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Irrigation and oil palm empty fruit bunch mulch enhance eggplant growth, radiation interception and dry matter yield

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ABSTRACT

Organic mulching is a well-known management practice that conserves soil water and nutrients as well as increases crop yield. Nonetheless, research on combined organic mulching using oil palm empty fruit bunch (EFB) and irrigation is limited. Field-based experiments were conducted over three seasons to test the sole and combined effects of EFB as organic mulch and irrigation on the growth, total dry matter yield (TDMY), accumulated intercepted photosynthetically active radiation (AIPAR), and radiation use efficiency (RUE) of African eggplant (*Solanum aethiopicum* L.) in a low fertile tropical sandy clay loam soil. Air-dried EFB was used as an organic mulch by spreading it on the soil surface at rates of 0 (EFB_0), 20 (EFB_{20}), and 40 t ha^{-1} (EFB_{40}), and either fully-irrigated (I_{100}), deficit-irrigated (I_{40}), or non-irrigated (I_0). The I_{100} plots were irrigated to field capacity (FC) every 3–4 days based on PR2 Profile Probe measurements and the resultant irrigation volume supplied to the plants via drip irrigation tubes. The I_{40} plots received 40 % of the water given to the I_{100} plots, and the I_0 plots were solely rain-fed. At the end of the third season, the 40 t ha^{-1} EFB-mulch increased soil pH, electrical conductivity (EC), soil organic carbon, potassium, cation exchange capacity, and the soil's specific surface area. In the first season, all the measured eggplant growth and yield parameters were neither responsive to irrigation only, EFB-mulch only, or both. In the second and third seasons, the EFB_{20} and EFB_{40} treatments significantly ($p <$ 0.05) increased leaf chlorophyll content index (LCCI), photosystem II (Fv/Fm ratio), absolute performance index (PI_{abs}), TDMY, AIPAR, and RUE compared to the non-mulched control treatment. Soil pH was high in the EFB-mulched plots and correlated positively with TDMY and AIPAR. The I_{100} significantly improved LCCI, Fv/Fm, PI_{abs}, and TDMY during the second season. In the third season, a highly significant interaction between irrigation and mulching was detected on TDMY, AIPAR, RUE, LCCI, Fv/Fm ratio, and pH (H_2O). This indicated a positive effect on soil nutrient availability especially phosphorus as TDMY and AIPAR correlated with soil pH. The I_{100} and I_{40} significantly increased AIPAR by 48.1 % and 37.2 %, and RUE by 26.7 % and 11.0 %, respectively, compared to I_0 during the third season. The total dry matter yield of the African eggplant was enhanced by EFB-mulch, with the effect increasing over up to three growing seasons, especially when combined with irrigation during dry periods.

1. Introduction

Tropical soils are often inherently infertile due to the occurrence of highly weathered clay minerals, low soil organic carbon (SOC) content, low water and nutrient retention ability, and low soil pH (Arthur et al., 2020, Oppong Danso et al., 2019, 2020). For extremely weathered

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tropical soils in sub-Saharan Africa, the projected rise in temperatures and prolonged droughts could negatively affect the soil's productivity. Given that the population of sub-Saharan Africa is expected to quadruple by the end of the century, food insecurity may emerge as a major issue in the region (Abubakari and Abubakari, 2015, Barrett, 2021, Adu et al., 2022). The effect could be severe if there are no instant plans to address the adverse effects of edaphic and climate factors on agricultural production. It is therefore imperative for countries in this part of the world to adopt sustainable and low-cost crop farming and soil management practices that are resource-efficient, climate change resilient, and affordable for resource-poor farmers.

Adding organic amendments to infertile tropical soils either as mulch or fertilizer has been recommended as a low-cost and sustainable way of improving soil fertility and increasing crop yield in smallholder farming systems in sub-Saharan Africa. The application of organic amendments to soils can provide essential nutrients, improve soil structure, increase soil organic matter and ameliorate degraded soils (Rickson et al., 2015, Obour et al., 2020, Oppong Danso et al., 2020, Adu et al., 2022). For example, the use of agricultural wastes such as empty fruit bunches (EFBs) from oil palm (*Elaeis guineensis* Jacq.) either as mulch or when incorporated into the soil as organic amendment is reported to enhance soil water and nutrient retention, and increase crop yield (Adu et al., 2022). Oil palm tree is the key source of plant oil in the tropical region (Anyaoha et al., 2018). The major global producers of palm oil are Indonesia, Malaysia, Thailand, Colombia, and Nigeria, contributing respectively 59.3 %, 24.0 %, 4.4 %, 2.3 %, and 1.8 % of global production (Index Mundi, 2024). EFBs are the fibrous residues that remain after the separation of palm fruits from the fresh fruit bunches. The EFB forms about 33 % of the total dry biomass of the oil palm (Geng, 2013). Annual worldwide production of oil palm generates nearly 99 million metric tons of the EFB (Geng, 2013, Adu et al., 2022). In a few instances, the EFBs are a source of renewable energy generation, and as biofuel and power utilization in the oil palm mills (Geng, 2013). However, the EFBs are mostly discarded as waste and are left to undergo natural decomposition or are incinerated, which exacerbates environmental pollution and the emission of greenhouse gases such as methane and carbon dioxide (Geng, 2013, Rosenani et al., 2016, Adu et al., 2022). Ghana contributes only about 0.4 % to global oil palm production (Index Mundi, 2024), but generates close to 390 t of EFB daily (Oppong Danso et al., 2019). This waste could be applied to the soil as organic mulch to improve the soil fertility.

EFBs applied as mulch decrease evaporation (Moradi et al., 2012, Moradi et al., 2015, Adu et al., 2022), control weeds (Singh et al., 2010), and serve as a soil cover to prevent erosion, particularly, splash erosion (Rhebergen et al., 2020). EFBs applied as mulch can enhance soil physical properties such as soil water retention (SWR), bulk density, and hydraulic conductivity (Arif et al., 2003, Moradidalini et al., 2011, Moradi et al., 2015). EFBs can also serve as an inexpensive source of organic fertilizer because, after a few months of application, they decompose and release nutrients such as N, P, K, Ca, and Mg along with the formation of soil organic matter (Zaharah and Lim, 2000, Abu Bakar et al., 2011, Hoe et al., 2016, Adu et al., 2022). Thus, the EFB mulch could improve soil fertility and plant uptake of essential nutrients (Zaharah and Lim, 2000, Carron et al., 2015). A study by Moradi et al. (2012) showed that plots mulched with EFB had significantly higher plant N, P, K, and Mg uptake than the non-mulched treatments. The addition of EFB-mulch at a rate of 150 kg per tree per year, representing 21 t ha^{-1} can increase soil pH by 1 unit compared to the non-mulch EFB plots (Abu Bakar et al., 2011). A ton of the EFB mulch can hold nutrients equivalent to 17 kg urea, 86 kg single superphosphate, and 50 kg muriate of potash (MOP) (Rosenani et al., 2016). Nithedpattarapong et al. (1996) demonstrated that plant nutrient value of EFB (0.158 % N, 0.08 % P, 0.70 % K, and 0.08 % Mg) is likely to return to the soil when EFB is used as organic mulch and could be regarded as an economically cost-effective benefit to crop performance and physicochemical soil properties.

In sub-Saharan African countries like Ghana, irrigated agriculture has been suggested as a crucial strategy for climate change resilience in the face of changing rainfall patterns and increased dry spells. This is because irrigation has the potential to lessen the detrimental effects of drought on cropping production which threatens the livelihood of many smallholder farmers in the region (Oppong Danso et al., 2018). Hence, the interactive effects of applying organic amendments as mulch and irrigation could be a key element of climate-smart agriculture and sustainable intensification which could serve as insurance against climate-induced drought, increase crop yield, and allow more cropping seasons per year (Rockström et al., 2017, Oppong Danso et al., 2018).

Despite the above challenges, many countries in sub-Saharan Africa are currently confronted with nutritional insecurity owing to vitamin and mineral deficiency from inadequate consumption of vegetables and fruits (Afari-Sefa et al., 2012). Vegetables including the African eggplant (*Solanum aethiopicum* L.) are important sources of human diet and rich in micronutrients such as Zn, Fe, and vitamins which are unavailable in most staples consumed in Ghana (Afari-Sefa et al., 2012, Fadairo et al., 2020). However, vegetable production in Ghana is too low to meet the recommended minimum per capita consumption of 200 kg $person^{-1}$ yr^{-1} (Afari-Sefa et al., 2012). Vegetable cultivation in Ghana is generally hindered by low soil fertility, adverse climate variation from exposure to heat and erratic rainfall, and pests and diseases which reduce production (e.g. Nelson et al., 2010, Adjei-Nsiah and Obeng, 2013, Fadairo et al., 2020). Increased eggplant production in Ghana using EFB mulch materials and irrigation is, therefore, necessary to ensure high productivity, secure human nutritional security and provide a lucrative source of employment for rural, urban and peri-urban inhabitants.

Currently, there is limited research on the impact of organic amendments on the predominant tropical soils (e.g. Acrisols) found in the semi-deciduous agroecological zones (SDAZ) in Ghana (Adjei-Nsiah and Obeng, 2013, Oppong Danso et al., 2019, Obour et al., 2020). For example, irrigation and/or rice husk biochar can improve the hydro-physical properties of tropical sandy clay loam soil in the SDAZ (Obour et al., 2019, 2020). Also, crop growth, yield, accumulated intercepted photosynthetic active radiation (AIPAR), total dry matter yield (TDMY), and radiation use efficiency (RUE) were increased when irrigation was combined with rice husk biochar (Oppong Danso et al., 2019, 2020). On the other hand, EFB has received very little research attention in the SDAZ, especially concerning vegetable production. Except for the research works by Adjei-Nsiah and Obeng (2013) and Adjei-Nsiah (2012) which examined the effect of oil palm bunch ash (PBA) on the growth and yield of maize and some vegetables in the SDAZ, no study has explored how EFB when used as mulch or in combination with irrigation may affect the growth and production of vegetables such as the African eggplant. This study aims to fill the research gaps by exploring how the combined effects of EFB-mulch and varying irrigation affect vegetable production in Ghana under different growing seasons. Thus, providing valuable insight for sustainable agriculture to smallholder vegetable farmers and hence increasing the recommended minimum capita consumption of vegetables in Ghana. We hypothesized that the combination of oil palm EFB and irrigation will improve tropical soil quality and increase crop productivity of the African eggplant. Based on the above-mentioned knowledge gaps and our aim to fill them, we set out to (i) explore the effect of EFB-mulch on soil physical and chemical properties; (ii) assess the growth of African eggplant by examining its leaf chlorophyll, fluorescence properties, and the fraction of intercepted photosynthetically active radiation (f_{PAR}) under the influence of EFB mulch; and (iii) evaluate the total dry matter yield and radiation interception of African eggplant under different irrigation regimes with or without the application of EFB used as organic mulch.

2. Materials and methods

2.1. Site description

Three consecutive field experiments each one starting right after the previous one on the same plots, covering the three distinct growing seasons in Ghana were conducted at the University of Ghana’s Forest and Horticultural Crops Research Centre (FOHCREC) located on 06° 08’ 37"N and 00° 54’ 10" W, Okumaning-Kade at an altitude of 180 m above sea level. The experimental site is located within the SDAZ of Eastern Ghana, an area recognized as one of the nation’s food production zones because of the favourable climate and soil conditions for crop growth. There are two different rainy seasons (major and minor seasons) in the area with an annual rainfall ranging between 1300 and 1800 mm. The main rainy season is from April to July and the minor season is from September to October with about 80 % of the annual rainfall occurring in the two seasons (Ofosu-Budu, 2003, Oppong Danso et al., 2019). There is a short dry spell in August and an extended dry period from December to March. The mean annual temperature is 28 °C with the maximum temperature recorded in March while the minimum temperature is recorded in August. The recorded annual potential evaporation is about 1400 mm (Oppong Danso et al., 2019, 2020). The annual mean relative humidity is about 80 % with the maximum mean humidity sandwiched between the two rainy seasons (July to September). The favourable climate and moderately fertile soils of the SDAZ in Eastern Ghana position it as a potential food basket, supporting the production of key crops for the country (Oppong Danso et al., 2019).

2.2. Oil palm empty fruit bunch and soil properties

Oil palm EFBs from farmers’ fields around FOHCREC were used as the mulching material. The bulk EFBs were air-dried and samples were dried in the oven to determine the moisture content. The moisture difference was considered in determining the required dry weight proportions spread on the soil as organic mulch. Some chemical properties of the raw EFB used in the experiment are presented in Table 1. The soil at the experimental location is generally well-drained forest Ochrosol developed from Precambiam phyllitic rocks (Adjei-Nsiah, 2012) which are sandy clay loam textured soils classified as Acrisols according to the WRB (2015) classification. The physical and chemical characteristics of the soil before the experiments are shown in Table 2.

The soil texture was measured using the procedure described in Gee and Bauder (1986). Soil pH, oxidation-reduction potential (ORP), and electrical conductivity (EC) were determined with a tabletop HI2550 pH/ORP & EC/NaCl Meter (Hanna Instrument, United Kingdom). Soil pH and ORP were determined by weighing 10 g of air-dried soil sample mixed with 25 mL of deionized water (1:2.5). For soil EC determination, 4 g of air-dried soil sample was weighed and mixed with 36 mL of deionized water, shaken for 1 h, and settled for 1 h. To determine total carbon content and total N, the samples sieved to 2 mm were subjected to ball milling prior to carbon oxidation at 950 °C using an elemental analyzer equipped with a thermal conductivity detector (Thermo Fisher Scientific, Waltham, MA, USA). The total C of the soil samples was taken as soil organic carbon as there were no carbonates present in the soil samples. P and K were extracted with sodium bicarbonate and ammonium acetate, respectively (Sørensen and Bülow-Olsen, 1994) and Fe with DPTA-calcium chloride solution. Cation exchange capacity (CEC) and specific surface area (SSA) of the soils were determined from hygroscopic water content measured at 47 % relative humidity using linear regression models for kaolinite-rich soils developed by Arthur (2017) and Yan et al. (2023), respectively.

2.3. Experimental layout and treatment description

The same experimental plots were used for all three growing seasons: (i) the first growing season fell within the minor rainy season from September 15, 2021 to December 29, 2021; (ii) the second growing season within the major rainy season from March 18, 2022 to June 30, 2022; and (iii) the third growing season within the dry season from November 30, 2022 to March 15, 2023. The experimental design used was a split plot in a randomized complete block design with four replicates. Three irrigation levels of full irrigation (I_{100}), deficit irrigation (I_{40}), and no irrigation (I_0) were the main plots with three EFB mulch levels on dry matter (DM) basis of 0 t DM ha^{-1} (EFB_0), 20 t DM ha^{-1} (EFB_{20}), and 40 t DM ha^{-1} (EFB_{40}) as the sub-plots. The dimension of the main plot was 9 m x 5 m, which was then divided into three sub-plots with dimensions of 3 m x 5 m (15 m^2). Buffer strips of 2 m and 0.5 m between the main and sub-plots, respectively, were left to provide access pathways and more importantly to minimize lateral movement of irrigation water and the EFB-mulch material between plots and blocks.

The applied EFB-mulch rates in the present study (20 and 40 t ha^{-1}) fall within the range rates from 18.75 to 90 t ha^{-1} applied to highly weathered acidic and low organic matter soils in previous studies (Caliman et al., 2001, Sabrina et al., 2011, Carron et al., 2015). Irrigation water was supplied through pressure-compensated drip emitters (discharge rate of 2.7 L h^{-1} at 100-kPa inlet pressure) of 16-mm drip laterals (Naandanjain, Jalgaon, India). The drip laterals were connected to a 32 mm polyethylene sub-main line and spaced 30 cm apart. Water for irrigation was pumped from a nearby dam and filtered using a 125 µm diameter (120-mesh) screen filter (Naandanjain, Jalgaon, India). The non-irrigated plots were demarcated with transplanting distances as that of the irrigated plots. Before the EFB mulch application, the soil was tilled to a depth of 15 cm using a hoe. Because of the bulkiness of the EFB material, the amount of the mulch applied was split into two equal amounts to avoid hosting pests. The first half of the EFB mulch amount was applied on September 10, 2021, while the second and final part was applied on March 4, 2022. During each split application round, 15 kg (10 t ha^{-1}) and 30 kg (20 t ha^{-1}) of air-dried EFB material were spread by hand on each plot size of 15 m^2. Thus, the EFB organic mulch treatments (EFB_0), (EFB_{20}), and (EFB_{40}) received 0, 10, and 20 t ha^{-1} during each split application, adding up to 0, 20 and 40 t ha^{-1} after the last application.

The experimental plots were transplanted with an African eggplant locally called “Aworoworo” in all the growing seasons. The variety used thrives in the forest areas and is well adapted to the area which is also popularly cultivated by farmers. Although the non-mulched (EFB_0) plots did not receive the EFB mulching material, they were also equally tilled as the EFB mulched plots during each split application to maintain evenness among treatments. After manually spreading the EFB material, a hand rake was used to evenly spread the material on the entire experimental plots. The seeds were first prepared into seedlings in seed trays (128 cells) with rice husk biochar-mixed-soil media (1:1 ratio, v/v) for 6 weeks before transplanting to the field. Two to three seeds were placed in each cell and later thinned to one after germination to ensure

Table 1
Some chemical properties of the oil palm empty fruit bunch used in the experiment.

pH (H_2O)	EC µS cm^{-1}	M	AC	ADL	OC	N	S	O	P	K	Cu	Zn	∑PAHs
					w/w%						mg 100 g^{-1}		
8.05	1150	12.8	7.10	16.0	47.1	1.90	0.14	40.0	45	930	15	38.0	0.2

EC, electrical conductivity; M, moisture content; AC, ash content; ADL, acid detergent lignin; OC, organic carbon; N, nitrogen; S, sulphur; O, oxygen; P, phosphorus; K, potassium; Cu, copper; Zn, Zinc; PAH: poly-aromatic hydrocarbons (calculated as the mathematical sum of 17 PAHs).

Table 2
Some soil physical and chemical properties before the start of the experiments.

Clay	Silt	Sand	ρ_b	pH	EC	SOC	TN	P	K	Fe
	%		g cm^{-3}	(H$_2$O)	µS cm^{-1}		%		mg 100 g^{-1}	
21	14	65	1.51	5.30	29.33	1.8	0.14	0.73	6.83	69.4

ρ_b, dry bulk density; EC, electrical conductivity; SOC, soil organic carbon; TN, total nitrogen; P, phosphorus; K, potassium; Fe, Iron.

good seedling establishment. Seeds were extracted from freshly matured eggplant (fruits with shiny and firm peels) from the first and second growing seasons and used as planting materials for the subsequent seasons. The eggplant seedlings were transplanted: on September 15, 2021; March 18, 2022; and November 30, 2022, for the first, second, and third seasons, respectively. The transplanting was carefully done by removing the whole roots with the media in each cell to limit possible transplanting shocks. The seedlings per cell were transported into holes of 5 cm depth to obtain one plant per hill giving a plant population of 30 plants per plot. A few seedlings that could not survive within the first seven days after transplanting (7 DAT) were replaced with seedlings from the same batch. After transplanting and during periods of no rainfall, all plots (both irrigated and non-irrigated) were irrigated with 3 mm of water every day for the first 25 days after which the irrigation treatments were imposed on 26 DAT. Mancodoc (Mancozeb 800 g/kg) and Suncozed (80 % WP Mancozeb) were applied as fungicides, whereas Akate (27 g/litre bifenthrin) and Attack (475 g/litre pirimiphos-methyl + 25 g/litre permethrin) were applied as insecticides in the mornings every two weeks from 20 DAT until 50 DAT at the initiation of the flower set. All treatments received the same amount of nitrogen (N), phosphorus (P), and potassium (K) fertilizers applied via urea, triple super phosphate (TSP), and muriate of potash at rates of 150 kg N ha^{-1}, 80 kg P ha^{-1}, and 100 kg K ha^{-1}. The P and K fertilizer amounts were applied at pre-transplant but for N fertilizer, 50 % was applied at 15 DAT and the remaining 50 % was added at 50 DAT (during flowering). All the fertilizer was banded and covered to a depth of around 5 cm along the eggplant rows.

2.4. *Sampling and measurements*

2.4.1. *Soil water content and irrigation management*

The soil water content (SWC) during the three seasons was measured on three replicate plots of each treatment using the PR2 Profile Probe instrument (Delta-T Devices, Cambridge-England) in vertically installed access tubes in the middle of each plot at an adjacent distance of about 3 cm from the emitter and to a vertical depth of 100 cm. The PR2 Profile Probe instrument was connected to HH2 Moisture Meter which aids in displaying and storing readings from the Profile Probe. The SWC at field capacity, FC (water content at –300 hPa), described as SWC determined 2 – 4 days after the soil had been thoroughly wetted by rain accompanied by natural drainage was measured before transplanting. SWC during all three seasons commenced after the establishment stage (26 DAT) and stopped at physiological maturity (104 DAT). The soil water content data from the Profile Probe were used to compute the soil water deficit (SWD), described as SWC at field capacity minus actual determined soil moisture content.

Metal core samplers of 100 cm^3 (6.1 cm diameter, 3.4 cm high) were used to collect 27 undisturbed soil samples (3 replicates from each plot × 3 organic mulch rates × 3 experimental blocks). The sampling was done at the end of the third growing season in June 2023 on only the fully irrigated plots to a depth between 0 – 15 cm. The sampling was from only the irrigated plots because we anticipated the mulch rather than irrigation would affect the physical and chemical properties of the soils. The three EFB mulch rates are 0 t ha^{-1} (EFB$_0$), 20 t ha^{-1} (EFB$_{20}$), and 40 t ha^{-1} (EFB$_{40}$). The samples were used for soil water retention (SWR) determination. The measurement of the soil water retention curve from –10 to –1000 hPa matric potential was done using sandboxes, vacuum pots, and pressure plates. For matric potentials between –10 and –100 hPa, the soil cores were placed in a sandbox and slowly saturated by capillary action with water from beneath to get rid of all entrapped air. The samples were then drained slowly to the respective matric potentials of –10, –30, –50, and –100 hPa. Vacuum pots and pressure plates were used for the matric potentials of –300, –500, and –1000 hPa following the process described by Scanlon et al. (2002). The water content at –15000 hPa matric potential was determined on the disturbed air-dried <2 mm samples using a WP4-T dewpoint potentiometer following the method by Scanlon et al. (2002). After measuring SWR at –1000 hPa matric potential, the core samplers were oven-dried for 24 h at 105 °C. Dry bulk density was computed as the ratio of the oven-dried soil mass to the total volume of each soil core. The total porosity (ϕ) was estimated from measured bulk density and an assumed particle density of 2.65 g cm^{-3}. Plant available water content (PAW) was determined as the difference between field capacity (water content at –300 hPa) and the PWP water content ($w_{15000\text{hPa}}$) measured with the WP4-T dewpoint potentiometer (Scanlon et al., 2002).

Finally, soil moisture depletion of eggplant at which yield decline is not expected (readily available water, RAW) was calculated as 45 % of PAW as reported by Allen et al. (1998).

Irrigation water was supplied to the crops of I$_{100}$, and I$_{40}$ treatments every three to four days to refill soil water deficit to back to field capacity as measured by early morning PR2 profile probe readings on the day of irrigation. The I$_{40}$ plots received 40 % of the amount given to the I$_{100}$ plots. The length of the drying cycle of the I$_0$ plots relied on the interval between successive rainfall events. The amount of irrigation water to apply was estimated using Eq. 1:

$$I = A \times d \times \left(\frac{1}{AE}\right) \times fw \tag{1}$$

where I is the amount of irrigation water (litres), A is the plot area (m^2); d is the irrigation depth (mm) which was equal to the determined SWD in the irrigated plots, AE is the application efficiency considered as 90 % for drip irrigation (Dworak et al., 2007) and fw is percentage of the wetted area taken as 40 % for drip irrigation (Allen et al., 1998).

2.4.2. *Growth and total dry matter yield of the African eggplant*

Leaf chlorophyll content index (LCCI), chlorophyll fluorescence of photosystem II (Fv/Fm), and performance index (PI) were monitored four times, during the early vegetative stage, full vegetative stage, flowering and fruiting stages. The four stages were on the 21, 35, 49, and 63 DAT which corresponded to thermal time after transplanting (TT, °C d) of 337, 561, 783, and 1008 in the first season; 338, 570, 797, and 1026 in the second season and 338, 544, 761, and 981 in the third season. The calculated daily TT for the three seasons were according to (Miller et al., 2001) and (León Pacheco et al., 2019):

$$TT = \left(\frac{T_{\max} - T_{\min}}{2}\right) - T_{base} \tag{2}$$

where $T_{\max}$ is the maximum daily air temperature (with temperatures above 30 °C relapsed to 30 °C), $T_{\min}$ is the minimum daily air temperature (°C), and T_{base} is the base temperature equal to 10 °C.

A handy Pocket PEA chlorophyll fluorimeter (Hansatech Instruments Ltd, UK) was used to monitor the chlorophyll fluorescence, while a chlorophyll meter (CCM-100, Opti-Sciences, Inc) was used for the leaf CCI. The chlorophyll fluorimeter was used in the second and third seasons only, where Fv/Fm is presented as a ratio of variable fluorescence

(Fv) over the saturated or maximum fluorescence value (Fm) and PI_{abs} indicated as the performance index on an absorption basis. For both instruments, data was taken in all the plots on four plants and two leaves giving a total of 8 measurements, which were averaged to find one value per plot.

At physiological maturity, fresh fruits from six plants in the middle of each plot were harvested manually every week. At the end of each growing season, six plants from each plot were randomly selected to estimate the total dry matter yield (TDMY, t ha^{-1}). The stem of each eggplant was cut at 3 cm above ground level and the leaves were separated from the stem, whereas the whole crop dry matter excluding the roots was cut into pieces. The leaves and the stems were oven-dried at 80 °C and weighed until they became constant for TDMY determination.

2.4.3. *Determination of radiation interception*

The photosynthetically active radiation (PAR) in the red (400 nm) and near-infrared (700 nm) waveband intervals of the eggplant canopy were measured using a hand-held AccuPAR model LP-80 PAR/LAI Ceptometer (METER Group, Inc. Pullman USA). To read both the incident PAR (PAR_i) and the transmitted PAR (PAR_t), the ceptometer measurements were recorded above and below the eggplant canopy, respectively. The readings were taken on a clear sky condition and at high solar inclination in each plot every 7–9 days from 14 DAT to physiological maturity (105 DAT). The fraction of intercepted photosynthetically active radiation (f_{PAR}) was computed using as:

$$f_{PAR} = \frac{(PAR_i - PAR_t)}{PAR_i} \tag{4}$$

Linear interpolation between the weekly measurement dates for each plot was carried out in GaphPad Prism (Version 8.0.2 263) to obtain f_{PAR} values for each day. The unknown f_{PAR} values were interpolated using the Beta growth then decline model by selecting the *fit a curve* with a linear regression model in the analyzing tool in the Prism. The model uses the equation by Yin et al. (2003) as:

$$Y = Y_m\left(1+\frac{t_e-t}{t_e-t_m}\right)\left(\frac{t}{t_e}\right)^{\frac{t_e}{t_e-t_m}} \tag{5}$$

where Y is the unknown f_{PAR} value, Y_m is the peak value of Y, t_e is the day on which f_{PAR} peaks, t_m is the inflection day at which the f_{PAR} rate reaches its maximum value, and t is the day of the interpolated f_{PAR}. Among the several models in the Prism, Eq. 5 best described and represents the f_{PAR} patterns which assume that each DAT has an ideal f_{PAR} value predicted with the addition or subtraction of random error. The GraphPad Prism afterward interpolated timely f_{PAR} values with iteration numbers between 14 and 106 DAT from standard curves at a 95 % confidence interval. From the computed f_{PAR} values and the measurement of incident global radiation at the local meteorological station, the amount of accumulated intercepted photosynthetically active radiation (AIPAR, MJ m^{-2}) that the eggplant intercepted from 14 to 105 DAT was calculated (Vargas et al., 2002, Zhou et al., 2017, Oppong Danso et al., 2019, 2020):

$$AIPAR = \sum_{14}^{105} 0.5 \times Q \times f_{PAR} \tag{6}$$

where Q is the daily global radiation (MJ m^{-2}).

We finally estimated radiation use efficiency (RUE) as:

$$RUE = \frac{TDMY}{AIPAR} \tag{7}$$

where *RUE* is in g MJ^{-1} and TDMY is in g m^{-2}.

2.5. *Statistical analysis*

Statistical analyses were performed on the data using the R software package version 4.4.2 (R Core Team, 2022). To determine the effect of treatment on ρ_b, PAW, pH, EC, SOC, TN, K, CEC, SSA, LCCI, Fv/Fm, PI_{abs}, AIPAR, and RUE, linear mixed-effect models were fitted to the data with the *lmer* function in the 'lme4' R package as:

$$Y_{ijsr} = \mu + I_i + E_j + G_s + I_i \times E_j + I_i \times G_s + E_j \times G_k + P_r + e_{jsrn} \tag{8}$$

where Y_{ijsr} is an observation of the dependent variable, μ is the overall mean, I_i is the effect of irrigation ($i = 3$, full, deficit, and no irrigation; for ρ_b, PAW, pH, EC, SOC, TN, K, CEC, and SSA, $i = 1$, full irrigation only), E_j is the effect of the EFB-mulch application rate (j = 0, 20 and 40 t ha^{-1}), G_k is the effect of the growing season (s = first, second, and third growing season; for ρ_b, PAW, pH, EC, SOC, TN, K, CEC, and SSA, s = third growing season only), P_r is the random effect of replication ($r = 4$) and e is the unexplained variation. The parameters of the models were estimated by the restricted maximum likelihood (REML) method. Model residuals were observed for normality and variables were log- or square-root-transformed to obtain normality of data. The criterion used for the statistical significance of the treatment effect was $p < 0.05$. When the treatment effect was significant, further analyses were performed to identify which treatment means were different by performing a pairwise comparison using the R *agricolae* package and Tukey's Honestly Significant Difference (Tukey's HSD) test. Regression analyses between AIPAR and TDMY and between pH and TDMY, AIPAR, and RUE were done separately for the irrigated and unirrigated treatments for each study season on all the EFB mulch rates.

3. Results

3.1. *Weather conditions*

The highest cumulative rainfall was recorded in the second season (621 mm), whereas the first growing season had 336 mm and the least rainfall of about 214 mm occurred in the third season. The rainfall distribution patterns during the growing season in the first two experiments in 2020 and 2021 were almost similar, except that the second season received an even distribution of heavy rainfall throughout the season while the first season experienced a similar uniform pattern but with limited rainfall amounts approaching the end of the season (Fig. 1). Conversely, long dry spells were experienced in the third season between 18 and 61 DAT, 62 and 68 DAT, and then from 78 to 88 DAT. Although some short dry spells occurred in the third season before 18 DAT, all the plots were irrigated with the same amount of water till 26 DAT. However, the total rainfall from the start of irrigation to the end of each season was 208, 494, and 165 mm for the first, second, and third seasons, respectively. The total irrigation amount for I_{100} was 178, 345, and 911 mm for the first, second, and third seasons, respectively. The computed seasonal cumulative reference evapotranspiration (ET_0) with the FAO Penman-Monteith equation (Allen et al., 1998) was 430, 500, and 512 mm for the first, second, and third seasons, respectively. Almost all the seasons experienced similar temperature patterns with 27.9 °C, 28.4 °C, and 28.1 °C mean temperatures for the first, second, and third seasons, respectively. The second season recorded the highest solar radiation with a mean value of 13.47 MJ m^{-2} day^{-1}, followed by the first, and third with mean values of 12.48 and 10.97 MJ m^{-2} day^{-1}, respectively (Fig. 1).

3.2. *Soil physical and chemical characteristics*

The soil water deficit (SWD) was generally higher in the third growing season than in the first and second growing seasons (Fig. 2). In the first season, the highest mean SWD for the I_{100}, I_{40}, and I_0 EFB_{40} treatments were 8.7 mm, 9.8 mm, and 25 mm, respectively. For the second season, the mean highest soil water deficit was 10.8 mm, 13.2 mm, and 51.8 mm, respectively while for the third season, the equivalent values were 9.2 mm, 18.3 mm, and 66.7 mm, respectively.

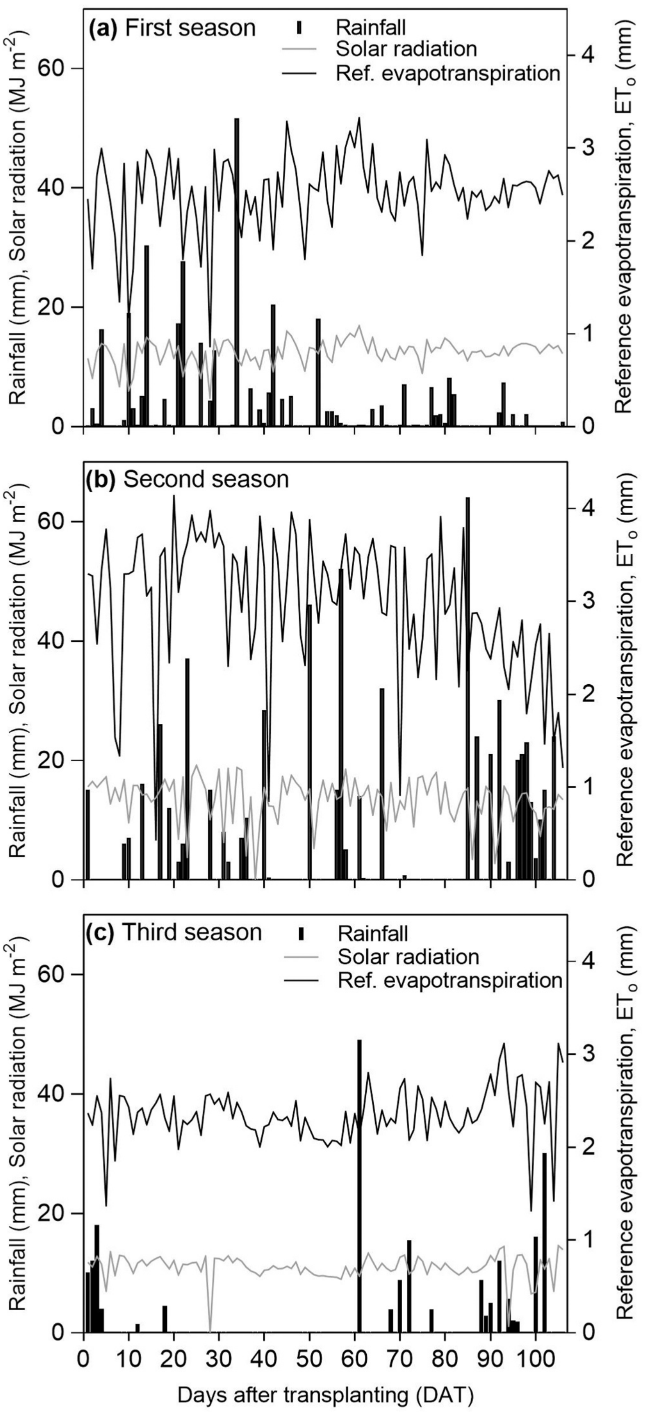

Fig. 1. Weather conditions from transplanting of eggplant to maturity for the first, second, and third growing seasons.

The I_0EFB_{40} treatment had two drying cycles in the first and second seasons, respectively. Nonetheless, the length of the drying cycles was shorter during the first season compared with the second season (Fig. 2a and b). For the third season, four drying cycles were recorded (Fig. 2c). In the second season, the first and second drying cycles for the I_0EFB_{40} treatment lasted for 12 and 15 days reaching 25.5 mm and 51.7 mm SWD, respectively. The I_iEFB_{40} treatments were irrigated three, and five times during these dry periods. During the third season, the four drying cycles for the non-irrigated treatments persisted for 35, 9, 23, and 8 days corresponding to 62.9, 38.0, 66.3, and 37.7 mm SWD, respectively. During these periods, the I_iEFB_{40} treatment was irrigated eleven, three, five, and one times, respectively.

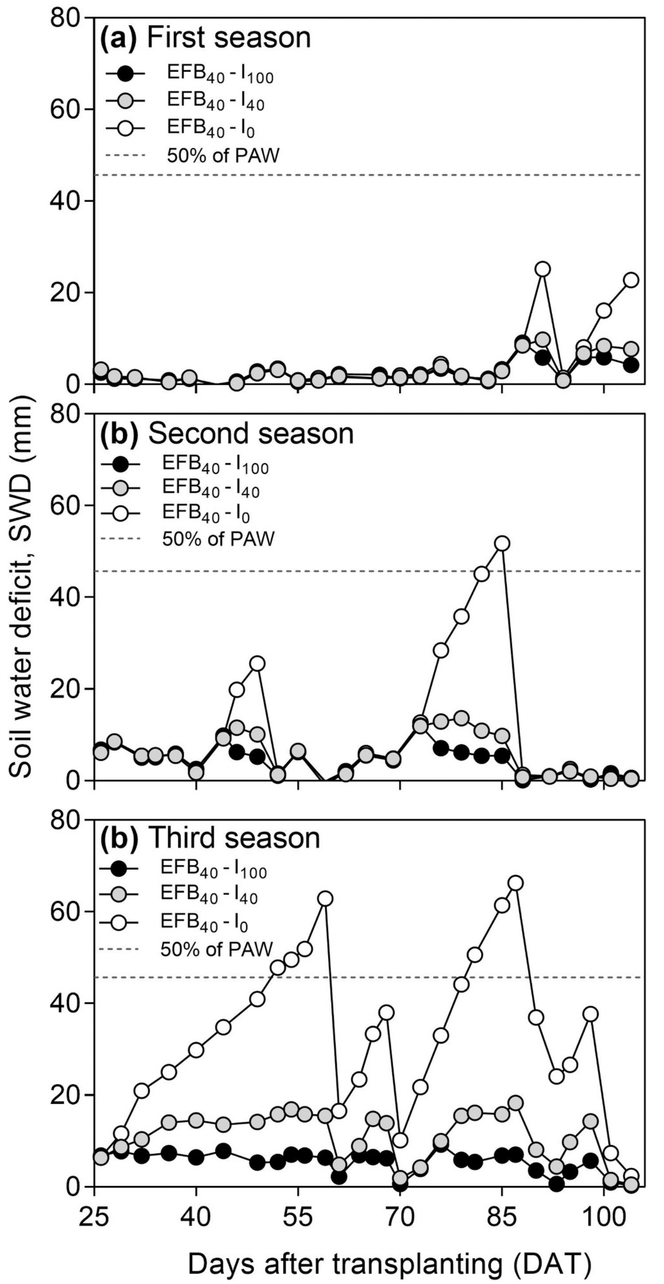

Fig. 2. Soil water deficit for the 40 t ha^{-1} EFB mulch rate (EFB_{40}) under I_{100}, I_{40}, and I_0 treatments during the first, second, and third growing seasons.

The EFB_{20} and EFB_{40} tended to increase soil water content at all the measured matric potentials compared to the control, 0 t ha^{-1} treatment (Fig. 3a). The PAW was slightly lower for EFB_{20} (Fig. 3b). EFB mulched plots marginally decreased ρ_b compared to the non-mulch plots (Table 3). Also, the addition of the EFB-mulch marginally increased the ϕ (m^3 m^{-3}) by approximately 7 % and 9 % for the EFB_{20} and EFB_{20}, respectively, compared to the non-mulch control treatment. Soil pH was also affected by the EFB-mulch rates where EFB rates were significantly higher than the control treatment and the EFB_{40} was also higher than the EFB_{20} treatment. The EC and TN in the EFB_{40} were 37 %, and 31 % higher, than the non-mulched treatment. For EFB_{40} and EFB_{20}, the EC and TN parameters were, however, not significantly different. Differences in SOC between treatments were observed. SOC was highest for the EFB_{40} followed by the EFB_{20} than the control treatment. From Table 3, K increased with increasing EFB mulch rates. The highest K

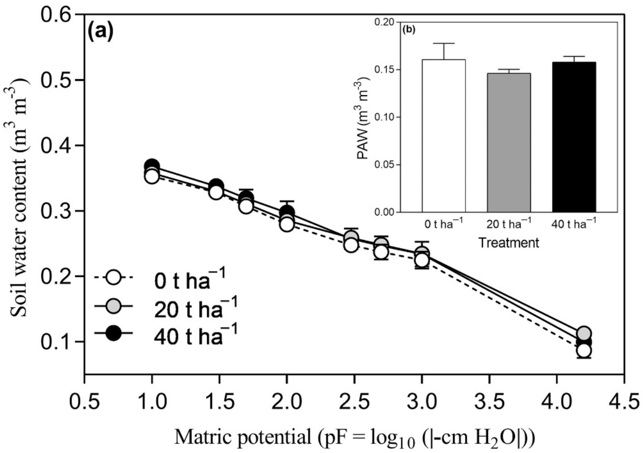

Fig. 3. (a) Soil water content at matric potentials between pF 1.0 and pF 4.2 for EFB-mulch rates of 0 t ha^{-1}, control (EFB$_0$), 20 t ha^{-1} (EFB$_{20}$), and 40 t ha^{-1} (EFB$_{40}$). (b) Plant available water (PAW) for the 0 t ha^{-1}, 20 t ha^{-1} and 40 t ha^{-1} treatments. Error bars indicate the standard error of the mean (n = 3).

value was observed in the EFB$_{40}$, followed by the EFB$_{20,}$ and the lowest in the non-mulched plots. The CEC and SSA values for the EFB-mulch rate of EFB$_{40}$ were higher than the non-mulched control treatment (Table 3).

3.3. *Leaf chlorophyll content index, and leaf fluorescence*

Table 4 shows the effects of EFB mulch and irrigation on leaf chlorophyll content index (LCCI), and fluorescence. Leaf fluorescence measurements were not done in the first season due to equipment failure. Regarding LCCI, data in the first season showed that neither irrigation nor EFB mulch significantly increased the chlorophyll content. Comparatively, in the first and second seasons, irrigation and EFB mulch did not interactively influence the leaf CCI, Fv/Fm, and PI$_{abs}$ (Table 6). In the second season, there was no significant difference between the I$_0$ and I$_{40}$ treatments, whereas the I$_{100}$ irrigated plots had higher leaf CCI, Fv/Fm, and PI$_{abs}$. In the third season with pronounced drought, irrigation had a significant effect on LCCI, Fv/Fm, and PI$_{abs}$ with I$_{100}$ recording significantly higher values compared to I$_{40}$ and I$_0$. Unlike the first season, the second and third seasons of EFB-mulch at 20 and 40 t ha^{-1} rates significantly increased leaf CCI, Fv/Fm, and PI$_{abs}$ compared to the 0 t ha^{-1} treatment (Table 4). In the drier third season, there was a synergetic interactive effect between irrigation and EFB-mulch on the measured leaf CCI and Fv/Fm (Table 6). In general, the values of the leaf CCI, Fv/Fm, and PI$_{abs}$ were marginally higher in the second season than the values in the first and third seasons. Whereas the EFB-mulch treatments had higher growth values in the last two growing seasons than the first season, the unamended EFB plots recorded low values in those seasons compared to the first season (Table 4).

3.4. *Seasonal radiation interception*

The dynamics of eggplant f_{PAR} under different EFB-mulch and irrigation is shown in Fig. 4. In the first season (Fig. 4a-f), f_{PAR} was not responsive to either EFB-mulch or irrigation levels. During the second (Fig. 4j-i) and third (Fig. 4p-r) growing seasons, the measured f_{PAR} was enhanced by EFB-mulch rates. For the impact of irrigation on f_{PAR} in the second season, significant effects within DAT were observed for 49 and 90 DAT under only the non-mulched EFB treatment (Fig. 4g). During the same second season, f_{PAR} was responsive to EFB-mulch rates, and the

Table 3
Physical and chemical properties of EFB mulch treatments under full irrigation in the third season.

EFB rate	ρ_b	ϕ	pH	EC	SOC	TN	K	CEC	SSA
t ha^{-1}	g cm^{-3}	m^3 m^{-3}		μS cm^{-1}	%		mg 100 g^{-1}	cmol$_+$ kg^{-1}	m^2 g^{-1}
0	1.52 a	0.43 a	5.07c	24.05 b	0.96c	0.097 b	9.85c	7.3 b	34.8 b
20	1.44 a	0.45 a	5.42 b	27.48 ab	1.42 b	0.113 ab	13.75 b	8.2 ab	37.1 ab
40	1.35 a	0.49 a	5.76 a	32.83 a	1.61 a	0.127 a	19.75 a	9.4 a	39.5 a

ρ_b, dry bulk density; ϕ, total porosity; EC, electrical conductivity; SOC, soil organic carbon; TN, total nitrogen; K, potassium; CEC, cation exchange capacity; SSA, soil's specific surface area. Values within the same column with different letters are significantly different at $p < 0.05$.

Table 4
Leaf chlorophyll content index (CCI), efficiency of photosystem II (Fv/Fm), and absolute performance index (PI$_{abs}$) as enhanced by oil palm empty fruit bunch mulch and irrigation treatments.

	First season EFB mulch rate (t ha^{-1})				–	Second season EFB mulch rate (t ha^{-1})				–	Third season EFB mulch rate (t ha^{-1})			
Irrigation	0	20	40	Mean		0	20	40	Mean		0	20	40	Mean
Leaf CCI														
I$_{100}$	55.3	55.4	55.0	55.2 a		62.1	66.8	69.5	66.1 a		55.1	68.0	73.7	65.6 a
I$_{40}$	55.6	55.3	55.5	55.4 a		60.0	65.9	68.5	64.8 ab		52.1	64.3	68.3	61.6 b
I$_0$	56.4	54.8	54.0	54.1 a		56.2	65.2	68.2	63.2 b		48.6	57.0	59.8	55.1c
Mean	55.8 A	55.1 A	54.8 A			59.4 C	66.0 B	68.7 A			51.9 C	63.1 B	67.3 A	
Fv/Fm ratio														
I$_{100}$	nd	nd	nd	nd		0.71	0.75	0.76	0.74 a		0.66	0.73	0.77	0.72 a
I$_{40}$	nd	nd	nd	nd		0.67	0.71	0.73	0.70 ab		0.60	0.69	0.72	0.67 b
I$_0$	nd	nd	nd	nd		0.63	0.67	0.69	0.66 b		0.57	0.64	0.69	0.63c
Mean	nd	nd	nd	nd		0.67 C	0.70 B	0.73 A			0.61 C	0.68 B	0.73 A	
PI$_{abs}$														
I$_{100}$	nd	nd	nd	nd		4.12	4.37	4.62	4.37 a		3.60	4.44	4.87	4.30 a
I$_{40}$	nd	nd	nd	nd		3.81	3.97	4.31	4.03 ab		2.96	3.93	4.34	3.74 b
I$_0$	nd	nd	nd	nd		3.54	3.66	4.04	3.75 b		2.70	3.84	4.04	3.53c
Mean	nd	nd	nd	nd		3.82 C	3.99 B	4.32 A			3.09 C	4.07 B	4.42 A	

Note: Photosystem II (Fv/Fm) and performance index (PI) values were not determined in the first season and hence nd denotes parameters not determined. Values within the same column (for EFB rates) or row (for irrigation levels) in the same experimental season without common letters are significantly different at $p < 0.05$.

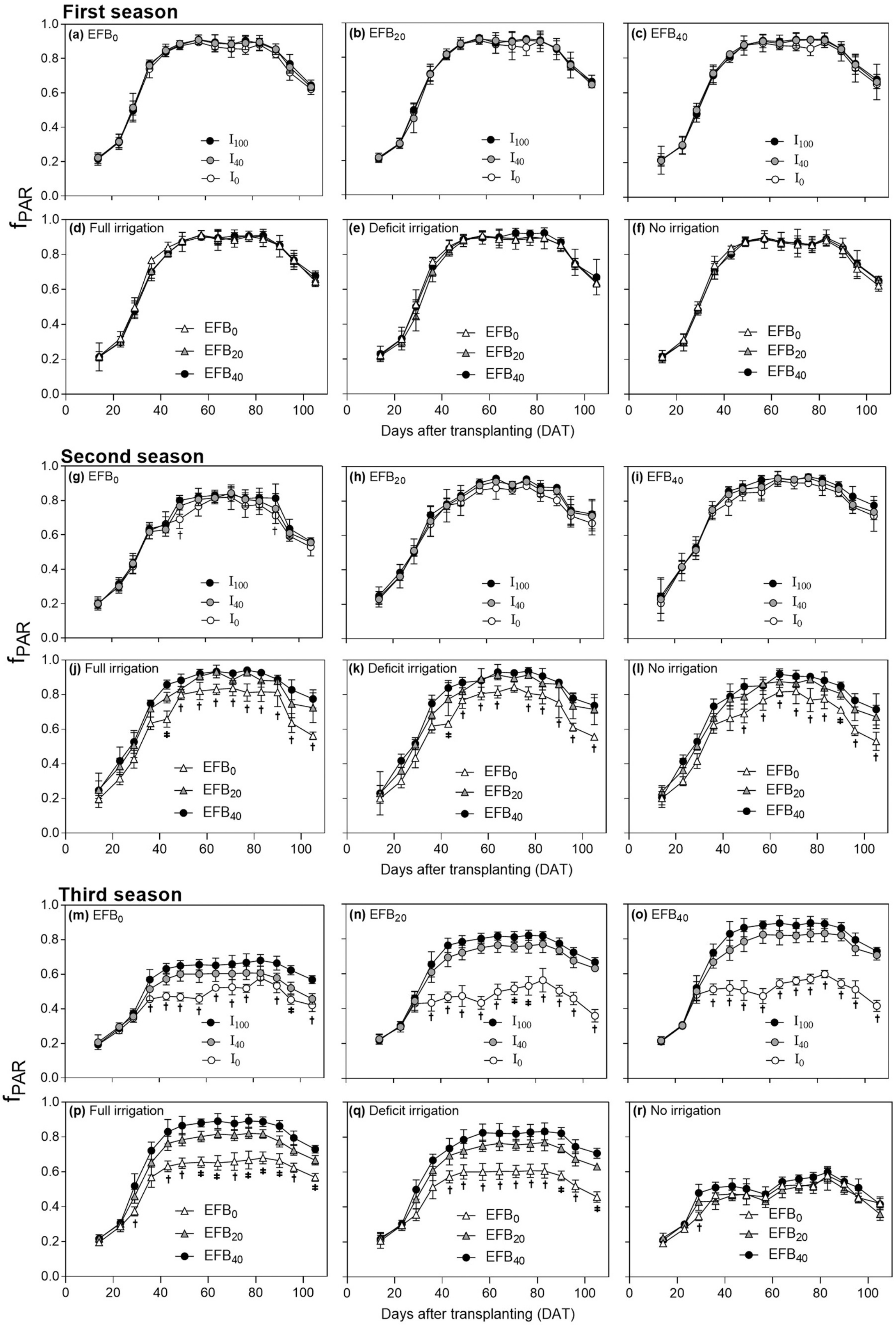

Fig. 4. Progression of the fraction of intercepted photosynthetically active radiation (f_{PAR}) over the first, second, and third growing seasons as enhanced by oil palm EFB rates of 0 t ha^{-1} (EFB$_0$), 20 t ha^{-1} (EFB$_{20}$) and 40 t ha^{-1} (EFB$_{40}$) under full, deficit and no irrigation levels. Error bars denote the standard error of the mean (n=4). ‡ indicates EFB$_{40}$ is significantly higher ($p < .05$) than both EFB$_{20}$ and EFB$_0$ in the EFB amended treatments or I$_{100}$ is significantly higher than both I$_{40}$ and I$_0$ in the irrigated treatments, † indicates EFB$_{40}$ is significantly higher than only EFB$_0$ or I$_{100}$ is significantly lower than only I$_0$, respectively.

EFB_{40} treatment recorded the highest values compared with those of EFB_{20} and EFB_0 treatment (Fig. 4j-l). In the third growing season, differences in the f_{PAR} were apparent relatively early between the irrigated and EFB treatments at 29 DAT (Fig. 4m-r). For the irrigated treatments (I_i) in general, during the first and second growing seasons, there were no significant differences between I_iEFB_0 and I_iEFB_{20} and between I_iEFB_{20} and I_iEFB_{40} treatments (Fig. 4d-f, and g-i). During the third season, however, the f_{PAR} for I_iEFB_{20} and I_iEFB_{40} was significantly higher than the I_iEFB_0 (Fig. 4p-r). In the same third season, the non-mulched EFB (EFB_0) treatment recorded significantly the lowest f_{PAR} values for the I_{100}, I_{40} and I_0 specifically from 43 DAT to 105 DAT (Figs. 4p and 4q). Also, significant differences commenced early (29 DAT) and continued till the end of the growing season (105 DAT). In general, the I_0 recorded the lowest f_{PAR} values throughout the third growing season. A significant difference was detected on only one measurement date (29 DAT) where the I_0EFB_0 was significantly lower than the I_0EFB_{20} and I_0EFB_{40} (Fig. 4r). On the other hand, the significant differences under the I_{100} (Fig. 4p) and I_{40} (Fig. 4q) for both EFB_{20} and EFB_{40} were higher than the treatment without EFB (0 t ha^{-1}).

Table 6
Analysis of variance showing significant levels of sole and interactive effects of irrigation and EFB-mulch on measured crop variables of total dry matter yield (TDMY), accumulated intercepted photosynthetically active radiation (AIPAR), radiation use efficiency (RUE), Leaf chlorophyll content index (LCCI), photosystem II (Fv/Fm), specific surface area (SSA), and pH (H_2O).

Variation	TDMY t ha^{-1}	AIPAR MJ m^{-2}	RUE g MJ^{-1}	LCCI	Fv/Fm ratio	SSA m^2 g^{-1}	pH (H_2O)
First season							
Irrigation	ns	ns	ns	ns	ns	nd	nd
EFB-mulch	ns	ns	ns	ns	ns	nd	nd
Irrigation × EFB-mulch	ns	ns	ns	ns	ns	nd	nd
Secon season							
Irrigation	**	**	*	**	**	nd	nd
EFB-mulch	***	***	**	***	***	nd	nd
Irrigation × EFB-mulch	ns	ns	ns	ns	ns	nd	nd
Third season							
Irrigation	***	***	**	***	***	nd	nd
EFB-mulch	***	***	***	***	***	*	**
Irrigation × EFB-mulch	**	***	*	*	*	nd	nd

For the F tests: * denotes p <.05, **p <.01 and ***p <.001. nd denotes analysis not determined as pH and SSA were considered only in the irrigated treatment in the third season. ns denotes not significant.

3.5. *Eggplant total dry matter yield, accumulated intercepted radiation, and radiation use efficiency*

There was no interactive effect between EFB-mulch and irrigation on TDMY, AIPAR, and RUE in the first and second seasons, but interactive i.e. synergetic effects emerged in the third season (Table 5 and Table 6). The TDMY was relatively higher in the second and third seasons compared to the first season for the irrigated EFB_{20} and EFB_{40} plots. In contrast, there was a consistent decline in the TDMY for the EFB_0 from seasons 1, 2, and 3. Both the irrigation and EFB-mulch did not statistically affect TDMY in the first season. In the second and third seasons, however, the EFB_{40} treatment had the highest TDMY which was statistically higher than only the non-mulched treatment. There was no irrigation effect on the TDMY in the first season. In the second season, the I_{100} produced the highest TDMY whereas the I_0 recorded the lowest values. The I_{100} and the I_{40}, and the I_{40} and I_0 levels were not statistically different in the same second season. However, the I_{100} was statistically higher than the I_0. In the drier third season, I_{100} was significantly higher than the I_{40} and I_0, while the I_0 was also significantly lower than the I_{40} (see Table 5). The AIPAR trend was similar to that of the TDMY in the first and third seasons where there were no irrigation and EFB-mulched effects in the first season, but significant effects emerged in the third season (Table 5 and Table 6). In the second season, the AIPAR for the I_{100} level was significantly higher than both I_{40} and I_0, while I_{40} was also significantly higher than I_0.

The EFB_{20} and EFB_{40} increased RUE in the second and third growing seasons relative to the EFB_0 treatment. No significant differences were observed in the first season between the EFB and irrigation. Also, the RUE was not significantly increased by irrigation in the second season but significantly increased for the irrigated EFB treatment in the second and third seasons relative to the non-irrigated treatment. In the third season, there was a synergistic interactive effect between both irrigation and EFB-mulch on the measured TDMY, AIPAR, and RUE (Table 6). The TDMY, AIPAR, and RUE generally increased in the second and third seasons for the EFB-mulched and irrigated treatments, whereas the non-irrigated and EFB_0 treatment (I_0EFB_0) decreased in the second and third

Table 5
Total dry matter yield (TDMY, t ha^{-1}), accumulated intercepted photosynthetically active radiation (AIPAR, MJ m^{-2}), and radiation use efficiency (RUE, g MJ^{-1}) for three eggplant growing seasons under oil palm empty fruit bunch (EFB) mulch and irrigation regimes.

	First season EFB mulch rate (t ha^{-1})				Second season EFB mulch rate (t ha^{-1})				Third season EFB mulch rate (t ha^{-1})			
Irrigation	0	20	40	Mean	0	20	40	Mean	0	20	40	Mean
Total dry matter yield (t ha^{-1})												
I_{100}	8.13	7.29	7.21	7.54 a	7.69	9.31	10.71	9.23 a	4.96	7.27	10.31	7.59 a
I_{40}	7.81	7.21	7.08	7.37 a	7.45	8.42	10.1	8.66 ab	4.21	5.65	7.42	5.85 b
I_0	7.86	6.86	7.67	7.46 a	4.83	7.94	9.21	7.33 b	2.33	4.64	5.05	3.83c
Mean	7.93 A	7.12 A	7.32 A		6.66 C	8.56 B	10.00 A		3.83 C	5.85 B	7.59 A	
AIPAR (MJ m^{-2})												
I_{100}	440.6	438.9	438.6	439.4 a	406.9	456.6	482.1	448.5 a	279.1	345.9	387.9	337.6 a
I_{40}	440.2	437.2	438.6	438.7 a	399.1	417.4	452.1	422.9 a	251.2	297.1	342.9	297.1 b
I_0	439.6	435.3	435.8	436.9 a	380.8	388.8	420.1	396.7 b	209.0	235.9	244.0	229.6c
Mean	440.1 A	437.2 A	437.6 A		395.6 C	421.0 AB	451.5 A		246.4 C	292.9 B	324.9 A	
Radiation use efficiency (g MJ^{-1})												
I_{100}	1.85	1.66	1.64	1.72 a	1.89	2.04	2.22	2.05 a	1.78	2.10	2.66	2.18 a
I_{40}	1.77	1.65	1.61	1.68 a	1.87	2.02	2.23	2.04 a	1.68	1.90	2.16	1.91 b
I_0	1.79	1.58	1.76	1.71 a	1.27	2.04	2.19	1.83 b	1.11	1.97	2.07	1.72 c
Mean	1.80 A	1.63 A	1.63 A		1.67 B	2.03 A	2.21 A		1.52 C	1.99 B	2.30 A	

Values within the same column (for EFB rates) or row (for irrigation levels) in the same experimental season without common letters are significantly different at $p < 0.05$.

seasons relative to the first season.

Fig. 5 shows that the TDMY correlated better with the AIPAR in the second ($r = 0.84$) and third ($r = 0.95$) seasons than observed for the first season ($r = 0.45$). The rather weak relationship between TDMY and AIPAR in the first season was regardless of the irrigation levels (Fig. 5a). In the first season, the variation in AIPAR was minimal and ranged from 435 to 440 MJ m^{-2} (Table 5 and Fig. 5a). However, during the second and third growing seasons, the AIPAR values varied widely with respective ranges of 102 MJ m^{-2} and 178 MJ m^{-2} as shown in Table 5 and Fig. 5b and c. Generally, AIPAR was influenced by treatments in the same manner as TDMY (Table 5, Table 6, and Fig. 5) with EFB-mulch and irrigated plots having higher values as compared with the non-irrigated control treatment, especially in the second and third seasons. The sole effect of the individual treatments was noticed in the second season. Nevertheless, a synergistic effect of irrigation and EFB-mulch was observed in the third season.

Fig. 6 illustrates linear regression analyses of pH against TDMY, AIPAR, and RUE. The measured TDMY, AIPAR, and RUE correlated positively with the pH with highly significant R^2 values of 0.79, 0.73, and 0.70, respectively. The highest coefficient of determination was observed for the 40 t ha^{-1}, whereas the control treatments produced the lowest pH values under all the analyses.

4. Discussion

4.1. *Effect of irrigation and EFB mulch on growth, total dry matter yield, radiation interception, and radiation use efficiency*

Irrigation increased the eggplant growth parameters (leaf CCI, Fv/Fm ratio, PI_{abs}), and other parameters like TDMY and RUE especially in the drier third growing season. Irrigation and EFB-mulch had significant synergetic effects (Table 6). Thus, adopting EFB-mulch along with irrigation can help vegetable farmers in Ghana stabilize and increase their yields during the rainy season. This combination can also enable them to generate additional income during the dry season, leading to greater economic empowerment, given that most vegetable farmers in Ghana rely on their crops to meet their families' needs. This increase in yield and year-round production is expected to enhance food security and improve nutrition for these farmers and their families. The eggplant did not respond to irrigation in the first season probably because of the high soil moisture content from the continued rainfall. In the second season, however, only the I_{100} improved the measured chlorophyll index, Fv/Fm ratio, PI_{abs}, and TDMY. Nevertheless, both the I_{100} and I_{40} increased the eggplant growth, TDMY, AIPAR, and RUE which were significantly higher than the non-irrigated treatment (Table 5 and Table 6). During this period, the increased TWS through irrigation likely (i) supplied the necessary amount of water to the crops to forestall drought stress, (ii) improved the availability of nutrients by dissolving them for plant uptake, and (iii) moderated the microclimate by offering cooling effects around the crops. This highlights the effect that irrigation has on lessening the negative effects of drought on crop production (Oppong Danso et al., 2018). A similar effect was observed by Oppong Danso et al. (2019),(2020) in the same location as the current experiment where irrigation did not affect maize yield during the first season with significant rainfall amounts. Irrigation reduces the environmental stress during dry spells (Mishra et al., 2020). This possibly promoted steady root development which led to increased eggplant growth and dry matter levels in the irrigated plots. Irrigation is therefore an important component of climate-smart agriculture and could serve as insurance against climate-induced drought, increase crop dry matter yield, and allow more cropping seasons per year (Rockström et al., 2017, Oppong Danso et al., 2018).

The growth of crops can hence be related to their accumulative light interception (AIPAR) by coupling the amount of incoming radiation to fractional light interception estimated from f_{PAR}, which is strongly related to the green leaf index. Comparatively, several studies have attributed increased radiation interception of crops to enhanced soil moisture and nutrient levels resulting in higher dry matter yield (Zhou et al., 2017, Oppong Danso et al., 2019, 2020, Li et al., 2021, Kalita et al., 2023). These findings agree with the observations in this study as the TDMY positively correlated with AIPAR, especially in the second and third seasons. Sadras et al. (2016) showed that radiation interception of a crop relies on incident radiation, leaf area index, and the canopy architecture. The relationship yielded r of 0.45, 0.85, and 0.95 for the first, second, and third seasons (Fig. 5). Lower eggplant growth, AIPAR, TDMY, and RUE under non-irrigated conditions in the second and third seasons is likely because drought stress resulted in stomatal closure, which eroded the relation between growth and green leaf area index under well-watered environments (Andersen et al., 1996, Oppong Danso et al., 2019). Decreased stomatal conductance under drought stress and low soil water decrease crop evapotranspiration (Allen et al., 1998) which reduces crop development and yield. Karam et al. (2009) reported that drought stress decreased the ability with which eggplant utilizes AIPAR to produce TDMY and hence the reduced RUE values under non-irrigation conditions. According to Legg et al. (1979), reduced AIPAR and RUE are due to drought-induced restriction of leaf area development and stomatal closure, respectively, depending on the growth stage of the crop at the time of drought.

Regarding drought stress, although we did not observe significant differences among the treatments with respect to the SWR curve, the EFB_0 treatment consistently recorded the lowest soil water content at all the measured matric potentials (see Fig. 3). This can be attributed to the release of organic compounds including lignocellulose from the EFB material in the second and third seasons into the EFB-mulched plots

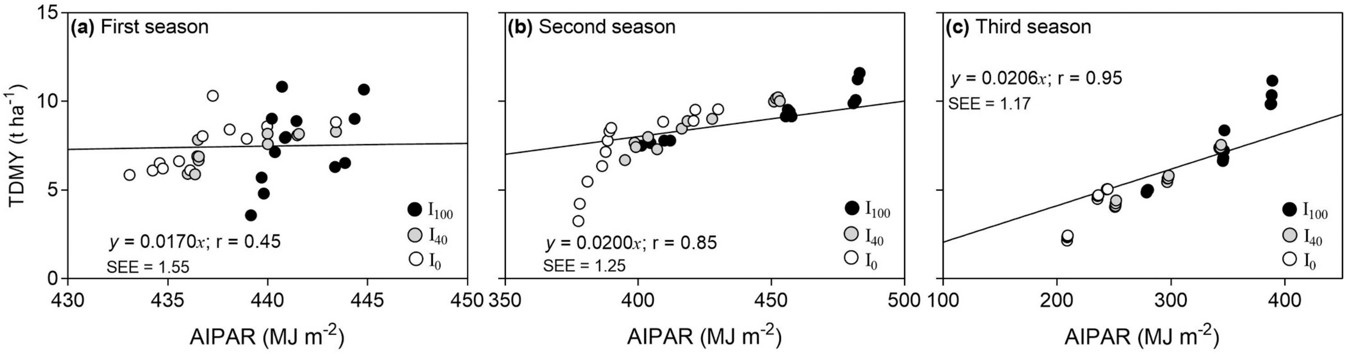

Fig. 5. Relationship between accumulated intercepted photosynthetically active radiation (AIPAR) and total dry matter yield (TDMY) for the EFB-mulched rates of 0 t ha^{-1} (EFB_0), 20 t ha^{-1} (EFB_{20}), and 40 t ha^{-1} (EFB_{40}) under full (I_{100}), deficit (I_{40}) and non-irrigated (I_0) regimes for the (a) first growing season, (b) second growing season and (c) third growing season. Lines indicate linear regression through the origin. r is the correlation coefficient. SEE is the standard error of the estimate (n=4). Note the different x-axis scale for for the 5a, b and c.

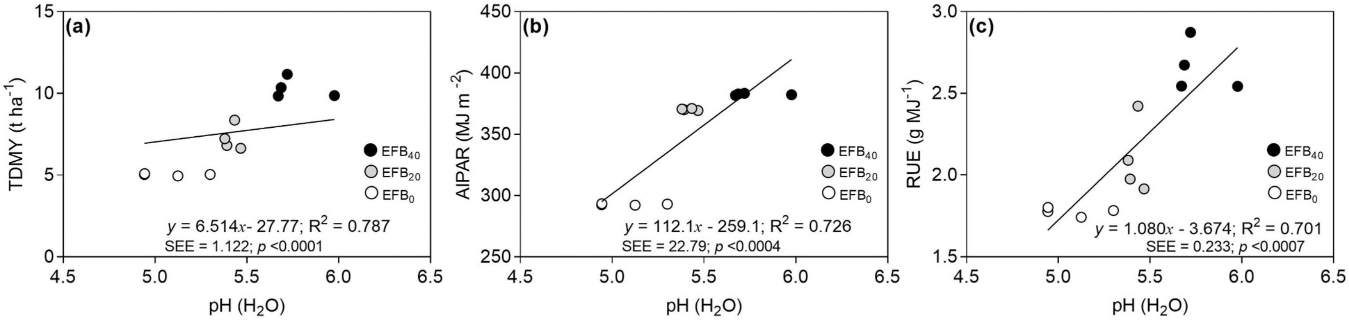

Fig. 6. Relationship between (a) soil pH (H_2O) and total dry matter yield (TDMY) (b) pH and accumulated intercepted photosynthetically active radiation (AIPAR), and (c) pH and radiation use efficiency (RUE) under fully-irrigated treatment (I_{100}) in the third growing season. Lines indicate linear regression including intercept. SEE is the standard error of the estimate (n=4).

(Table 3). EFB-mulch could also decrease soil water evaporation, which is important in the early growth stages before the crop canopy covers the transplanting area. Added to the irrigation effect on seasonal drought stress, the mulch could also moderate the soil temperature during hot conditions which reduces drought stress on plants and helps maintain SMC and hence the effects on the eggplant development. Organic matter generally functions as a link between soil particles via exchangeable Ca, Mg, and K cations to enhance the formation of microaggregates which are further bound together by plant roots, fungal hyphae, and other binding materials to produce soil's macroaggregates (Oades, 1984, Moradi et al., 2015, Obour et al., 2018). The increased CEC and SSA in the EFB-mulch treatments further confirmed this effect. The effects of the EFB on the SWR curve and ϕ in this study could improve the soil's macroporosity since increased ϕ is directly related to the soil ρ_b. Lal and Shukla (2004) highlighted that soil water content mostly depends on both soil texture and structure. Because soil structure is a function of soil organic matter content, increasing the organic matter through any practice (e.g. organic mulching) would improve soil structure and hence soil water retention (Oades, 1984, Moradi et al., 2015, Obour et al., 2018). The improved soil structure in the EFB-mulched treatments and the related soil water characteristics could have enhanced the growth of the eggplant and hence the strong correlation between TDMY and AIPAR in the second and third seasons (Fig. 5). The effect of the EFB-mulched rates on the measured soil and eggplant parameters is consistent with other findings which either compared EFB-mulch with non-mulched soils or other treatments. For example, the study by Moradi et al. (2012) used four mulching materials including EFB, ECO-mat, pruned oil palm fronds (OPF), and a construction of silt pits (SIL). Their results showed that the EFB-mulched treatment increased soil ϕ, SWR, and saturated hydraulic conductivity and decreased the ρ_b compared to the control. In another study, Moradi et al. (2015) used relatively similar conservation practices including the EFB-mulch treatment. The study indicated that soil aggregate stability, soil available water content, and SWC at FC were significantly higher in the EFB-mulch conservation practice relative to the ECO-mat, OPF, and SIL. Consistent with our results, Moradi et al. (2015) demonstrated that there was no noticeable effect of the mulching material on the soil water retention curve. This could be because EFB applied as mulching material on the field mainly serves as a soil cover to prevent splash erosion from raindrops and erosion (Arif et al., 2003, Moradidalini et al., 2011, Moradi et al., 2015, Rhebergen et al., 2020), control weeds and decrease evaporation (Singh et al., 2010, Moradi et al., 2012, Moradi et al., 2015, Adu et al., 2022). EFB mulching can therefore be considered as conservational agricultural principle for sustainable intensification in sub-Saharan Africa countries where oil palm is produced, especially when combined with irrigation during the dry season. However, the adoption of irrigation by most smallholder farmers in sub-Saharan Africa has not yet materialized due to a plethora of challenges, including financial constraints, land tenure, social conflicts, inadequate knowledge of operating the irrigation systems, and limited irrigable water (Burney et al., 2013, Amankwaa-Yeboah et al., 2023).

4.2. Soil fertility

Several studies (e.g. Singh et al., 2010, Sung et al., 2010, Sabrina et al., 2011, Abdulrazzaq et al., 2014, Claoston et al., 2014, Anyaoha et al., 2018) have demonstrated that EFB when used as organic mulch, can help increase plant nutrient levels, soil microfauna while enhancing the physico-chemical properties after few months of application. The low bicarbonate extractable P (Olsen P) of the reference soil (0.73 mg 100 g^{-1}) reinforces that the nutrient levels at the experimental site are at a level that limits crop yield. This result is consistent with the P value obtained by other studies at the same site of the field experiment (e.g. Oppong Danso et al., 2019) and this is far lower than what is considered very low and yield limiting (Olsen P $<$ 2 mg P 100 g^{-1}) elsewhere (Ferry et al., 2010, Oguntade et al., 2012, Rubæk et al., 2013, van der Bom et al., 2019). Although the same amount of inorganic nutrients was given as basal fertilizer, the decreased values in the EFB_0 were probably due to an increasing deficiency of nutrients in the unamended control plots due to the consecutive yearly cropping on the same plots. Studies that used EFB as mulching materials (i.e. Budianta et al., 2010, Abu Bakar et al., 2011, Moradi et al., 2012, Rudolf et al., 2021) have indicated that increased crop yield with increasing organic EFB-mulch rate was associated with the enhancement of some soil fertility characteristics such as pH, P and exchangeable K, Mg, Ca, TN, CEC in the mulched plots. This is underlined by the synergetic effect of EFB-mulch rate and irrigation rate on TDMY and AIPAR, as such strong synergetic effects between increased rates of nutrition and irrigation are common (e.g. Andersen et al., 1996, Perry et al., 2009). This ultimately leads to increased crop growth via increased leaf area index and AIPAR (Lopez et al., 2022, Kalita et al., 2023). For example, Moradi et al. (2012) reported EFB mulching to be more effective in increasing soil K, SOC, pH, Mg, and Ca compared to the other treatments.

The EFB used in this study had comparatively higher K, organic C, N, and EC compared to the reference soil (Table 3). The study by Moradi et al. (2012) shows that the very high K concentration in the EFB results in its release to plants faster than of N and P. Zaharah and Lim (2000) also found that the rate of nutrient release from the EFB was gradual for N, P, Ca, and Mg, but was very fast for K. This could also explain the low eggplant growth and dry matter yield in the first stage of this study, even when water in all the plots was still not limited. Both Zaharah and Lim (2000) and Moradi et al. (2012) have shown that increasing K, Mg, and Ca in the soils with EFB mulching may increase soil pH by producing hydroxyl ions. The pH (H_2O) of the experimental soil (5.30) was low (Table 2) while the EFB material used for the mulch had a high pH of 8.1 (Table 1). Several developments such as ammonification of organic N and alkalization by excess bases have been associated with pH change by organic materials such as EFB-mulch (Zhi-An et al., 2008). Also, Elert et al. (2015) reported that the illitic and smectic clay edges were protected by organic matter which highly increased the pH. As seen from Fig. 6, pH as enhanced by EFB-mulch was positively and strongly correlated with TDMY, AIPAR, and RUE. Such strong response to pH most likely is related to better availability of soil-bound P. Eduah et al. (2019) found that in soil from the same location, P availability was strongly limited by the presence of high contents of non-crystalline and crystalline Fe and Al oxides. These led to a high adsorption capacity for P, as quantified by a very high Langmuir sorption maximum (Q_{max}) of the soil of 395 mg kg^{-1} while the addition of biochar increasing the pH leads to increased P-desorpability via an increased pH (Eduah et al., 2019). Thus, the EFB mulch probably reduced soil acidity leading to higher TDMY, and AIPAR in the mulched treatments compared to the non-mulched control plots.

Other authors such as Budianta et al. (2010) and Rudolf et al. (2021) also showed that EFB-mulch at rates of 37.3 t ha^{-1} and 40 t ha^{-1}, respectively, improved SOC and oil palm yield. The application of EFB-mulch in our study significantly increased SOC, TN, CEC, and SSA after the third season compared to the non-mulched control plots (Table 3). Also, our study showed that after 19 months of application of the EFB total N was significantly higher in the 40 t ha^{-1} EFB-mulched plots. Like the studies of Zaharah and Lim (2000) and Moradi et al. (2012), earlier data by Rosenani and Wingkis (1999) also indicated that half of N of the applied EFB is released within 9 months of application. This may have further added to the beneficial effects of EFB-mulch in the second and third seasons of this study, while the initial C/N of above 50 may have decreased N availability by immobilization. Other studies also reported that CEC in EFB-mulched plots is usually influenced by the increase in C and pH (Budianta et al., 2010, Rosenani et al., 2016). This is consistent with this study as our results indicated an increase in pH and SOC in the EFB-amended plots compared to the non-mulch control plots. The results of this study also indicate higher values of CEC and SSA in the 40 t ha^{-1} EFB-mulched soils compared to the control soil. Organic matter fractions are known to be part of the few factors that affect soil's CEC (Arthur, 2017) and SSA (Arthur et al., 2018, Yan et al., 2023). Chowdhury et al. (2021) have associated rapid reduction in CEC, as well as organic N and C with continuous cultivation on agricultural soils. Relating this to our results, the continuous cropping on the non-mulched plots could limit the capacity of the tropical sandy clay loam of our experimental soil to retain vital nutrients required for crop development and its ability to serve as a buffer against alterations in pH (Arthur, 2017). This could also be the same for the EFB-mulched plots, nevertheless, higher CEC in the EFB-mulched plots might retain vital nutrients from the gradual and natural decomposition of the EFB-mulch material (Table 3) which is suitable for the eggplant yield. This effect can also lead to biotic sequestration of C in the EFB-mulched soils as shown by Chowdhury et al. (2021). Specific for the higher EFB_{40}, the effects of the higher EFB-mulched rates from the organic matter on SSA in the mulched plots could have influenced soil moisture, drainage and infiltration during saturation, soil structural formations, microbial processes, adsorption and release of plant nutrients (Arthur et al., 2018) which might influence growth and dry matter yield of the eggplant. The lignocellulose properties such as hemicellulose, cellulose, and lignin (Zaharah and Lim, 2000, Singh et al., 2010, Sabrina et al., 2011, Claoston et al., 2014, Idris et al., 2015) also makes the EFB-mulch a suitable substance in influencing soil fertility characteristic for plant productivity.

5. Conclusion

The effects of oil palm EFB-mulch and irrigation levels on eggplant growth and dry matter yield were compared on a weathered tropical soil. EFB-mulch significantly increased eggplant growth, radiation interception, dry matter yield, and radiation use efficiency. Applying EFB at 20 and 40 t ha^{-1} significantly increased growth, radiation interception, total dry matter yield, and radiation use efficiency whether the eggplant was irrigated or not during the second and third seasons. Irrigation increased total dry matter yield and radiation interception in the second growing season and especially in the drier third season. A strong synergetic interaction between EFB-mulching and irrigation indicated that the EFB-mulch primarily increased nutrient availability rather than soil water. As dry matter yield and radiation use efficiency were strongly related to pH, the most limiting nutrient was likely P. Apart from higher pH and P availability, the EFB-mulch had a range of beneficial effects on soil health including decreased ρ_b, evaporation, increased ϕ, and TN, CEC, and SSA in the EFB_{20} and EFB_{40} treatments than the EFB_0 treatments. We recommend the conservational practice of mulching with oil palm empty fruit bunches and irrigation as a climate-resilient approach to improve AIPAR, increase TDMY, and enhance RUE. To ensure efficient smallholder vegetable production and effective ecosystem management practices, we recommend that farmers adopt irrigation combined with EFB-mulch at a rate of 20 t ha^{-1}. Long-term research is required to determine how long the EFB would persist in the soil and positively impact soil and vegetable production as well as how the effect could be maintained by supplementary additions of EFB.

CRediT authorship contribution statement

John Bright Amoah Nyasapoh: Writing – review & editing, Writing – original draft, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Eric Oppong Danso:** Writing – review & editing, Writing – original draft, Supervision, Resources, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Daniel Selorm Kpodo:** Writing – review & editing, Writing – original draft, Investigation, Data curation. **William Amponsah:** Writing – review & editing, Methodology, Investigation, Formal analysis. **Emmanuel Arthur:** Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Investigation, Funding acquisition, Conceptualization. **Edward Benjamin Sabi:** Writing – review & editing, Writing – original draft, Resources, Project administration, Investigation, Funding acquisition, Conceptualization. **Peter Bilson Obour:** Writing – review & editing, Methodology, Investigation, Conceptualization. **William Akortey:** Writing – review & editing, Data curation. **Bernard Kwabena Boadi Mensah:** Writing – review & editing, Data curation. **Elorm Grace Ayayi:** Writing – review & editing, Data curation. **Mathias Neumann Andersen:** Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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