and physiological processes also have an impact on plant development and photosynthetic capability, which ultimately affects crop production [45].

The plants considered in this study, green mustard and water spinach, showed similar patterns of high-growth responses to water. The crop height of green mustard showed a lower response in the 10–20 DAPs compared to water spinach, and considerably higher growth in the 30–40 DAPs. Water spinach showed considerable height growth at 20–30 DAPs. Green mustard showed a greater response to a reduction in IWRA, while water spinach showed a positive growth in height with a reduction in IWRA. The results for the crop height response to IWRA are presented in Figure 7.



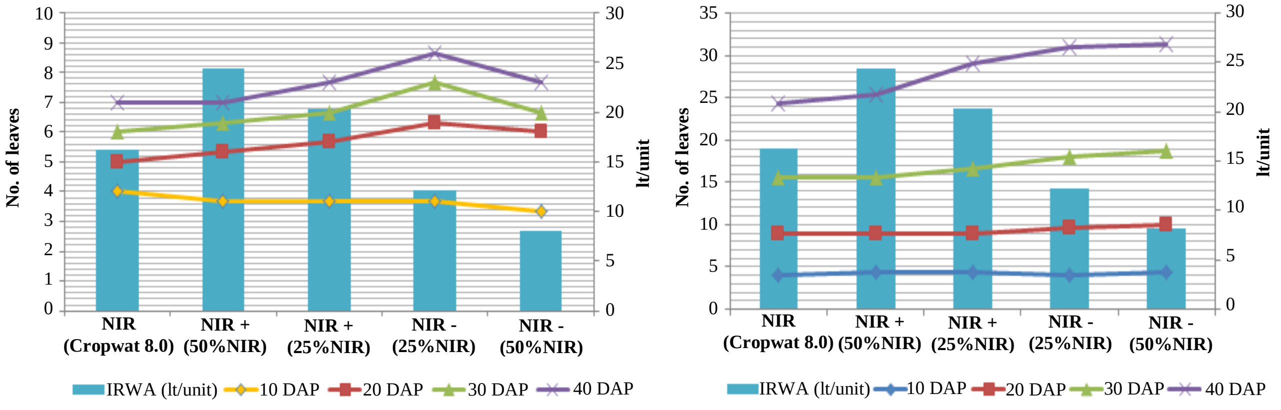
a) Green mustard b) Water spinach

Figure 7 Effect of IRWA on crop height

Green mustard and water spinach showed slightly different patterns for the number of leaves in response to water. Green mustard showed considerable leaf growth in the early phase (10–20 DAPs), while water spinach showed more leaf growth in the late phase (30–40 DAPs). The number of leaves showed a concomitant increase with IRWA until a reduction of 50%. However, water spinach showed an increase in crop leaves which tended to be slightly stable in the IWRA reduction of 50%. The results for the number of leaves grown in response to water are shown in Figure 8.

Green mustard and water spinach showed similar patterns for crop production in terms of the crop fresh weight in response to water application (IWRA). The fresh weights of both crops reached a maximum for NIR + 50%, and tend to decrease to a minimum for NIR − 50%. NIR + 50% resulted in a better fresh crop weight compared to NIR. However, we note that green mustard showed a better response to water (IWRA) compared to water spinach.

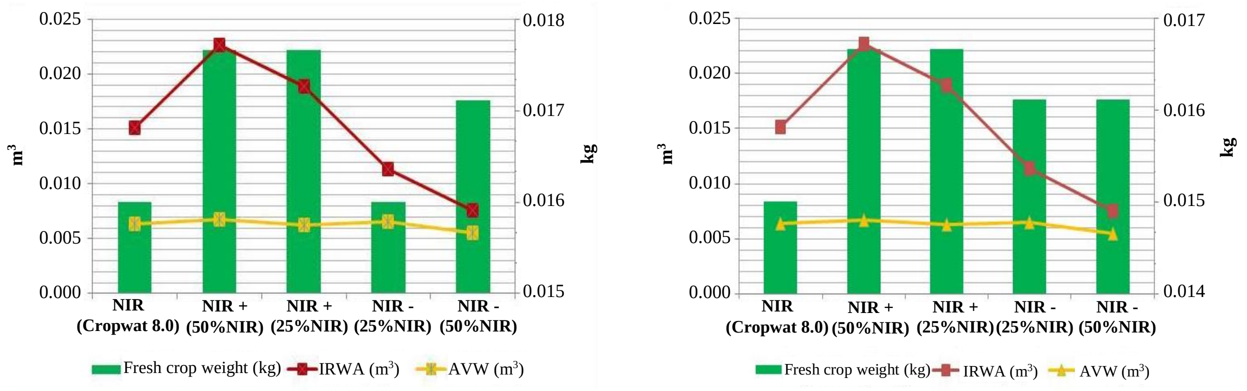
Our results showed that both crops had stable soil water availability. Ines et al. [45] have reported that soil water status determines the performance of crop growth and production. The continuation of IWRA at each stage of the growing period enables the availability of soil water and hence ensures water uptake. Our results for the effect of IWRA and AVW on the fresh crop weight are presented in Figure 9.



a) Green mustard

b) Water spinach

Figure 8 The effect of IWRA on the number of leaves



a) Green mustard

b) Water spinach

Figure 9 The effect of IWRA and AVW on fresh crop weight

Anda et al. [46], in Tomia District, Wakatobi, Indonesia, observed that fluctuations in IWRA affected the height of onion plants, the leaf width, and the leaf area index but had no discernible impact on the fresh weight. Prakash et al. [47] reported that variations in IWRA (100% ETc, 80% ETc, 60% ETc, and 40% ETc) indicated that a 80% crop evapotranspiration irrigation level could be recommended for successful cucumber production in water-deprived areas of the US without significantly reducing yield. The discrepancy between their results and those of this study is due to several factors, including the difference between the crops (which leads to a different response to water), and the difference in crop cultivation management methods (as cucumber farming is more intensive, with a greater application of fertiliser). There was also a difference in the objectives of the studies: the cucumber study sought to find the crop response to deficit irrigation, while our aim was to find better ETc compensation.

3.3 Crop water response model

Particularly in agriculture, forestry, and the environmental sciences, plant growth modelling has emerged as a critical scientific endeavour. Plant growth models have advanced dramatically over the previous two decades, as a result of increased computation infrastructure and the exchange of experiences among biologists, mathematicians, and computer scientists [48].

Existing plant growth models in the form of CWP models have historically been established based on empirical observations of crop yield response to applied irrigation from farming or regional surveys. An understanding of how plant growth and development interact with environmental elements such as climate, soil quality, and water availability is critical for increasing agricultural production. The two variables that form a CWP model, crop output and seasonal irrigation water use, are heavily influenced by the climate conditions in the crop growing season and irrigation practices. Consequently, modelling is an important way of assessing the effects of water shortages and climate change on agricultural production [48, 49].

Crop water models are composed of three input variables, ETo, IRWA, and AVW, and three response variables, crop height, the quantity of leaves, and crop fresh weight. All response models show a better fit to a reduced quadratic model. Our results were similar to those reported by Rai et al. [50] and Koehuan [14], where a reduced quadratic model was preferred because it was better suited to the observed data. All the models were significant (p-value < 0.0001), had significant model components, and had substantial coefficients of multiple determinations (R^2), adjusted R^2, and predicted R^2. There was sufficient signal to balance out the noise, and the ratio was higher than standard (adequate precision > 4). The PRESS residual was accepted for the residual analysis.

In terms of responses to climate and water, we observed that the growth and production of green mustard were significantly affected by ETo, the available water and their interaction. The fresh weight response had more significant model components, higher multiple determination coefficients, higher adequate precision and medium PRESS compared to the height and number of leaves responses. The specifications for the growth and production response model for green mustard are presented in Table 4.

Table 4 Growth and production response model for green mustard

Indicators	Green mustard		
	Height	Number of leaves	Weight
Model forms	Reduced quadratic model		
Analysis of variance (ANOVA)	Significant (p-value < 0.0001)		
Significant model components	ETo and ETo-AVW	ETo-AVW	ETo, AVW, and ETo-AVW
Coefficient of multiple determination (R^2)	0.943	0.964	0.970
Adjusted R^2	0.914	0.946	0.955
Predicted R^2	0.864	0.913	0.916
Adequate precision	17.20	19.982	22.327
PRESS	324.4	16.28	92.12

Mathematical expressions for the growth and production responses of green mustard are as follows:

$$\text{Crop height} = 381.591 - 55.219\ \text{ETo} + 11.462\ \text{IRWA} - 184.795\ \text{AVW} - 1.409\ \text{ETo IRWA} + 27.261\ \text{ETo AVW} + 1.932\ \text{IRWA AVW} - 0.629\ \text{IRWA}^2 - 2.735\ \text{AVW}^2 \quad (9)$$

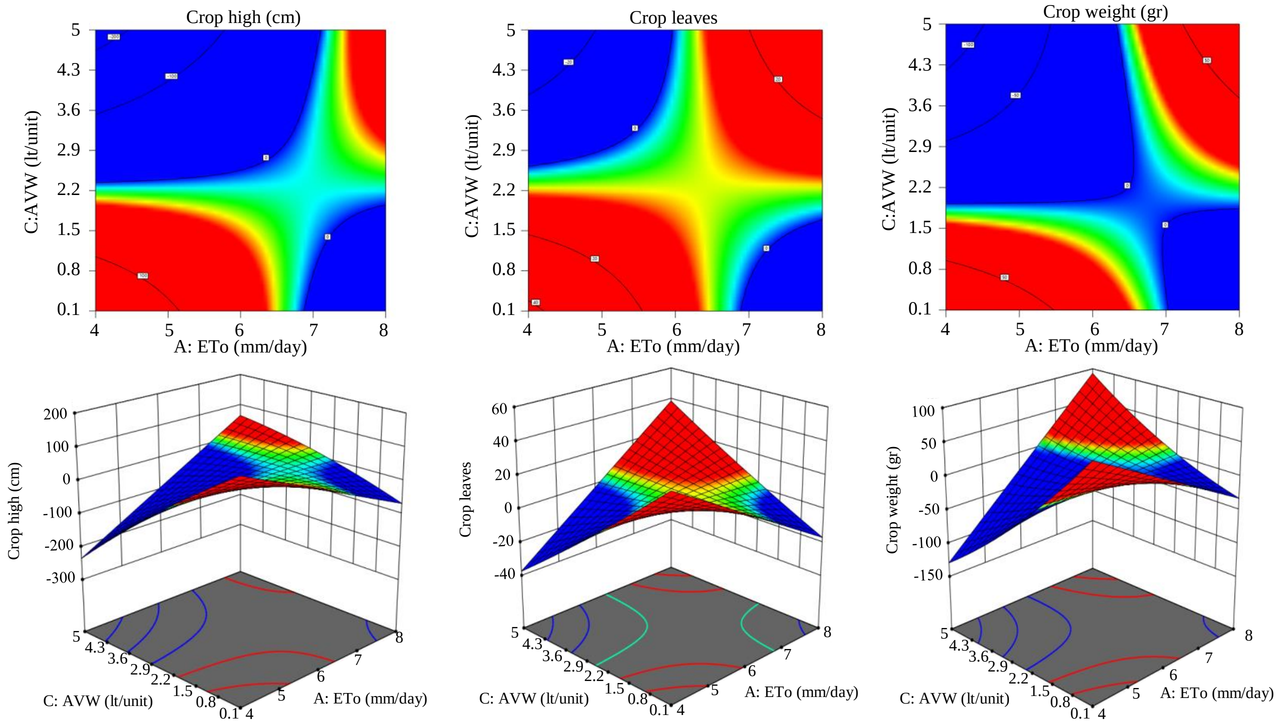
$$\text{Crop leaves} = 105.041 - 15.269\ \text{ETo} + 0.740\ \text{IRWA} - 45.528\ \text{AVW} - 0.093\ \text{ETo IRWA} + 6.953\ \text{ETo AVW} - 0.028\ \text{IRWA AVW} - 0.030\ \text{IRWA}^2 + 0.267\ \text{AVW}^2 \quad (10)$$

$$\text{Crop weight} = 221.617 - 31.267\ \text{ETo} + 4.946\ \text{IRWA} - 131.767\ \text{AVW} - 0.641\ \text{ETo IRWA} + 17.865\ \text{ETo AVW} + 0.544\ \text{IRWA AVW} - 0.196\ \text{IRWA}^2 + 2.340\ \text{AVW}^2 \quad (11)$$

where ETo = Potential evapotranspiration (mm/day), IRWA = Irrigation water application (lt/unit); AVW = Available water (lt/unit).

The climate–soil water interaction (ETo-AVW) was the only factor that significantly influenced the growth and production responses of green mustard. The results showed a minimum–maximum effect, or a saddle surface, in which a certain combination would create either a minimum or maximum effect [14, 33]. The interaction effect of ETo-AVW with regard to the crop height, number of leaves, and fresh weight showed similar patterns.

The height and leaf growth of green mustard reached a maximum when the interaction between ETo and AVW was either at its minimum or its maximum. The fresh weight of green mustard was a maximum under the condition that the ETo and AVW were at their lowest or highest values. The maximum condition was seen for a value for ETo of about 4.0–6.5 mm/day at a value of AVW of about 0.1–1.6 lt/unit, and the ETo reached about 7.5–8.0 mm/day at an AVW of about 2.2–5.0 lt/unit. The minimum weight was achieved at the point where ETo was around 6.9–7.3 mm/day at an AVW of around 1.5–2.0 lt/unit. The interaction effect of ETo-AVW on the growth and production of green mustard is illustrated in Figure 10.



a) Crop height b) Number of leaves c) Fresh weight

Figure 10 Significant effect of the ETo-AVW interaction on the growth and production of green mustard

For the response model of water spinach to climate and water, we saw that the growth and production of the crop were significantly affected by ETo, the available water, and their interaction. The fresh weight response had more significant model components, higher coefficients of multiple determination, higher adequate precision, and the lowest PRESS value compared with the responses for the height and number of leaves. The specifications for the water spinach response model are presented in Table 5.

Table 5 Growth and production response model for water spinach

Indicators	Water spinach		
	Height	Number of leaves	Weight
Model forms	Reduced quadratic model		
Analysis of variance (ANOVA)	Significant (p-value < 0.0001)		
Significant model components	AVW and ETo - AVW	AVW and ETo – AVW	ETo, AVW, ETo – AVW, and AVW^2
Coefficient of multiple determination (R^2)	0.949	0.945	0.972
Adjusted R^2	0.928	0.923	0.961
Predicted R^2	0.901	0.889	0.932
Adequate precision	19.526	18.656	25.114
PRESS	274.80	282.80	66.83

Mathematical expressions for the growth and production responses of water spinach are as follows:

$$\text{Crop height} = 423.445 - 61.612\ \text{ETo} + 0.654\ \text{IRWA} - 168.790\ \text{AVW} + 26.132\ \text{ETo AVW} + 1.996\ \text{IRWA AVW} - 0.500\ \text{IRWA}^2 - 4.436\ \text{AVW}^2 \qquad (12)$$

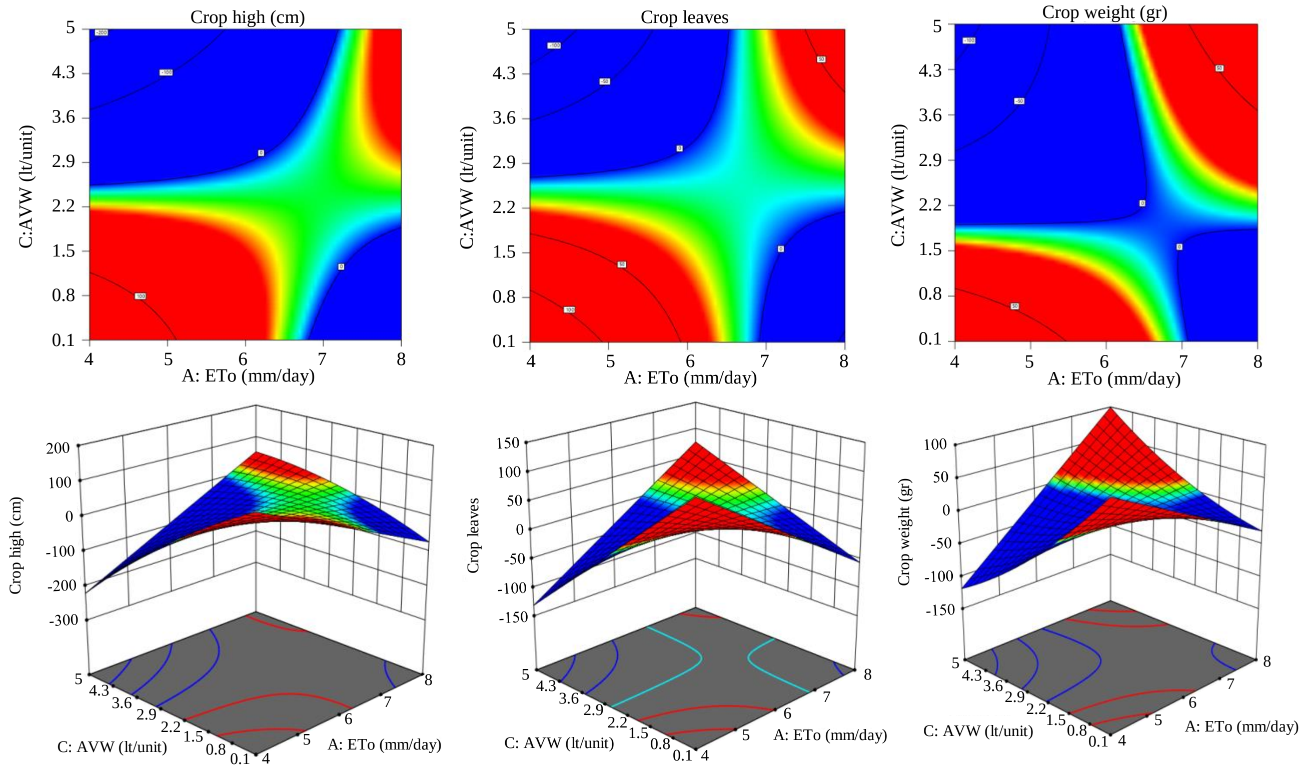
$$\text{Crop leaves} = 368.276 - 52.636\ \text{ETo} - 0.801\ \text{IRWA} - 144.585\ \text{AVW} + 0.093\ \text{ETo IRWA} + 20.826\ \text{ETo AVW} + 1.151\ \text{IRWA AVW} - 0.253\ \text{IRWA}^2 \qquad (13)$$

$$\text{Crop weight} = 211.139 - 29.780\ \text{ETo} + 5.788\ \text{IRWA} - 128.969\ \text{AVW} - 0.759\ \text{ETo IRWA} + 17.451\ \text{ETo AVW} - 0.089\ \text{IRWA}^2 + 3.036\ \text{AVW}^2 \qquad (14)$$

where ETo = potential evapotranspiration (mm/day); IRWA = irrigation water application (lt/unit); AVW = available water (lt/unit).

The climate–soil water interaction (ETo-AVW) was the only factor that significantly influenced the growth and production responses of water spinach. The results showed a minimum–maximum effect, or a saddle shape, which had a minimum or maximum effect [14, 33]. The effect of the ETo-AVW interaction on the crop height, number of leaves, and fresh weight showed a similar pattern. The height and leaf growth of water spinach reached a maximum point when the interaction between ETo and AVW was either at a minimum or a maximum.

The fresh weight of water spinach was a maximum under the condition where the ETo and AVW were at their lowest or highest values. The maximum condition was seen when ETo at about 4.0–5.2 mm/day that combined with AVW at about 0.1–1.0 lt/unit similar to when the ETo reached about 7.5–8.0 mm/day at the AVW of about 2.5–5.0 lt/unit. The minimum weight was achieved under conditions where the ETo was around 4.0–7.0 mm/day and AVW was around 2.5–5.0 lt/unit or conditions where the ETo was around 6.8–8.0 mm/day and the AVW was 0.1–2.0 lt/unit. The significant effect of the ETo-AVW interaction on the growth and production of water spinach is illustrated in Figure 11.



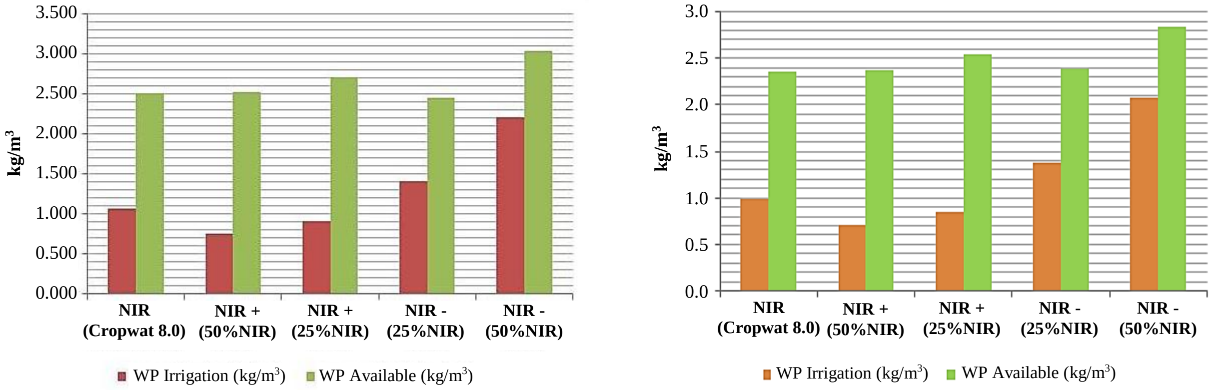
a) Crop height b) Number of leaves c) Fresh weight

Figure 11 Significant effect of the ETo-AVW interaction on the growth and production of water spinach

3.4 Crop water productivity

As expected, the values for CWP based on IWRA and AVW showed a stark difference. The values of $WP_{Availabile}$ for green mustard and water spinach were higher than $WP_{Irrigation}$, with the difference arising from the fact that the denominator or the AVW was lower than the IWRA. It can be inferred that the available water was more effective for crop growth and production, since it was stored in the crop root zone. On the other hand, the IWRA was less effective for crops, because some of it evaporated from the soil surface and drained out of the medium. In addition, since the same soil medium was used with the same water holding capacity, the AVW will naturally be more or less the same, even if the plants were watered more.

The values of $WP_{Irrigation}$ for green mustard ranged from 0.750 kg/m^3 (NIR + 50% NIR) to 2.205 kg/m^3 (NIR – 50% NIR). The values of $WP_{Available}$ for green mustard ranged from 2.446 kg/m^3 (NIR – 25% NIR) to 3.028 kg/m^3 (NIR- 50% NIR). For water spinach, $WP_{Irrigation}$ ranged from 0.706 kg/m^3 (NIR + 50% NIR) to 2.073 kg/m^3 (NIR – 50% NIR), and $WP_{Available}$ ranged from 2.355 kg/m^3 (NIR) to 2.846 kg/m^3 (NIR – 50% NIR). Green mustard had a slightly higher WP than water spinach. The highest values of WP for both green mustard and water spinach cultivated in polybags were achieved when the plants were irrigated with NIR – 50% NIR. The results for crop water productivity are presented in Figure 12.



a) Green mustard

b) Water spinach

Figure 12 Crop water productivity

This study also contributes to the body of research on water productivity in semi-arid developing nations, and particularly the West Timor region. It adds to the previous studies by Koehuan et al. [4, 38] in which it was concluded that water productivity for rice was between 0.290 and 0.930 kg/m^3, and for corn between 0.553 and 1.590 kg shells/m^3. Liu et al. [51] argued that CWP was a crucial metric that could offer benefits in terms of measuring the amount of regional agricultural output and assessing the sustainability of food supply. To mitigate the negative consequences of climate change, a quantitative analysis of how crop production and CWP will respond to future climate change is essential.

4. Conclusions

The values for CWR for green mustard (*Brassica juncea*) and water spinach (*Ipomoea aquatica*) were predicted with the help of FAO-Cropwat version 8.0, with some strong assumptions in regard to the crop and soil characteristics due to insufficient data and expertise. This kind of prediction imitates the limitations that are common to users and farmers in developing nations. Subsequently, the CWR was used as the basis for exploring the variation in IWRA as part of a strategy to tackle these limitations. Both small vegetables showed a similar relationship between water and crop height, although there were slightly different effects from water on the number of leaves, and different effects on the fresh weight.

The growth and production responses of these crops to water were modelled using RSM, and it was found that all of the models gave a better fit to the reduced quadratic model, with significant p-values, considerable coefficients of multi-determination, and acceptable residuals. The most important components of the model were ETo, AVW, and the interaction between ETo and AVW. The last of these affected the crop height, the number of leaves, and the production, with saddle responses. Maximum effects were achieved under conditions of a minimum in both ETo and AVW, or a maximum in both ETo and AVW. Higher values of AVW did not guarantee maximum responses, particularly when ETo was in the low-to-medium range.

We note that $CWP_{Available}$ outperformed $CWP_{Irrigation}$, and that $WP_{Available}$ was higher for green mustard than for water spinach. The highest WP for both green mustard and water spinach was achieved when the plants were irrigated with the IRWA variation of NIR – (50% NIR). CWP proved to be an appropriate indicator to explain the intricate relationship between water, crop growth and production.

We therefore recommend that irrigation prediction and application for small vegetables cultivated in polybags in semi-arid regions with insufficient data should be carried out using FAO-Cropwat version 8.0, with the reduction of IRWA, additionally should be added more replications and more practical response functions should be applied. We also recommend using the FAO AquaCrop model to simulate crop growth responses under varying environmental conditions. Furthermore, we suggest experimenting with crops that are cultivated in fields.

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