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Harvesting the sun twice: Energy, food and water benefits from agrivoltaics in East Africa

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ABSTRACT

Food, energy and water insecurity are concomitant challenges facing many communities in East Africa. Agrivoltaic systems – agriculture integrated with photovoltaic panels – address all three challenges, providing low carbon electricity, food production and water conservation on the same land area. Agrivoltaics have proven benefits for the food-energy-water nexus in the USA, Europe and Asia, but research is lacking in sub-Saharan Africa, where energy access remains low, and climate change and water scarcity threaten food systems. This study presents evidence for concomitant electricity generation, food production and water conservation from agrivoltaic systems in Tanzania and Kenya, demonstrating the viability of these systems for both grid-tied agribusinesses and rural, off-grid communities. Performance of some crops improved under agrivoltaics, generating higher incomes for farmers and agribusinesses while reducing energy bills and/or enhancing energy supply. Crop survivability during a warm period was greater under the agrivoltaic system, indicating potential for climate change resilience. Panel shading reduced irrigation demand, thus some crops achieved greater yields while needing less water input. Rainwater harvesting from panel runoff further reduced irrigation needs. Combining energy infrastructure with agriculture enhanced land productivity for all crops at both sites. Agrivoltaics, whether grid-tied or off-grid, could address multiple Sustainable Development Goals in East Africa simultaneously by contributing to energy security, climate change-resilient food production, and water conservation in the region.

1. Introduction

Electrification improves quality of life and is crucial for achieving almost all Sustainable Development Goals (SDGs), from advancing health and economic development to accessing more secure water supplies [1], but more than half of the population in East Africa lacked access to electricity in 2020 and many rely on biomass for energy [2,3]. To address this challenge, East Africa is experiencing one of the fastest electrification rates in the world, with millions gaining access every year and electricity consumption forecasted to triple by 2040 [2]. However, underdeveloped national infrastructure is a barrier to this scaling up of electrification in the region [4], as it is typically only available in densely populated areas and subject to frequent blackouts [5]. The cost of extending grid access to rural and remote areas is prohibitively high [4], leaving decentralised systems (off-grid and mini-grid) as the only means to economically provide electricity to rural, off-grid communities [6]. Solar photovoltaic (PV) technologies can offer low carbon, renewable electricity both on- and off-grid, and the deployment of PV is forecast to expand [7,8]. The unrealised capacity for PV technologies to meet energy needs in East Africa is enormous: the region receives an average of 4.0–6.9 kWh/m^2/day of solar insolation [9], which could deliver universal electricity access [10], yet solar electricity accounts for less than one percent of the electricity generation mix. However,

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Nomenclature

Abbreviations

ANOVA	Analysis of variance
AV	Agrivoltaic
C	Control plot
GDP	Gross domestic product
GHI	Global Horizontal Irradiation
KES	Kenyan shilling
LAS	Latia Agribusiness Solutions
Lat	Latitude
LER	Land use Equivalent Ratio
LMM	Linear mixed-effects model
Long	Longitude
max	maximum
min	minimum
MKES	Million Kenyan shillings
MTsh	Million Tanzanian Shillings
NS	Not significant
PAR	Photosynthetically active radiation
PV	Photovoltaic
SAT	Sustainable Agriculture Tanzania
Tsh	Tanzanian shilling
USA	United States of America
USD	United States Dollar

Symbols

Ya	Yield from agrivoltaic plot
Yc	Yield from control plot
Da	Panel density of agrivoltaic system
Dc	Panel density of conventional ground-mounted solar park

Units

°C	degrees Celsius
Ah	Amp hour
cm	centimetre
g	gram
GW	Gigawatt
ha	hectare
kg	kilogram
kWh	kilowatt hour
kWp	kilowatt peak
L	Litre
m	metre
mm	millimetre
W	Watt

recognising the potential of solar energy, governments have established several electrification initiatives and collaborations to provide electricity for those without access [11–13], which has led to substantial growth in PV [14–16].

Food insecurity also impairs well-being and hinders poorer communities from sustainable economic growth in East Africa. Irrigation is unavailable or unreliable for most smallholder farmers [17], and this challenge is prevalent in drier arid and semi-arid lands (ASALs) [18]. Nearly half of households, 48 %, experienced some form of food insecurity in 2018/19 [19], and climate change is forecast to decrease major crop yields 8–45 % by 2050 [20]. Increased solar electricity generation will help meet the growing demand for sustainable electricity sources, but without appropriate implementation it may cause conflicts with other development objectives [1]; for example, PV infrastructure can come at the expense of traditional land rights and uses [21]. Where agricultural land previously used for food production is converted for PV, electricity benefits may come at the expense of food security. Realising multiple development objectives while avoiding potential trade-offs between them is a critical challenge for achieving the SDGs: there is an urgent need to develop innovations that offer climate change resilience and food and energy security in synergy.

Agrivoltaics - PV panels integrated with agriculture - offer energy and food security, improved crop-water relations, while also mitigating potential land use conflicts associated with conventional ground-mounted solar [1,22–24]. The technology can be implemented with either crops or livestock [25–28]; this research focuses on the former. The past decade has seen a rapid increase in agrivoltaic research in Europe, North America, and Central and East Asia, with studies demonstrating that agrivoltaics can deliver synergies for energy, food and water security [29–33] (reviewed in Refs. [34–36]) if conducted with appropriate crop selection and designed for local environmental conditions. With appropriate design, gaps between panels allow a sufficient amount of photosynthetically active radiation (PAR) to reach underlying shade-tolerant crops. The panels partially shade the crops and soil from direct solar radiation, reducing ultraviolet (UV) radiation damage, growth-limiting evapotranspiration and, consequently, irrigation demands [29–31,35] – particular challenges in semi-arid regions such as East Africa. These features may result in an improved crop-growing environment, depending on a range of factors such as crop type, local environmental conditions, soil type and agrivoltaic system design, but research to establish the impact of these parameters on crop performance is lacking in this region. Interviews with stakeholders in the region highlighted the potential for the technology to address energy and climate change challenges facing farmers and agribusinesses, but note both the lack of, and the need for, evidence of system performance and value to support decision making [37]. Given the reported impacts of agrivoltaics on the challenging environmental conditions that reduce agricultural productivity in East Africa [38], and combined with high solar potential and an expanding PV market, research investigating the performance of the technology in the region is required to determine if it could be a viable approach for addressing these challenges.

This work presents empirical data on crop performance, electricity production, irrigation and environmental parameters collected from two fully operational agrivoltaic systems in East Africa: an off-grid system in Tanzania and a grid-tie system in Kenya. The study aimed to answer the following research questions.

1. Crop performance: How are the yields and morphological traits of locally relevant crops affected when grown under agrivoltaic systems in East Africa?
2. Water use: To what extent does the partial shading of solar panels reduce irrigation needs?
3. Energy potential: What impact do the agrivoltaic systems have on a) the energy supply and consumption for an off-grid agribusiness, and b) the energy supply and bills of a grid-tied agribusiness?
4. Land use: To what extent does combining electricity generation and crop production affect land use productivity?

The yields (and growth and market value in some cases) of nine locally relevant crops from both sites and several seasonal timepoints are investigated. The crop yields per water input are calculated by combining yield data with irrigation and precipitation data, and the monetary savings of the electricity generated by the panels are quantified. The relative land use productivities of the different crop-energy combinations are compared to respective single use alternatives. The findings evidence the potential for agrivoltaics to synergistically address the food-energy-water nexus. The challenges facing the application of these systems in East Africa are discussed – a region where the benefits of the technology for food and energy security may be far greater than existing installations in Europe, the US and Asia, but where research to demonstrate these benefits is currently lacking.

2. Material and methods

2.1. Experiment locations and climates

The agrivoltaic system in Tanzania is located at Sustainable Agriculture Tanzania (SAT)'s Farmer Training Centre, Morogoro (lat. −6.7413, long. 37.5494). The site is at an elevation of 537 m, and the climate is tropical and semi-arid. The mean annual temperature is 22.6 °C, ranging from 20.4 °C in July to 24.4 °C in February, and Morogoro is characterised by a bimodal annual precipitation cycle with a mean of 972 mm (max: 199 mm in March, min: 15 mm in July). The area receives an average of 8.0 h of sunshine a day, and 5.2 kWh/m^2/day of global horizontal irradiation (GHI).

The agrivoltaic system in Kenya is located at Latia Agribusiness Solutions (LAS), Isinya, Kajiado County (lat. −1.6850, long. 36.8308). The site is at an elevation of 1646 m and is characterised by clayey soils associated with gypsum, silicified lithics and limestone. The climate is tropical semi-arid, with a bimodal annual precipitation cycle. The mean annual temperature is 19.1 °C, ranging from 17.3 °C in July to 20.8 °C in February, and there is 687 mm of mean precipitation annually (max: 115 mm in April, min: 14 mm in September). The area receives an average of 7.5 h of sunshine a day, and 5.4 kWh/m^2/day of GHI.

2.2. System designs

The agrivoltaic system at SAT has a peak capacity of 36.6 kWp. It comprises 106 × 345 W PV modules, measuring 34 × 13 m (442 m^2). It is off-grid with a 19,200 Ah lead-acid battery storage system, providing electricity to the farmer training centre that previously relied on diesel generators. The system at LAS has a peak capacity of 62.1 kWp, comprises 180 × 345 W PV modules, measures 40 × 20 m (800 m^2), and is grid-tied, supplementing the grid electricity supply. Drone images annotated with key design and experiment features for both systems are displayed in Fig. 1. The system capacity at SAT, an off-grid location previously with little electricity supply powered by diesel generators, was based on a forecast demand given electrification of the site and the farming machinery where applicable. At LAS, the system capacity was based on the existing electricity consumption of the site.

In both systems, the PV modules are connected into groups of three along the wider edges of the modules, and these panel groups are tilted 10° towards the north. A lower angle of ~2–3° would maximise PV generation, but a tilt of 10° was selected to allow for sufficient water runoff and reduce panel soiling. The panels are raised 3m above the ground at the lower edges to provide sufficient space for manual farming labour and use of tools. The PV arrays are supported by a steel mounting structure fixed into concrete foundations. Both systems have a 50 % panel density. While studies in Europe revealed that such higher densities reduced the yields of most crops [39], in those locations solar insolation is lower than in semi-arid tropical locations with high solar insolation, such as at SAT and LAS [9], and thus likely more of a limiting factor for most crops. Conversely, given the high solar insolation in East Africa, water loss is a greater challenge for many farmers, and shade netting is already used to alleviate heat and water loss stresses [37–39]; thus, a higher panel density was selected under the assumption that the greater partial shading would reduce water loss while permitting sufficient sunlight to reach the underlying crops. The arrays are oriented on a north-south axis to improve diurnal distribution of sunlight over the underlying crops; if the panels were oriented on an east-west axis, typical for conventional solar parks, then the crops directly underneath the panels would primarily be in the shade, while those directly under the gaps between the panels would primarily be unshaded.

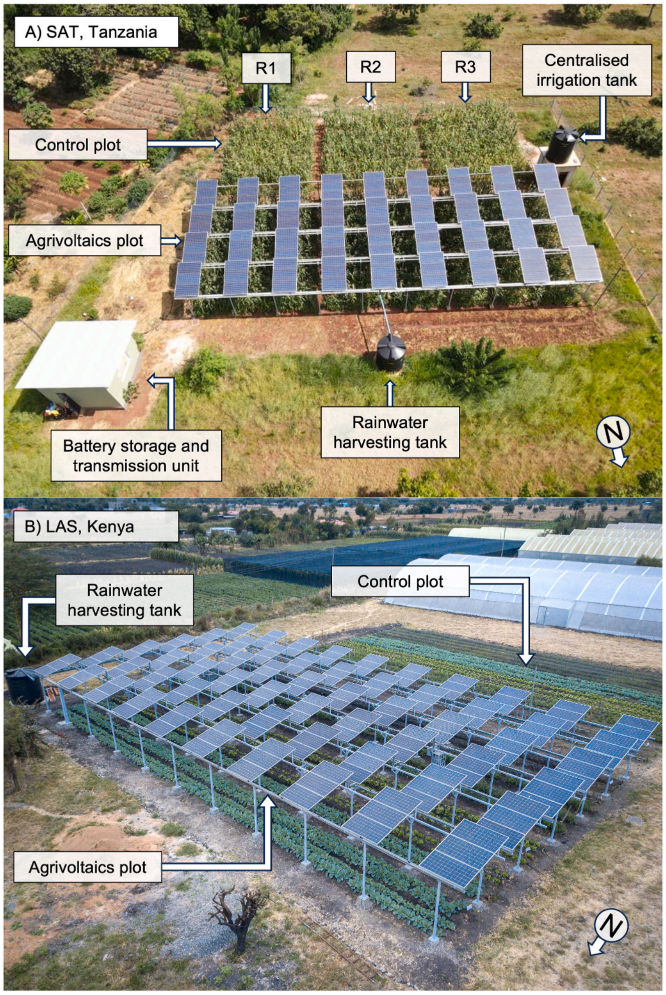

Fig. 1. Aerial photos of the two agrivoltaic systems. A) The 36.6 kWp off-grid system at Sustainable Agriculture Tanzania (SAT), illustrating the nested experimental design with each of the agrivoltaic and control plots split into three replicate blocks. Each replicate block contains eight growing beds with four rows of crops. B) The 62.1 kWp system grid-tie system at Latia Agribusiness Solutions (LAS), Kenya, comprising 12 growing beds running the length of the plot. Guttering at the lower edges of the panels channels water run-off into the rainwater harvesting tanks, which can supplement the centralised irrigation systems. Photo credits: Chloride Exide Ltd.

A rainwater harvesting system with guttering at the lower edges of the PV panels channels rainwater and panel cleaning water runoff into 10,000 L storage tanks, supplementing the existing centralised irrigation systems during periods of water scarcity. Open-field control plots of the same dimensions were established adjacent to the agrivoltaic systems, separated by a 2.5 m gap.

2.3. Agricultural experiments

The crops studied were selected by the farming managers and technicians at each study site based on the relevance of the crops to their local agronomic systems. Table 1 lists each crop type that was studied, along with the dates for the period that they were grown and the measurements taken from them during those periods.

At SAT weeding was conducted manually, and biofertilisers and biopesticides were applied by the farming technicians. The mixture of bokashi and compost was used before transplanting, and super magro was used as a liquid soil booster. Neem extracts and apichi were used to control crickets and grasshoppers immediately after transplanting. Bicarbonate of soda was used to control powdery mildew on spinach and leaf spots on sweet pepper. The compositions, quantities and application

Table 1

Crops studied and parameters recorded at the two sites. An asterisk (*) denotes crops harvested throughout the harvest period. Crops without an asterisk were harvested in one harvest. AV = Agrivoltaics; C = Control.

Date	Crop	Total plant count	Plants sampled	Sampling resolution	Parameters recorded
Sustainable Agriculture Tanzania					
2 Jun - 6 Oct 2022	Onion (*Allium cepa,* var. red creole)	AV: 13,056 C: 9272	N/A	Bed	Total yield and value
2 Jun - 31 Oct 2022	Sweet pepper (*Capsicum annum,* var. yolo wonder)*	AV: 699 C: 562	AV: 699 C: 562	Plant	Total yield and values; number of fruiting plants; number of fruits per plant; fruit weight per plant
2 Jun - 6 Oct 2022	Swiss chard (*Beta vulgaris,* var. fordhook giant*)**	AV: 756 C: 526	1st harvest: AV-panel: 96 AV-gap: 94 C: 93 2nd harvest: AV-panel: 150 AV-gap: 115 C: 113	Leaf	Total yield and value; leaf length, width and weight
16 Dec 2022–29 Mar 2023	Beans (Phaseolus vulgaris, bush type)	AV: 3053 C: 2964	AV: 50 pods C: 50 pods	Plant	Total yield and values; germination and survival rate; pod length and weight
16 Dec 2022–29 Mar 2023	Maize (*Zea mays,* landrace yellow type)	AV: 1586 C: 1572	AV: 691 cobs C: 708 cobs	Plant	Total yield and values; germination and survival rate; cob length and weight
16 Jun - 26 Sep 2023	Eggplant (*Solanum melongena,* var. black beauty)*	AV: 677 C: 672	AV: 677 C: 672	Plant	Total yield and values; fruit count; fruit weight per plant
16 Jun - 1 Sep 2023	Kale (*Brassica oleraceae,* var. collard sukuma)*	AV: 1090 C: 1073	AV: 1090 C: 1073	Plant	Total yield and values; leaf count; plant yield
16 Jun - 5 Oct 2023	Onion (*A. cepa,* var. red creole)	AV: ~10,080 C: ~10,080	N/A	Bed	Total yield and values;
Latia Agribusiness Solutions					
27 Jan–Apr 2023	Cabbage (*Brassica oleraceae,* var. Kiboko F1)	AV: 24 C: 24	AV: 24 C: 24	Plant	Weight and diameter
28 Jan–Apr 2023	Onion (*Allium cepa,* var. red pinoi)	AV: 24 C: 24	AV: 24 C: 24	Plant	Weight and diameter
22 July – 24 Aug 2023	Coriander (*Coriandrum sativum,* var. American longstanding)	AV: 24 C: 24	AV: 24 C: 24	Plant (height) and block (yield)	Plant height and yield
8 Jul – 26 Aug 2023	Kale (*B. oleraceae,* var. Ahadi F1)	AV: 24 C: 24	AV: 24 C: 24	Plant	Plant height; leaf length and width

of the biofertilisers and pesticides are listed in Table 2.

The yields, morphological traits and market values of onion, sweet pepper, Swiss chard, beans, maize, eggplant and kale were studied over three growing seasons at SAT. The agrivoltaic and control experiment plots were split into three 11 × 13 m blocks, with eight 10 m long growing beds per block. Each bed contained four rows of crops, each row containing one crop type, and crop row planting was randomised across all the beds. Control beds 7–8 were not planted during the first growing season and the control plant numbers were standardised to the agrivoltaic plot size to account for the reduced control plot size. The sale values of the produce were provided by the SAT finance office.

Data were collected from every plant at either the plant level or the bed level. Four soil moisture samples were recorded using soil moisture probes at random locations in every bed immediately after irrigation in the morning and again at 16:00 in the afternoon, biweekly between 7 Feb - March 21, 2023. In the agrivoltaic plot the soil moisture content was recorded directly underneath the PV panels and underneath the gaps between the panels. Photosynthetically active radiation (PAR) was recorded using a PAR meter at five random locations in the control plot, underneath the PV panels, and underneath the gaps between the panels in the morning, at midday and in the afternoon between 11–20 March 2023, excluding the 12 and 19 March. Direct PAR values in the maize crop were reduced by shading from the foliage in both plots, though clear differences between the treatments were still detected.

At LAS, Wuxal foliar NPK fertilisers and pesticides (Actara, Belt 480SC, Escort, Luna Sensation, Oshothane, Pentagon 50 EC (Lambda cyhalothrin), Thunder 145 OD) were applied as per LAS' crop management strategy. Growth and yield parameters for cabbages, onions, coriander and kale were measured between May and August 2023. Eight 2 × 2 m blocks were randomly selected from each plot, excluding the edges, and five plants (in the first growing season) or three plants (in the second growing season) were randomly selected from these blocks for measurement. Photosynthetically active radiation was recorded in the control plot, under a solar panel and under a gap between the solar panels every 5 min using PAR sensors (HOBO RXW-LIA-868; Onset, Massachusetts, US).

At both sites, each plot was irrigated for a period of 1 h per experimental block when the top 5 cm of soil was observed as dry by the field technicians. Irrigation quantity was recorded via analogue water meters. Total yields were measured using mechanical scales, while plant-specific weights such as fruit or leaf weights were recorded using digital scales.

2.4. Electricity recording and PV modelling

Electricity generation data at SAT were recorded online via the Fronius inverter web app (Fronius International, Wels, Austria), while the sources of consumption (direct PV vs battery supply) were recorded online via the Victron Energy portal (Victron Energy B.V., Almere, The Netherlands). Electricity generation and consumption (direct PV vs. grid consumption) data at LAS were recorded online via the Fronius inverter web app. The potential PV performance of each system was estimated using the European Commission's international PVGIS (v5.2) PV performance tool, assuming a 14 % system performance loss over a 20 year operating period [40].

Table 2
Biofertiliser and biopesticide inputs at SAT. The compositions, quantities and application of biofertilisers and biopesticides at SAT.

Input	Composition	Quantity per plot per growing season	Application
Biofertilisers			
Compost	Ash, cow dung, Gliricidia plant, dried glasses.	1440 kg	Applied at the start of each growing season.
Bokashi	Rice husk, charcoal, molasses, cow dung, maize bran, soil	250 kg	Applied in the first growing season only.
Super magro	Cow dung, water, milk, molasses, yeast, ash,	550 L dilution	1:11 dilution with water. Applied five times per growing season: once during the first month then twice per month thereafter due to flowering or harvesting stages.
Biopesticides			
Apichi	Chilli pepper, ginger, garlic and vinegar	50 L	1:11 dilution with water. Applied in the first growing season only, twice a week for the first three weeks due to cricket and grasshopper infestations.
Neem extract	Grounded neem mixed with chilli	120 L	3 kg of grounded neem and 1 kg of grounded chilli mixed in 20 L of water. Applied in the first growing season only, twice a week for the first three weeks due to cricket and grasshopper infestations.
Bicarbonate of soda	Bicarbonate of soda	1 kg	200 g diluted in 20 L of water. Applied in the first and third growing seasons only, five times per growing season. Application depended on the intensity of infection.

2.5. Data analysis

Data were analysed with R (v4.1.2) using the lme4 (v1.1.34) package. Yield data from SAT were standardised to t/ha and differences in yields between the agrivoltaic and the control plots were compared. A linear mixed-effects model (LMM) was fitted using the lme4 package to test for significant effects of the agrivoltaic system on the measurement parameters (i.e. the yields and morphological traits). The LMM comprised two sub-models: a full model and a reduced model. The full model tested the effects of the independent variable (i.e. the agrivoltaic treatment) and random variables (e.g. the blocks, beds, and, depending on the crop, the individual plant), while the reduced model tested only the effects of the random variables. A likelihood ratio test determined the significance of effects of the agrivoltaic system on the measurement parameters by performing ANOVAs between the full model (i.e. with the fixed variable) and the reduced model (i.e. without the fixed variable). Where data were not collected on the random variables, such as for the bean pod morphology at SAT, significant differences between the treatments were assessed using Mann-Whitney or Kruskal-Wallis tests. All p values were corrected for multiple comparison false discoveries using the Benjamini-Hochberg method, and null hypotheses of no significant differences between assessed groups were rejected if the corrected p values were less than 0.05. Unless stated otherwise, percentages are reported as the difference in the agrivoltaic plot compared to the control plot.

Crop yield:water input ratios at SAT were calculated as a function of the amount of irrigation from both the centralised irrigation system and the rainwater harvesting system applied to each bed, and the amount of precipitation recorded with the site's HOBO weather station. Precipitation quantities were halved for the agrivoltaic plot to account for the 50 % panel density, with the panel runoff accounted for in the harvested rainwater use.

The land use equivalent ratio (LER) was calculated to compare the combined crop and electricity land use productivity from the SAT agrivoltaic plot with equivalent sole use agriculture or sole use energy plots (Equation (1)). The difference between the panel coverage density of the agrivoltaic system (50 %) at either SAT or LAS and of a conventional ground mounted solar park (~66 %) at Garissa in northeast Kenya was used as a proxy for the difference in electricity generation.

$$LER = \frac{Ya_i}{Yc_i} + \frac{Da}{Dc} \tag{1}$$

The land equivalent ratio (LER) is calculated for each crop by combining the difference between the yields from the agrivoltaics plot (Ya) and the yields from the control plot (Yc) with the difference between the agrivoltaic plot panel density (Da) and a conventional ground-mounted solar park panel density (Dc).

3. Results

3.1. Crop performance – sustainable agriculture Tanzania

Performance varied between the crops, with some producing greater yields under the agrivoltaic system while others had similar or lower yields. At Sustainable Agriculture Tanzania (SAT), beans and Swiss chard had significantly greater yields under the agrivoltaic system, while onions (the 2022 crop), sweet peppers and eggplants had significantly lower yields. Despite the yield reductions in the latter crops, these generated the largest incomes in absolute terms, highlighting that yield changes alone do not represent the full impact of agrivoltaics on livelihoods. Beans had a substantial increase in yield under the agrivoltaic system, reflecting improved plant survival compared with the control plot. Further, the bean pods were longer and heavier than those from the control plot, and the SAT farming technicians stated that such beans are more desirable at the point of sale. The maize, grown during the same period, also had greater survival; this maintained the same overall yield as the control plot, despite cobs being shorter and lighter under the agrivoltaic system. The increase in Swiss chard yield under the agrivoltaic system reflected the larger and heavier leaves of plants grown there compared to those grown in the control plot. Fig. 2 shows the yields and sale values of the crops studied at SAT. Figs. 3 and 4 show the plant survival rate and pod/cob morphology for beans and maize, respectively. Fig. 5 shows the Swiss chard leaf morphology results.

While the sweet pepper yields per fruiting plant were not significantly different between the plots (control: 109.1 ± 0.8 g, agrivoltaics: 108.0 ± 0.8), the fruiting rates were 30.9 % lower under the agrivoltaic system ($p < 0.001$), resulting in an overall lower yield. In eggplants, overall yield was lower in the agrivoltaic plot, as were fruiting rate (−31.8 %, $p < 0.001$) and yield per plant (−17.5 %, $p = 0.002$).

3.2. Crop performance – Latia Agribusiness Solutions

Similar to the Swiss chard at SAT, the kale leaves at Latia Agribusiness Solutions (LAS), Kenya, were heavier and wider, and the plants taller in the agrivoltaic plot compared with the control. There was no significant difference between the kale plants growing directly underneath a solar panel and underneath a gap between the panels. Coriander was also taller on the agrivoltaic plot, with no difference between whether the plant was under a panel or under a gap between panels;

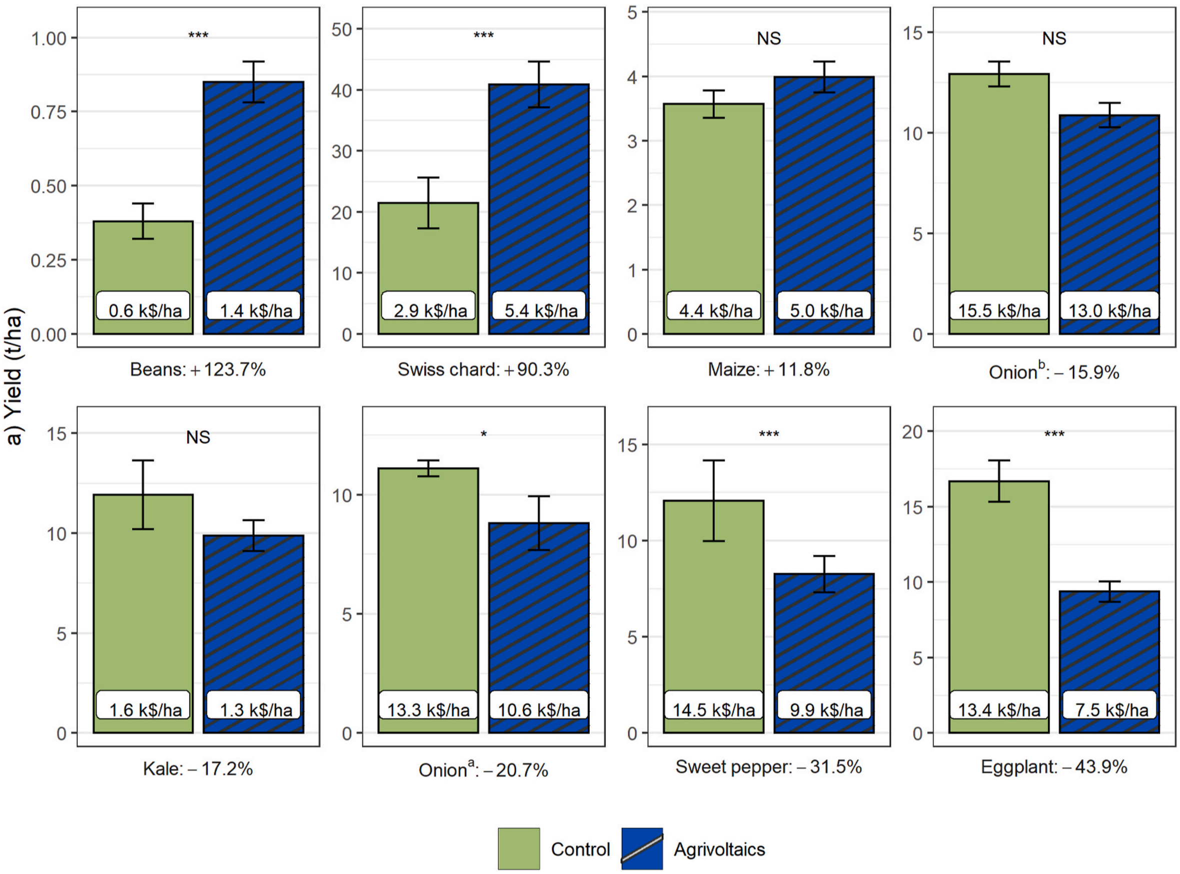

Fig. 2. Crop yields and values. Mean standardised crop yields and sale values from the eight crops studied at SAT. Error bars represent standard errors, p values were calculated with the LMM, asterisks denote statistical significance (NS = not significant, $*p < 0.05$, $***p < 0.001$), ^{a} = 2022 growing season, ^{b} = 2023 growing season, and sale values are in k$ USD per ha.

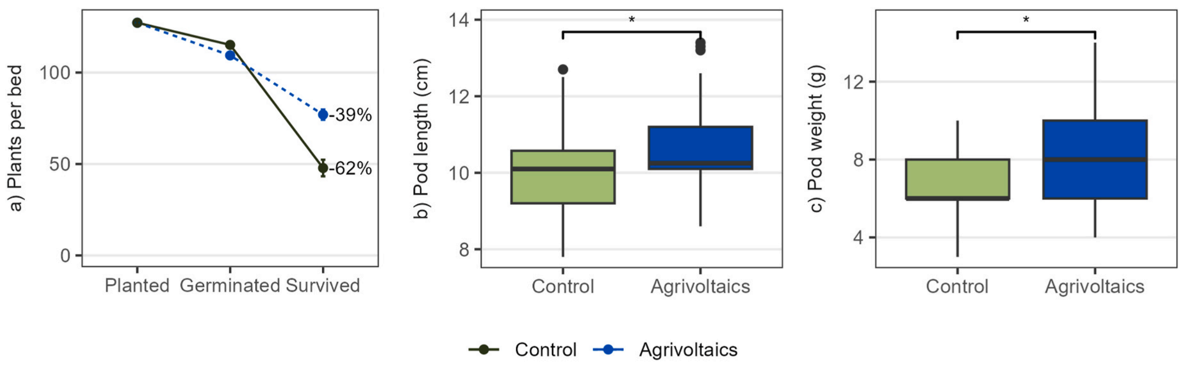

Fig. 3. Bean survival rate and pod morphology. a) The mean number of bean plants that were planted, that germinated, and that reached maturity during the Nov 2022–Jan 2023 growing season. Error bars represent standard errors. The percentage of the planted crop lost to mortality is shown. b) and c) The median and interquartile ranges of bean pod length (b) and weight (c) from beans grown in the control plot (n = 50) and in the agrivoltaic plot (n = 50) at SAT. P values were calculated with Wilcoxon tests, and asterisks denote statistical significance ($*p < 0.05$).

however, the plants under a gap produced a similar weight yield to those in the control plot, while those directly under a panel produced a significantly higher yield. In contrast, onions were smaller and lighter in the agrivoltaic plot than the control plot, and there was no significant difference in the agrivoltaic plots between those grown under a panel and those under a gap between the panels. Cabbages displayed similar trends to the onions, with smaller and lighter crops under the solar panels compared with the control, although crops grown under a gap between the panels were not significantly different from either the control plot or those grown directly under a panel. Fig. 6 shows the cabbage, coriander, kale and onion yields recorded at LAS, and Fig. 7 shows the morphologies of the harvested produce.

3.3. Environmental parameters, irrigation and crop yields:water input

Photosynthetically active radiation (PAR) was significantly lower under the agrivoltaic plot compared with the control plot at SAT, especially directly underneath the PV panels; here it was 77.5 % lower than the control during midday during the March 2023 recording period. There were similar patterns in PAR at LAS. The PAR observations

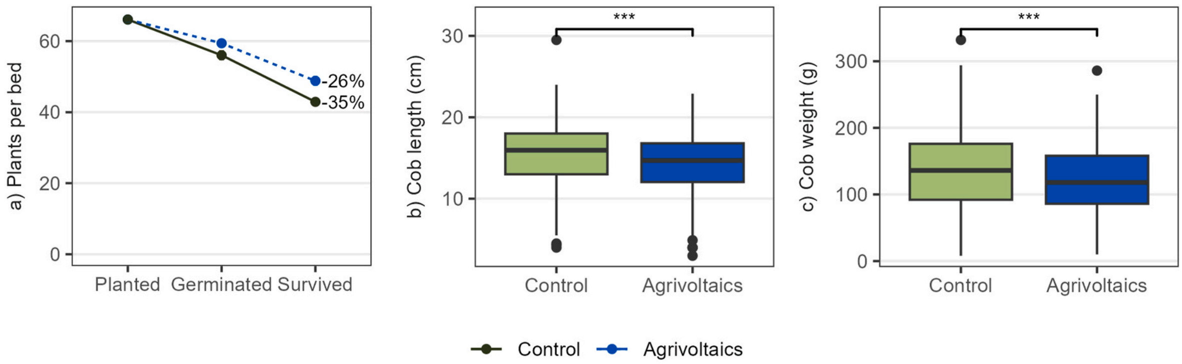

Fig. 4. Maize survival rate and cob morphology. a) The mean number of maize plants that were planted, that germinated, and that reached maturity during the Nov 2022–Jan 2023 growing season. Error bars represent standard errors. The percentage of the planted crop lost to mortality is shown. b) and c) The median and interquartile ranges of maize cob length (b) and weight (c) from maize grown in the control plot ($n = 708$) and in the agrivoltaic plot ($n = 691$) at SAT. P values were calculated with the LMM, and asterisks denote statistical significance (***$p < 0.001$).

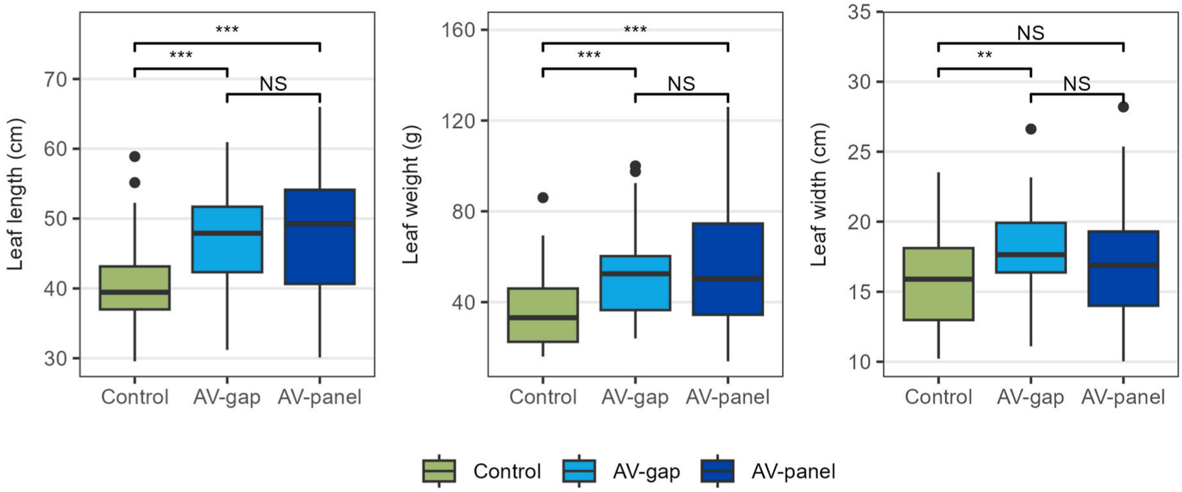

Fig. 5. Swiss chard leaf morphology. The median and interquartile ranges of leaf length, width and weight from Swiss chard grown in the control plot ($n = 206$) and in the agrivoltaic plot under a gap between solar panels (AV-gap, $n = 209$) and directly underneath a solar panel (AV-panel, $n = 246$) at SAT. P values were calculated with the LMM, and asterisks denote statistical significance (**$p < 0.01$, ***$p < 0.001$).

for SAT and LAS are displayed in Fig. 8.

Reflecting the reduced direct solar radiation and associated evaporative water loss, soil moisture content was higher under the agrivoltaic system at SAT, more so directly under the panels (control plot: 21.33 ± 0.16 %; under gaps between PV panels: 30.64 ± 0.32 %; under panels: 37.83 ± 0.44 %). This resulted in a 12.6 % reduction in total irrigation use (Control: 1057 L/m^2; Agrivoltaics: 925 L/m^2). The rainwater harvesting system contributed 12.7 % (20 L/m^2) of irrigation used for the agrivoltaics plot during the second growing season, reducing the overall demand on SAT's centralised irrigation system by 14.4 % for the duration of the experiment (Control: 1057 L/m^2; Agrivoltaics: 905 L/m^2). This was most prominent during the first growing season, which saw a 21.7 % reduction in irrigation use, followed by a 7.6 % and a 6.1 % reduction in the second and third growing seasons, respectively. The cumulative irrigation consumption from the site's centralised irrigation source is displayed in Fig. 9, which is also annotated to indicate the three growing seasons.

Beans and Swiss chard produced significantly greater yields under the agrivoltaic system while simultaneously requiring significantly less water. Maize and the 2022 crop of onions had no significant differences in the yields, but they were grown with significantly less water per kg output. Only the eggplant crop received significantly more water per kg output. The crop yields per water input are displayed in Fig. 10.

3.4. Electricity generation

The off-grid agrivoltaic system at SAT generated 12.55 MWh/year to meet the consumption demand between June 2022 and May 2023, inclusively. The equivalent cost to purchase this electricity from the Tanzanian national grid would be 2.97 MTsh/year ($12,686 USD/year), based on 236.37 Tsh/kWh (0.101 USD/kWh) as of Aug 2023 (SAT electricity bills). As a new electrification initiative for this site, it is not yet used to its full capacity. The PVGIS tool [40] estimates that the system could provide up to 4.38 MWh/m, worth 12.42 MTsh/year ($5310 USD/year).

Latia Agribusiness Solutions consumed 54.31 MWh/year of electricity between June 2022 and May 2023, inclusively, from both the national grid supply and the agrivoltaic system. The monthly consumption, displayed in Fig. 11, ranged from 2.52 to 6.06 MWh/m. The agrivoltaic system generated 30.13 MWh/year (min 1.62 – max 3.40 MWh), which is 56 % of the total electricity consumed. Based on the mean electricity price of 30.0 KES/kWh (0.19 $/kWh USD) between Jan–July 2023 (LAS electricity bills), the agrivoltaic system is saving the farm approximately 903,900 KES ($5725 USD) annually. Fully utilised, this system could generate up to 96.9 MWh/year worth 2.9 MKES/year ($18,461 USD/year).

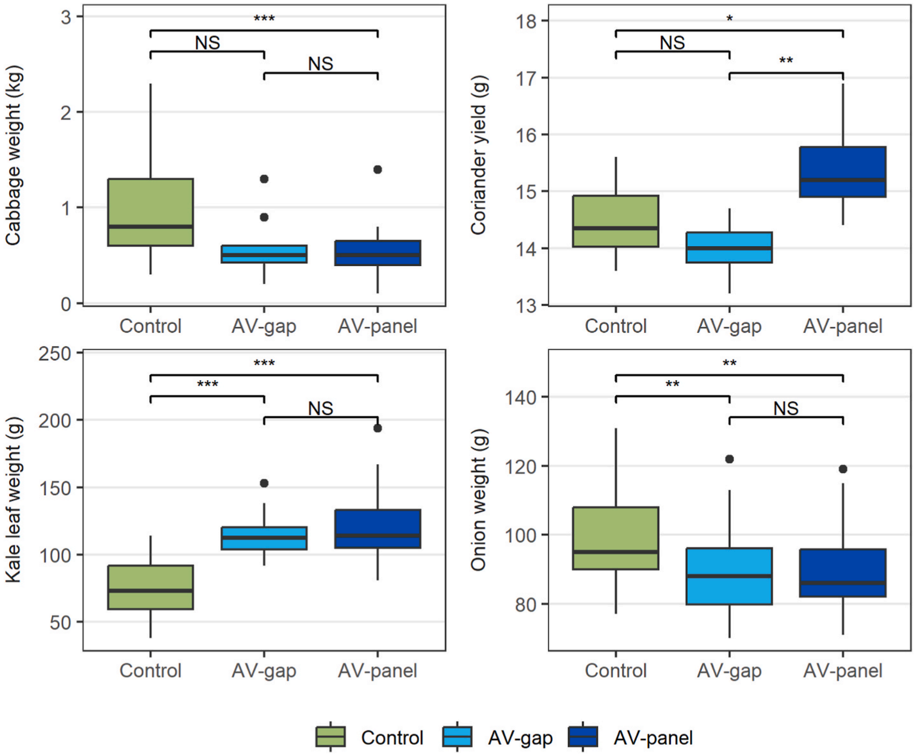

Fig. 6. Cabbage, coriander, kale and onion yields. The median and interquartile ranges of cabbage, coriander, kale and onion yields grown in the control plot and in the agrivoltaic plot under a gap between the solar panels (AV-gap) and directly underneath a solar panel (AV-panel) at LAS (n = 24 for each crop and treatment). P values were calculated with the LMM, and asterisks denote statistical significance (NS = not significant, *p < 0.05, **p < 0.01, ***p < 0.001).

3.5. *Land productivity*

Combining the different crop yield results with the reduction in panel density - and hence potential electricity generation over conventional solar - reveals that land productivity for food and energy combined, measured as the land equivalent ratio (LER), increases in all crop scenarios, even when crop productivity was reduced. The LERs for each crop are displayed in Fig. 12, and the mean LERs across all the growing seasons were 1.88 at SAT and 1.77 at LAS.

4. Discussion

4.1. *Crop performance*

This study demonstrates the extent to which agrivoltaic systems can deliver food production, electricity generation and water conservation concomitantly in East Africa, providing evidence for the benefits of this technology in this region, and potentially for other semi-arid locations globally. Generally, yields increased in leafy vegetables or drought sensitive crops (e.g. beans), and decreased for shade intolerant species such as those in the Solanaceae family. The crops tested are all regionally important, contributing to nutritious diets e.g. beans and leafy greens, and/or providing a staple food source and income for farmers e.g. maize and onions. Maize, for example, is grown on ca. 25 % of farmland in Tanzania [41] and 80 % of production is grown by smallholder farmers for food and for sale [42]. Maize, a C4 plant, is generally shade intolerant [43], and agrivoltaic studies in France observed lower yields [44]. The lack of such a decrease in this study was therefore surprising, especially considering the yield was 11.8 % higher under the agrivoltaic system and 2.7 times higher than the average for the region [45]. Maize grown under agroforestry systems in the region also produced higher yields [46], and while agrivoltaics does not benefit soil fertility as agroforestry does, the partial shading influences evapotranspiration in a similar way. These results demonstrate the potential for agrivoltaics to reduce physiological stress in maize under future climate change scenarios [47,48].

The positive yield results for Swiss chard have promising implications for growing nutritious crops with agrivoltaics. The control plot was sufficiently irrigated, with yields comparable to those in a rainfed study in South Africa [49], so drought stress does not explain the lower yields compared to the agrivoltaic plot. Instead, the partial panel cover is potentially creating a more suitable growing environment by protecting the crops from heat stress and/or UV damage. More comprehensive microclimate monitoring together with plant physiological data is needed to identify the mechanisms underpinning the benefits of growing beneath PV panels. For example, research in a semi-arid region of the USA found that tomato and jalapeno water use efficiencies increased under agrivoltaics [29]. Shade netting and shade trees are already used in East Africa to protect some crops from excessive light, associated radiation damage and temperature stress [50–52], and the results from this study show that partial shading from PV panels can also reduce plant losses. At SAT beans are typically grown in cooler periods but were trialled in a warmer period to assess if this was possible under the agrivoltaic shading. Although the yields under the panels were more than four times lower than the expected yield for Tanzania [45], the situation was significantly worse for the control plot yields, which were an order of magnitude lower than typical and where the beans had higher mortality. Agrivoltaic systems may therefore provide improved resilience to the yield-reducing temperature rises forecast under climate change [20,47,48].

Only eggplants had a yield more than a third lower than the control, although both plots were within the expected range for yields in Tanzania [53]. Similar yield reductions were observed for eggplants under agroforestry systems in West Africa [54], suggesting partial shading inhibits eggplant fruit production. While eggplants, onions (in 2022) and sweet peppers had lower yields in the agrivoltaic plots compared to the control plot, these were still the highest value crops, generating the greatest incomes for the farm regardless of the plot

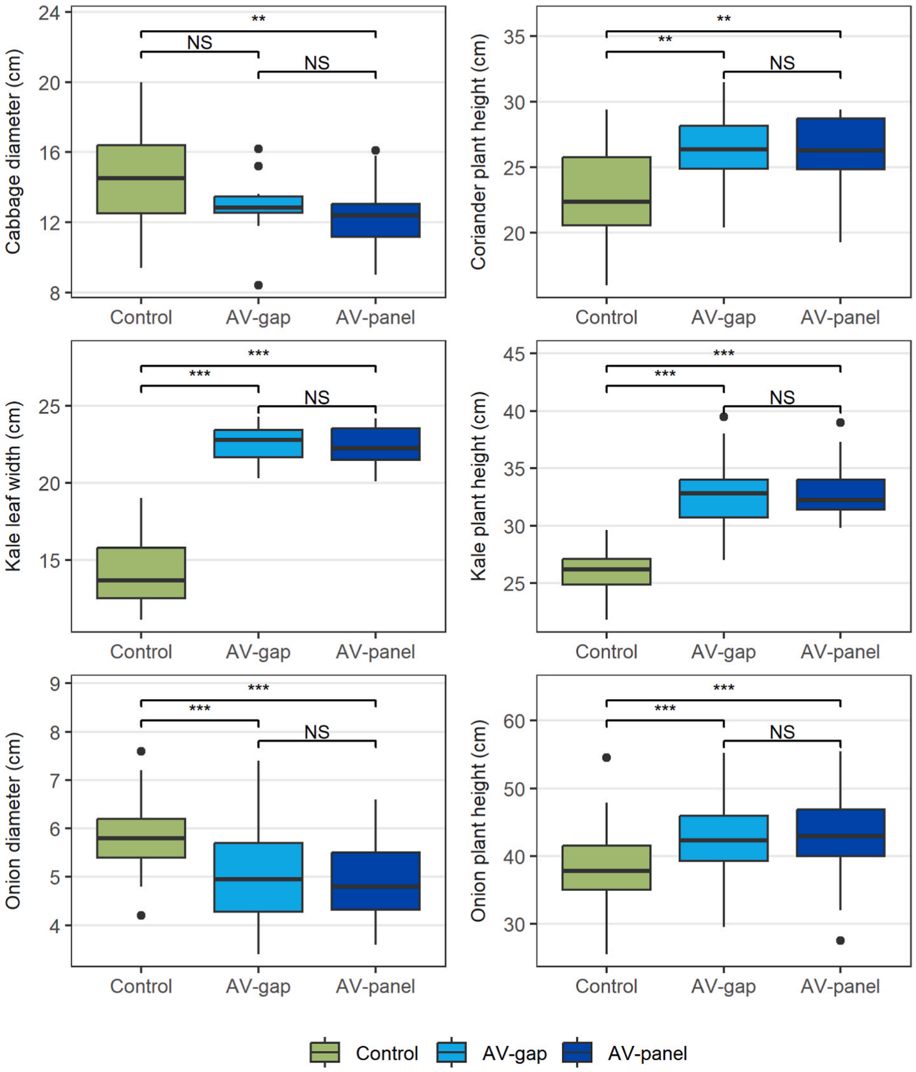

Fig. 7. Cabbage, coriander, kale and onion morphologies. The median and interquartile ranges of morphological results for cabbages, coriander, kale and onions grown in the control plot and in the agrivoltaic plot under a gap between the solar panels (AV-gap) and directly underneath a solar panel (AV-panel) at LAS ($n = 24$ for each crop and treatment). P values were calculated with the LMM, and asterisks denote statistical significance (NS = not significant, *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$).

treatment. Growing these crops under agrivoltaics could therefore still be economically viable because of the high value per kg of produce.

The farming technicians at LAS noted that the kales were “greener with more vigour”, an observation mirrored for Swiss chard at SAT; the fuller and greener appearance of the Swiss chard, and the longer bean stems, were more attractive for sale, indicating that agrivoltaics could improve marketability of crops as well as overall yields.

The variations observed for the same crops grown between different seasons, between similar crops grown at the two sites during the same time of year, and between different crop types, all support the observation from much research on agrivoltaics that crop yields under these systems vary depending on the crop type, system design, local environmental context, and seasonal variations in climate (see Refs. [35,36,55,56] for reviews and examples). Further studies are needed in East Africa if the findings are to support this goal: much of the published research on agrivoltaics is from temperate regions with lower levels of solar radiation and evaporative water loss. For example, a recent meta-analysis of studies in temperate regions found that panel densities correlated negatively with crop productivity [39], whereas this study reveals that a relatively high panel density can result in significant yield improvements in the environmental conditions of East Africa.

4.2. Water conservation and rainwater harvesting

Some crops produced more food using less water, valuable in a region where water scarcity threatens food security, most farmers rely on rainfall for their crops, and climate change is likely to make rainfall less predictable [57]. Swiss chard grown during a dry period had the second greatest increase in yield:water ratio, indicating the potential of agrivoltaics to support otherwise drought-sensitive leafy greens. The reductions in irrigation demand under the agrivoltaic system means more water is available for other uses and can be stored for use during periods of drought. The 10,000 L rainwater harvesting tank at SAT filled up with just a few days of heavy rainfall and provided up to eight days of additional irrigation, which could be sufficient to prevent livelihood losses through a crop failing to reach maturity. Long-term storage of water will be particularly susceptible to evaporation, although this will be minimised with covered systems like the water tanks used in this study, which are commonly available across the region. Combined with the improved survival rates observed, these findings have promising implications for climate change resilience offered by agrivoltaic systems that incorporate rainwater harvesting.

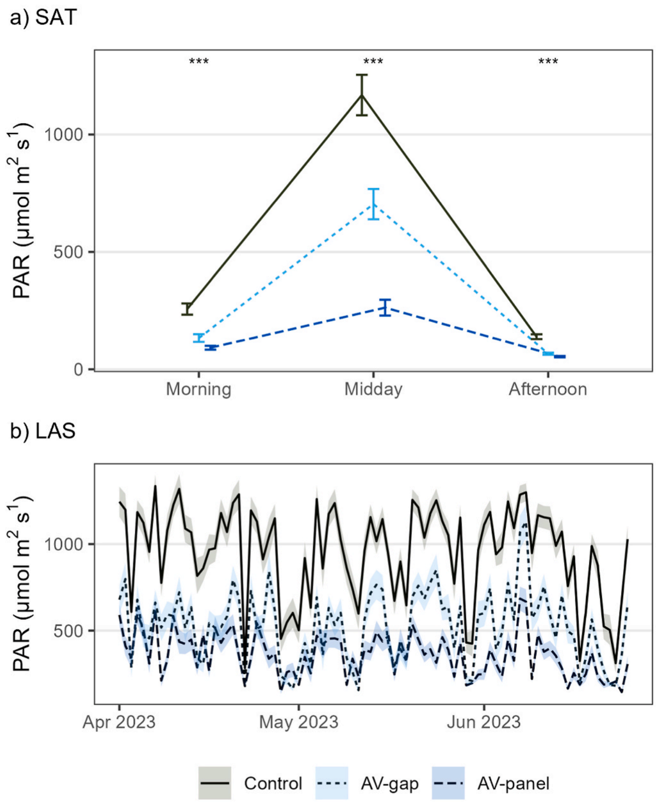

Fig. 8. Photosynthetically active radiation (PAR). a) SAT: Mean PAR recorded in the control plot, underneath a gap between the agrivoltaic solar panels (AV-gap) and directly underneath a solar panel (AV-panel), at approximately 08:00 in the morning, midday, and 16:00 in the afternoon. Error bars represent standard error, and p values were calculated with the LLM, testing for the effects of the treatments on the model for each time point. Asterisks denote statistical significance (***$p < 0.001$). All LLM post-hoc test p values were <0.05. b) LAS: Mean daytime PAR, recorded every 5 min between April and July 2023 in the control plot, underneath a gap between the agrivoltaic solar panels (AV-gap) and directly underneath a solar panel (AV-panel). Shaded areas represent standard error.

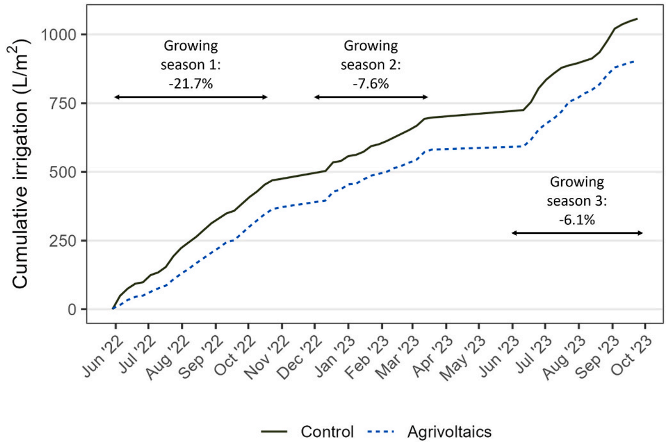

Fig. 9. Irrigation consumption. The cumulative centralised irrigation consumption by the control and the agrivoltaic plots at SAT for the duration of the experiment. The rainwater harvesting system contributed a further 20 L/m^2 to the agrivoltaic plot during the second growing season.

4.3. *Energy potential*

At SAT, the off-grid system has been used to enhance the capabilities of the Farmer Training Centre by powering charging points for students' devices, lighting for evening studying and activities, and fridges to store food and drinks. As the off-grid site did not previously have such a supply capacity, demand has increased as the training centre has taken advantage of the new source of power, and SAT now plans to replace polluting and expensive diesel generators with electric connections. This progressive connection of electrical devices which is below the system's capacity partly explains the underutilisation of the system compared to the modelled theoretical maximum. The system has remaining capacity for connection of additional devices, which SAT plans to do once the cable infrastructure is expanded to the farther farm buildings housing the higher load machinery. The size and capacity of the agrivoltaic demonstrator is appropriate for the scale of PV mini-grid implementation for rural electrification in sub-Saharan Africa, powering small-medium agribusinesses or a village of ∼500 people (based on the trend of electricity demand per capita in Tanzania [58]). This experiment therefore represents a real-world application of agrivoltaics. The grid-tie system at LAS has reduced the agribusiness' operating costs, thus redistributing money for enhancing the training facilities. The system is not fully utilised as some consumption occurs outside of daylight hours, relying on the grid supply. Further, consumption during cloudy periods may be greater than the effect of clouds on surface insolation used in the PVGIS model. This explains why the system only provides 58 % of the site's consumption, despite having the capacity to provide it all. Adding battery storage will maximise the use of the generated electricity and avoid curtailing excessive generation during peak sun and minimising grid requirements during nighttime or low levels of insolation. Like most PV technologies, agrivoltaics is modular and easily scalable to achieve higher capacities where required.

4.4. *Land use*

Combining the crop yields with electricity generation potential, agrivoltaics land productivity was higher than the land use with either energy or agriculture alone, in every growing season and at both sites. This echoes the LER models in France [59], Germany [33], India [60], Italy [61] and Spain [62], which found similar, but slightly lower, LER ranges. Notably, the high LERs in this East African study were greater than those reported previously, mainly due to the substantial yield increases observed. Furthermore, they were very similar at both sites, despite differences in the crops grown and the local conditions. This indicates that agrivoltaics can address land use conflicts in East Africa (see Ref. [63]). Detailed economic analyses, such as those that build on levelised cost of energy (LCOE) methods [64] and account for agricultural outputs and operating costs, will extend this assessment of the multifunctional value of agrivoltaics.

4.5. *Limitations*

The conclusions presented in this study reflect the specific locations, crops, timescales and experimental designs of the study. The study tested the performance of an off-grid and a grid-tie agrivoltaic system with 50 % panel density at two semi-arid locations in East Africa using nine different crops over three growing periods. This provides valuable insights regarding the performance of agrivoltaics in this region, but the results for other crops may be different, especially for shade intolerant crops where growth under panels could lower yields. Further, electricity generation, crop performance and water conservation will likely vary in other climatic zones. For example, in more arid regions the benefits for crop yields and water conservation may be greater as evapotranspiration rates and heat stress will typically be higher, and thus the partial shading could better protect plants from such stresses, as long as water supply is sufficient to enable agriculture in these regions. Conversely, in humid

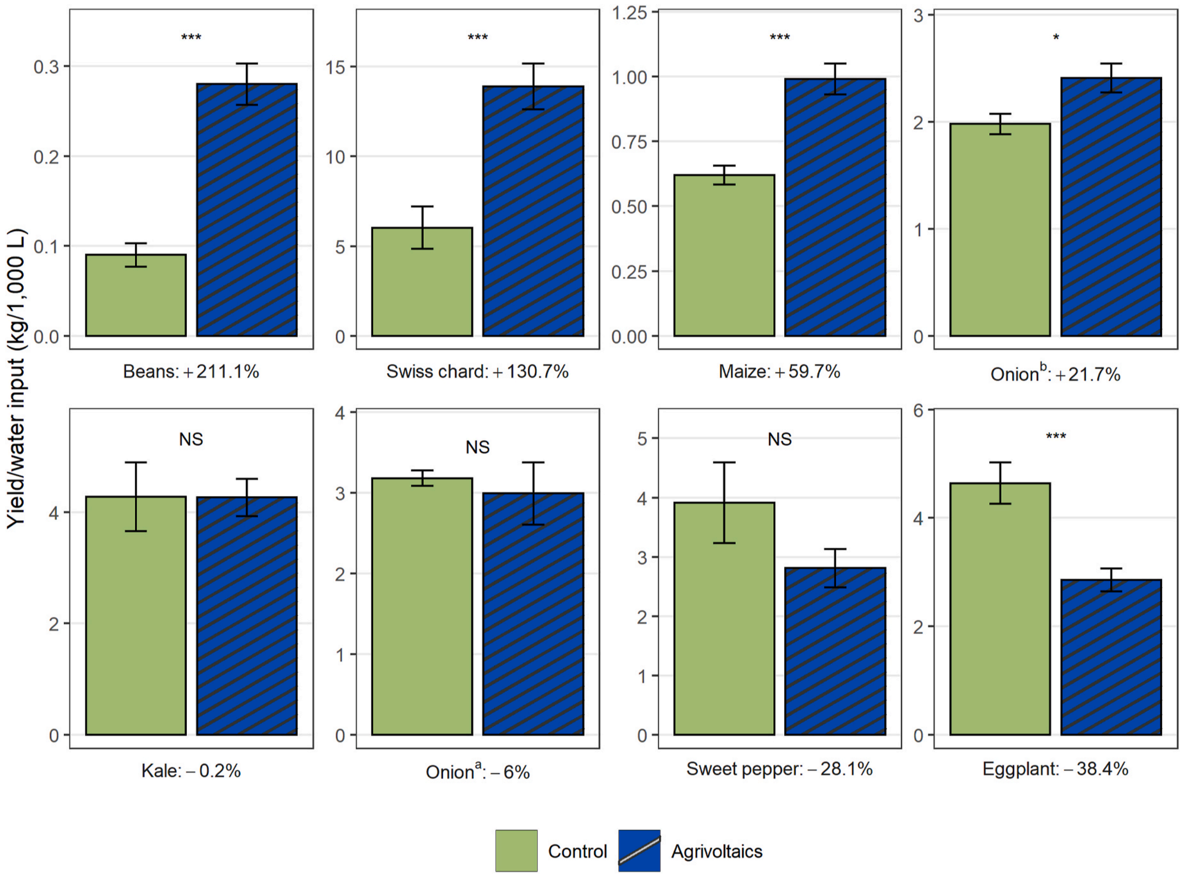

Fig. 10. Crop yields and water input. The mean crop yields as a function of the amount of irrigation, rainwater harvesting and precipitation input. Error bars represent standard errors, p values were calculated with the LMM, asterisks denote statistical significance (NS = not significant, $^*p < 0.05$, $^{***}p < 0.001$), ^{a} = 2022 growing season, and ^{b} = 2023 growing season.

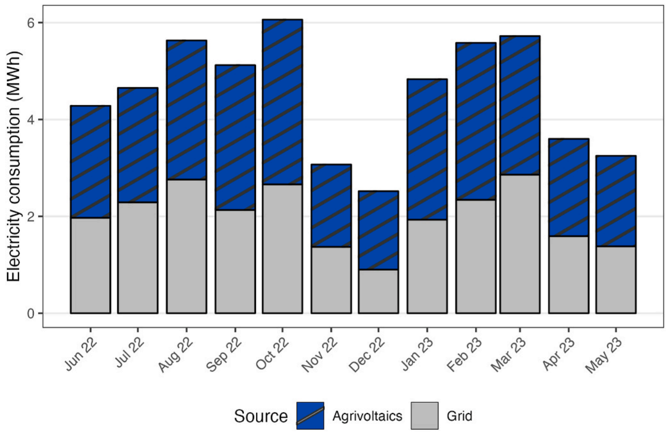

Fig. 11. Electricity consumption at LAS. The monthly electricity consumption from the grid-tied agrivoltaic system and the national grid at LAS.

and cloudy regions the PV performance may be lower, and panel densities may need to be decreased to improve direct PAR levels reaching the underlying crops. Enhancing the predictability of outputs from agrivoltaic systems through more replicated studies across multiple sites, seasons, system designs (especially panel densities) and crop types (including for mechanised agriculture) will improve confidence in the ability to deliver enhanced food, energy and water security, and potentially support increased deployment across different climatic zones in East Africa.

4.6. *Supporting agrivoltaics for sustainable development in East Africa*

This study demonstrates the application of agrivoltaics for off-grid and grid-tied agribusinesses. With the potential for local and decentralised electricity generation, grid-tie opportunities and scalable designs, agrivoltaics could also have a range of other applications in East Africa. For example, off-grid agricultural communities seeking electrification could develop PV mini-grids as agrivoltaic systems, potentially supported by government initiatives [14]. This would avoid either losing existing farmland to conventional mini-grids, or seeking alternative land further from settlements for PV development - which would increase transmission costs and raise other land use conflicts [1]. Grid-tie systems for government and civil society organisations with farming activities and seeking self-sustainable energy solutions could also be developed as agrivoltaics, adding local electricity generation while supporting agriculture. As a scalable technology [65], PV in the form of agrivoltaics could be developed at both small and large scales, although the economic viability must be determined. Innovative business models to determine the financial viability of this technology will be needed if solar developers, agricultural communities and agribusinesses are to capitalise on the opportunity to deliver low carbon electricity integrated with agricultural services – particularly in the context of improving energy access for rural communities currently lacking grid connection [66]. Solar PV offers energy price stability, averting the challenge of fluctuating grid-supplied electricity prices or fuel prices for diesel generators. Despite this, high upfront costs and access to finance form a major barrier for developing solar energy solutions in the region [37,67]. Improved and diversified incomes offered by agrivoltaics, particularly with the sale of high value crops, could help secure finance to cover these costs: a cost-benefit analysis of a similar agrivoltaic

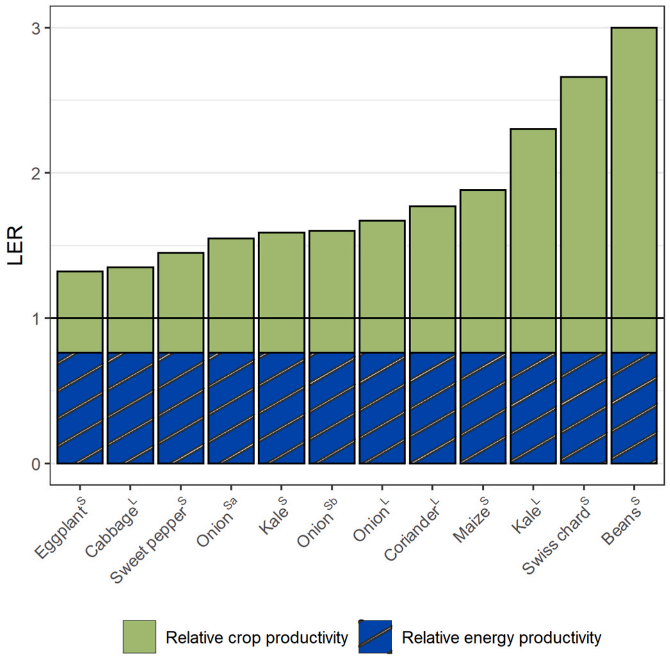

Fig. 12. Land productivity. The land equivalent ratios (LERs) of the agrivoltaic crop yields relative to the control yields, combined with the difference in electricity generation potential between the agrivoltaic system and a reference ground mounted solar park at Garissa. This relative energy productivity was calculated as 0.76, based on the difference in panel density between the agrivoltaic systems and Garissa solar park. ^{S} = Sustainable Agriculture Tanzania, ^{L} = Latia Agribusiness Solutions, ^{a} = 2022 growing season, and ^{b} = 2023 growing season. The horizontal black line signifies an LER of 1, where land productivity is equal to single use for energy or agriculture.

system design in India estimated a payback period of just under eight years [68]. Business models utilised for conventional PV in East Africa [69] are a potential starting point for creating agrivoltaic business models, so could provide a basis for solar developers to explore new markets with farming communities and agribusiness. Studying the economics of agrivoltaics combined with different agricultural contexts, e.g. staple crops, high value crops and livestock, will identify where the greatest livelihood benefits can be achieved and how best to realise them.

The Africa Renewable Energy Initiative aims to triple the current installed renewable energy capacity to 300 GW by 2030 [70,71], while the Comprehensive Africa Agriculture Development Programme seeks more than 6 % annual growth in agricultural GDP to achieve food security and economic development [72]. Agrivoltaics could progress both these goals. As a multifunctional land use spanning two distinct sectors - energy and agriculture - development policy reform may be necessary to enable such co-uses of land [73–76].

East African nations also have significant ambitions to meet the targets of the UN Sustainable Development Goals, but a recent UN report [77] highlights that progress has been uneven, with significant differences among sub regions, countries, and rural and urban areas. The findings here suggest agrivoltaic systems could be a way to address multiple SDGs simultaneously and on the same land area. For example, with appropriate design and crop selection, agrivoltaics could support progress towards SDG 2 – Zero Hunger, specifically targets 2.1, 2.3 and 2.4 [78], by improving yields of – and thus access to – nutritious crops and enhancing resilience to climate change challenges for crop production, such as high temperature stress and more unpredictable rainfall. Reducing susceptibility to climate change-induced droughts by reducing water loss also advances progress towards SDG 13 – Climate Action target 13.1, whilst the energy produced from agrivoltaic systems clearly addresses SDG 7 – Affordable and Clean Energy targets 7.1 and 7.2 [78] by advancing low carbon, sustainable electrification for rural agricultural communities.

5. Conclusion

This study provides a multi-site, multi-season, and multi-crop assessment of agrivoltaics in a tropical semi-arid region, informing how the development of on- and off-grid PV infrastructure can address the food-energy-water nexus in East Africa, and potentially other semi-arid locations. Several crop yields either increased or were maintained under agrivoltaics, while those that had lower yields still generated economic returns expected for the region. The benefits for energy security were clear, as were those for water security: the results show a clear reduction in evaporative water loss and irrigation demand – a critical issue for farmers facing unpredictable rainfall and water scarcity under future climates.

These results contrast with those found from existing agrivoltaics research in temperate regions, highlighting that agrivoltaic systems must be based on locally relevant assessments, rather than transferred from existing regions where the contexts and environmental conditions differ. With the potential for generating low-carbon, off-grid electricity concomitantly with food production, water conservation and better resilience to climate change, agrivoltaics could address multiple Sustainable Development Goals simultaneously. This technology could therefore offer significant benefits to governments and decision-makers seeking to optimise development investments for maximum impact.

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CRediT authorship contribution statement

R.J. Randle-Boggis: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing – original draft, Visualization, Project administration, Funding acquisition. **G.A. Barron-Gafford:** Conceptualization, Writing – review & editing, Funding acquisition. **A.A. Kimaro:** Conceptualization, Resources, Writing – review & editing. **C. Lamanna:** Methodology, Resources, Writing – review & editing, Funding acquisition. **C. Macharia:** Resources, Project administration. **J. Maro:** Resources, Project administration. **A. Mbele:** Methodology, Investigation, Project administration. **S.E. Hartley:** Conceptualization, Methodology, Writing – original draft, Writing – review & editing, Visualization, Supervision, Funding acquisition.

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.

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Data availability

Data supporting the findings of this study and used to produce the figures are available within the text and/or the online data repository, UK Data Service ReShare.

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