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Improving the Land Use Efficiency of Farmland by Using Agrivoltaics

Kago Rabasoma[1,2] | Nicholas Jenkins[1] | Janaka Ekanayake[1]

[1]Cardiff University, Wales, UK | [2]University of Botswana, Gaborone, Botswana

Correspondence: Kago Rabasoma (rabasomak@ub.ac.bw)

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ABSTRACT

The design and performance analysis of agrivoltaics installations for a tomato farm in the hot and dry climate of Botswana is presented. The study investigates unique agrivoltaics solutions to solve some energy, food and water issues in rural Southern Africa. Two agrivoltaics scenarios, the low PV density and high PV density, were mapped out together with the research control scenario, which was just ordinary tomato farming. The three study cases were then modelled and simulated using the STICS (Simulateur mulTIdisciplinaire pour les Cultures Standard) crop model and PV*SOL software to deduce the tomato growth and energy output of the PV installations, respectively. The results from the crop growth simulations showed that tomato harvest is reduced when cultivated in agrivoltaics settings, and that worsens as the PV density is increased. Validation of the aforementioned results by comparing with other similar studies highlighted some possible limitations of crop modelling, since in practice, shade-tolerant plants tend to thrive in low-density agrivoltaics. The generation of PV electricity improved the land use efficiency of the farm by 15% and 8% in the low-density and high-density agrivoltaics, respectively. This means that the farmer or landowner extracts more value from their land by implementing agrivoltaics instead of persisting with conventional tomato farming. Therefore, it is concluded that agrivoltaics technology can be successfully implemented in the hot and dry climate of Botswana to enjoy some synergetic benefits between crops and PV systems, as well as improve the overall efficiency of the land use.

1 | Introduction

Worsening environmental issues caused by global warming and climate change, such as extreme weather and unreliable rainfall, have devastated the farming industry. Abiodun et al. (2018) have reported that intensified droughts have led to food insecurity in Southern Africa. The impacts of climate change on agriculture, coupled with the continued population increase, have resulted in food shortages all over the world (Maia et al. 2020). The aforementioned population growth is also accompanied by rapid urbanisation, with projections that in the next 30 years, almost two-thirds of the world population will reside in urban areas, hence the expansion of cities that consumes more and more agricultural land (Carreño-Ortega et al. 2021; Ravi et al. 2016). There is also a desperation to satisfy an ever-rising demand for energy through renewable sources, such as solar PV. However, solar PV generation also requires space in populated areas where land is at a premium, and this has led to conflicts over land use for energy generation versus food production (Feuerbacher et al. 2021; Ravi et al. 2016). Another resource that is increasingly stretched by the demand for more food is water, because at least 70% of global freshwater is used for agriculture (Elamri et al. 2018).

There is no doubt that the world is faced with many energy and food production challenges. That being said, some of these challenges can be solved, at least in part, by the use of agrivoltaics (Anatoliivna 2021; Dinesh and Pearce 2016; Elamri et al. 2018). According to Trommsdorff et al. (2020) and Braik et al. (2021), agrivoltaics can be broadly described as farming under a canopy of PV panels. It is the dual land use through the colocation of solar energy generation and farming that was first introduced in the 1980s and has been reported to bring about food–energy–water synergies as well as ensure ecological sustainability (Campana et al. 2021; Dupraz et al. 2011; Marrou et al. 2013; Proctor et al. 2020; Riaz et al. 2021; Xue 2017). The synergetic benefits of agrivoltaics have been reported to increase land use efficiency, and this was proven by the Haggelbach agrivoltaics pilot farm in Germany, where a 186% land use efficiency was achieved (Trommsdorff et al. 2020). Furthermore, a study by Rabasoma et al. (2024) proved that agrivoltaics can also have a positive economic impact by making farming and energy generation more profitable when colocated on the same land.

Anatoliivna (2021) has reported that the two broad classifications of agrivoltaics consider the main purpose of the system. That is, crop sector agrivoltaics are used alongside crop cultivation, whereas livestock sector agrivoltaics involve growing livestock together with PV generation on the same piece of land. The most common are crop agrivoltaic systems, which are divided into three major types, namely crops grown between ground-mounted panels, PV greenhouse and stilt-mounted panels, which allow for the cultivation of crops underneath using farm machinery (Braik et al. 2021; Sekiyama and Nagashima 2019). We can proceed to further classify agrivoltaics by the orientation of the panels within a system. The panels may be in straight rows, vertically orientated, at a specified angle, or even in checkerboard patterns (Anatoliivna 2021). The checkerboard orientation has been reported to be very friendly for crops because it allows for a fairly uniform shading effect throughout the day as the sun changes its position.

It is widely reported that the implementation of agrivoltaics brings about sustainability through food, energy and water synergies. This is corroborated by various authors who reported that agrivoltaics reduced the demand for irrigation water by up to 20% (Anatoliivna 2021; Dinesh and Pearce 2016; Proctor et al. 2020; Trommsdorff et al. 2020). This reduced irrigation demand is a consequence of several phenomena, many of which emanate from the creation of a favourable microclimate under the canopy of PV panels. The shade cast by the panels also cools down the soil surface, hence reducing the evaporation and ensuring that the soil moisture is retained for longer. On top of this, the crops are also protected against heat stress, which reduces transpiration and retains more water. Humidity is also generally maintained at a higher level under the PV canopy, thus reducing the tendency for water loss (Gese et al. 2019). Furthermore, for water conservation, gutters may be added to the PV arrays to harvest rainwater, and even to collect panel-cleaning runoff water, which can then be recycled (Randle-Boggis et al. 2021). The canopy of PV panels protects the crops from extreme weather, such as storms, snow, frost, scorching sun, wind and others (Anatoliivna 2021; Trommsdorff et al. 2020). This ensures that as extreme weather events become more frequent due to global warming, a complete loss of the whole harvest in the event of once-off extreme weather is prevented. The crops are also beneficial to the PV panels; they cool down the panels through evapotranspiration and convective cooling, hence increasing the efficiency of the panels on hot days (Barron-Gafford et al. 2019).

There have been quite a few successful agrivoltaics pilot projects all over the world. One of those was presented by Barron-Gafford et al. (2019), who carried out an experimental study in the hot desert of Tucson Arizona to compare an agrivoltaics system against standalone PV and agriculture settings. Their experiments showed that the agrivoltaics farm had a 57% better water use efficiency while producing the same or more yield of tomatoes and peppers. This was because the soil moisture under the canopy of panels was retained 15% better, which allowed for irrigation every 2 days instead of every day, hence the water savings. Agrivoltaics panels also generated 3% more energy than their standalone counterparts because they were cooled by the crops underneath through evapotranspiration (Barron-Gafford et al. 2019).

Another study was also carried out by Sekiyama and Nagashima (2019) in Japan to investigate the usefulness of agrivoltaics on shade-intolerant crops like corn. The researchers planted sweetcorn under low-density and high-density PV modules in April 2018, and during the harvest in July, they found out that the corn yield increased by 6% under low-density panels. The conclusion from their experiment is that even shade-intolerant crops can thrive in agrivoltaics. Lettuce, a shade-tolerant crop, performed even better, as higher yields were reported from a crop model simulation study with 29% water savings (Dinesh and Pearce 2016). The first results of an APV pilot plant in Chile were also positive. They showed that partial shading by agrivoltaics reduced irradiation levels by 19%–25% and increased humidity by 3%, which formed a conducive microclimate for potato farming (Gese et al. 2019). However, the authors warned that their results are only indicative; they cannot be fully relied upon since the pilot farm is relatively small and cannot maintain a reliable microclimate all the time. In India, Malu et al. (2017) found that more revenue was generated from the colocation of grape farming with a PV plant using trellises. Most of the experimental studies have reported the problem of increased panel soiling due to cultivation activities, which reduces PV panel efficiency. As such, there is an obvious need for regular panel-cleaning using water, which may be unsustainable unless that water is collected and recycled accordingly. The current study investigates the potential benefits of growing tomatoes in agrivoltaics settings for a hot and dry climate of Southern Africa.

2 | Methodology

2.1 | Design of Agrivoltaics Research Scenarios

The steps and considerations that were made in the design of the agrivoltaics research cases are discussed in this section. Three research scenarios were designed for this study, namely Cases 1, 2 and 3, which are discussed below.

2.1.1 | Case 1—Control

Case 1 was just ordinary tomato farming without any PV installations. This was used as a control setup to be compared with Cases 2 and 3. Figures 1 and 2 represent the isometric and orthographic drawings of Case 1. Tomato plants were spaced 90 cm away from each other, which resulted in 253 tomato plants on the farm.

2.1.2 | Case 2—Low-Density (LD) Agrivoltaics

In Case 2, tomatoes were grown under a canopy of PV modules, hence making an agrivoltaics farm. All the crop settings from the control case were maintained to ensure reliable comparisons. The panels were mounted 3 m above the ground on stilts at an inclination angle of 25 degrees (the latitude of Gaborone, Botswana), as shown in Figures 3 and 4. This low-density scenario consisted of 25 300Wp Si monocrystalline panels that were arranged in five parallel strings, each of them with five panels connected in series. Although they were in straight rows, the panels within each row were shifted by 1 m to create an overall checkerboard pattern, which ensures uniform shading to all crops throughout the day. In this scenario, successive array strings were spaced 2 m apart to ensure plenty of sunlight passed through to the crops. The shading effect on the farm due to the PV array was calculated to be around 20%.

2.1.3 | Case 3—High-Density (HD) Agrivoltaics

This research scenario was similar in every way to Case 2 except that the spacing between successive array strings was reduced from 2 m to 1 m. Therefore, more panels (40 in total) were crammed into the space above the tomato crops. This increased the shading effect to 33%. Further specifications of Case 3 are shown by the isometric and orthographic projections of the research setup in Figures 5 and 6.

2.2 | Crop Growth Simulation (STICS Crop Model)

After designing the three research scenarios, the STICS crop model was then used to simulate the growth of tomatoes in each of those scenarios. The STICS (Simulateur mulTIdisciplinaire pour les Cultures Standard) crop model was developed at the French national institute for agricultural research in 1996 (INRAE 2022). The model uses a dynamic approach to predict crop growth on daily time steps with input variables relating to climate, soil and cropping systems (Beaudoin et al. 2008; Corre-Hellou et al. 2009; INRAE 2022). According to Brisson et al. (2003), the STICS model is divided into modules that document the eco-physiological processes, such as phenology, yield formation, crop management, microclimate, root growth, water and nitrogen balances, radiation interception and many more. The STICS crop model combines all inputs and then uses them to stress or promote the crops accordingly and thereby predict the crop growth and other yield outputs of agronomic interest. It presents the output of crop yield in quality and quantity of the harvested organs, and can also predict environmental variables like the amount of nitrate leaching (Brisson et al. 2003). The STICS crop model was

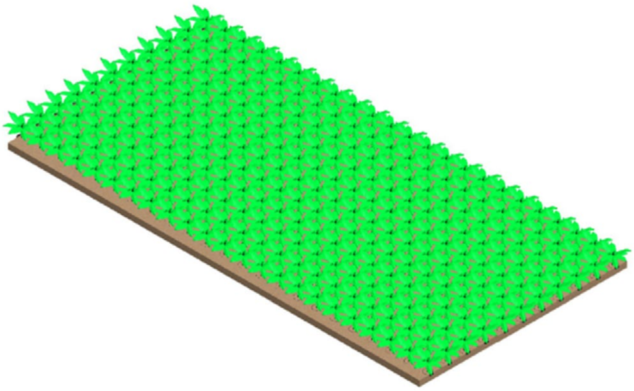

FIGURE 1 | Case 1 isometric view.

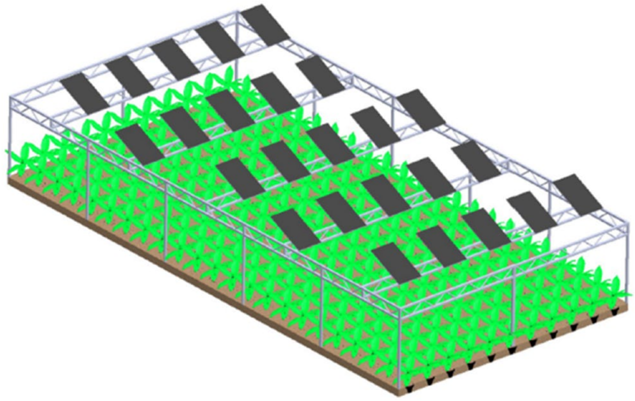

FIGURE 3 | Case 2 isometric drawing.

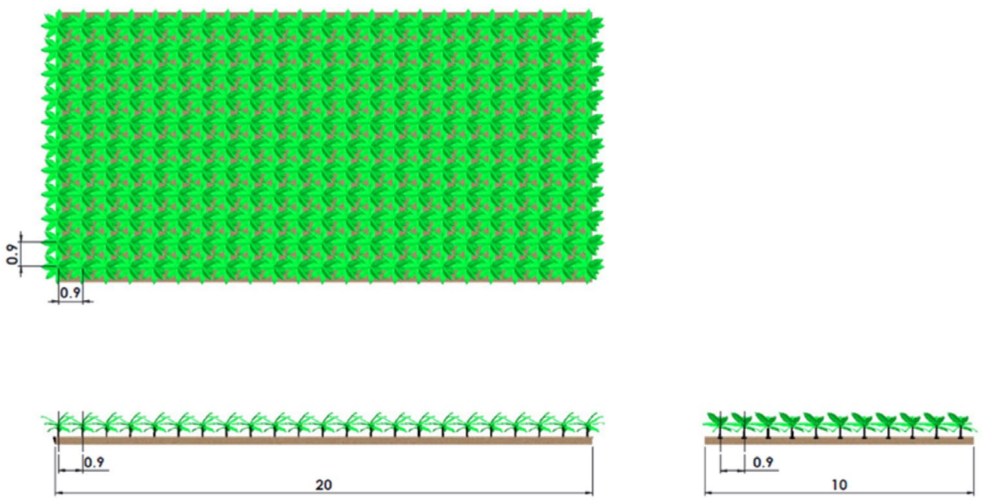

FIGURE 2 | Case 1 orthographic view.

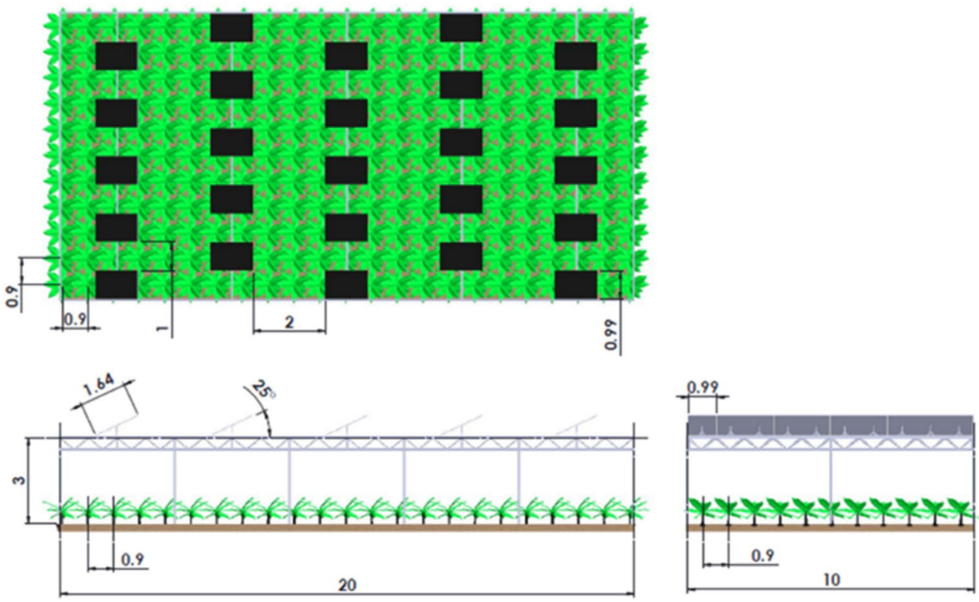

FIGURE 4 | Case 2 orthographic drawing.

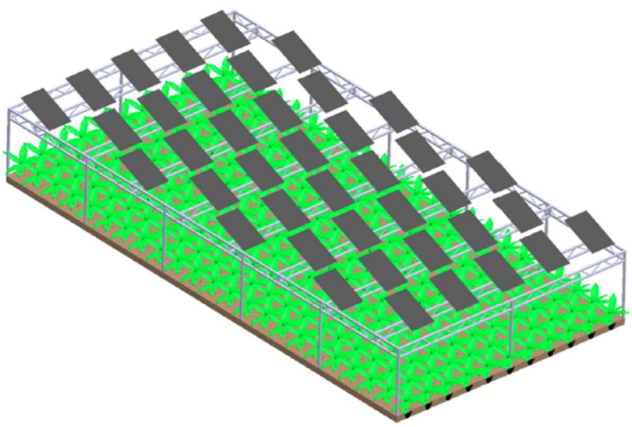

FIGURE 5 | Case 3 isometric drawing.

preferred for this study when compared to other crop models, such as DSSAT and GECROS, because it is adaptable to a wide range of agro-environmental issues since it uses generic parameters. Table 1 shows some major input parameters for the crop model in this study.

2.3 | Simulation of PV Systems Performance (PV*SOL)

This section of methodology outlines the procedures followed to simulate the PV energy generated from the agrivoltaics farms in Cases 2 and 3. The software PV*SOL was used for these simulations as it is a reputable and reliable software for solar energy applications. The PV panels that were selected for this study were 300Wp Si monocrystalline panels with an operational efficiency of 18.1%. Twenty-five (25) of those panels were installed in Case 2 to make a 7.5 kWp-rated plant, whereas in Case 3, there were 40 panels (12 kWp-rated farm). They were installed facing north as Botswana is in the southern hemisphere, and with an inclination angle of 25 degrees. A soiling factor of 10% was estimated because farming activities and cultivation are likely to cause more dust formation, which reduces the panels' efficiency unless they are cleaned regularly.

2.4 | Land Use Efficiency

The question of whether or not more value is obtained from the farm by adding the PV systems is answered by determining the land use efficiency of the agrivoltaics setups. This land use efficiency is measured using a metric known as land equivalent ratio (LER) (Dupraz et al. 2011; Neupane Bhandari et al. 2021). LER is an index that reflects the benefits of the colocation of multiple activities on the same piece of land (Liu et al. 2018; Yu et al. 2015). It is calculated as the sum of the relative outputs from the component activities in a multi-use space compared with their respective sole applications. The Equation (1) shows the formula that was used to calculate LER. A standard PV farm on the 200 m^2 piece of land was designed to consist of 80 PV panels (24 kWp-rated) and annually generate 44.6 MWh.

$$\text{LER} = \left(\frac{\text{Agrivoltaics Crop Yield}}{\text{Crop Yield Standard farm}}\right) + \left(\frac{\text{Agrivoltaics Electricity}}{\text{Standard PV farm Electricity}}\right) \quad (1)$$

Interpretation of the LER metrics:

a. LER = 1, when producing only crops or only PV electricity without colocation of the two on the same farm.

b. If LER > 1, then the agrivoltaics system is more effective than producing only crops or only PV electricity on the selected piece of land.

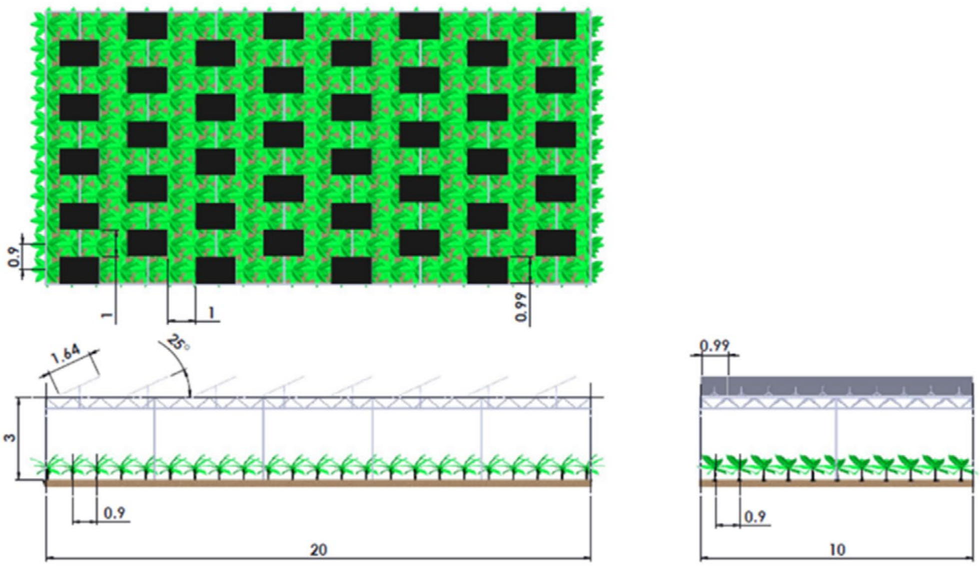

FIGURE 6 | Case 3 orthographic drawing.

TABLE 1 | Crop model inputs.

Plant and genotype	
Plant name	Tomato (Variet—Heinz)
Radiation interception	Beer's law (Ratio of PAR = 0.48)
General parameters	
Simulation options	Water stress activation (YES) Nitrogen stress activation (YES) Mulch effect (drying of soil surface) activation (YES)
Initialisations	
Start of simulation	3 November 2021
End of simulation	12 March 2022
Growing period	129 days (approximately 4 months)
Crop management	
Sowing date	313 Julian day (8 November 2021)
Sowing depth	10 cm
Irrigation efficiency	95%
Fertiliser type	Ammonium nitrate (103 kg/ha)
Method of harvest	Picking
Climate	
Weather station	Gaborone, Botswana Latitude (−24.62) & Longitude (25.85)
Solar radiation	Case 1–no shading (uninhibited radiation) Case 2%–20% shading effect Case 3%–33% shading effect

c. If LER < 1, then dual land use (agrivoltaics) is less efficient when compared to producing only crops or only PV electricity on the land. In this instance, the implementation of agrivoltaics would not be encouraged.

3 | Results and Discussion

3.1 | Farm Yield

The results depicted in Figure 7 show that shading does reduce the yield of tomatoes as the agrivoltaics cases produced less harvest than the control. The reduction in overall yield under the shade was contributed to by the reduced number of fruits as well as the reduced weight for each fruit; hence, the total harvest index dropped. Tomato is a shade-tolerant crop; however, as the shading was increased by a higher density of PV panels, the crop was more stressed; hence, the farm yield was poorest for high-density agrivoltaics. A reduced crop yield on its own may appear unattractive for agrivoltaics, but the loss in crops may be compensated for by the electricity generated.

Although crop model simulations are crucial, they can be limited in that they cannot always account for all the synergetic benefits of farming in agrivoltaics. For instance, the STICS crop model simulates the effect of water and nitrogen stresses on the crops, but it does not consider the stresses due to excessive direct solar radiation. This causes sunburns on the plants and increases the rate of evapotranspiration; hence, more loss of water. These sunburns are more prevalent in sensitive plants like tomatoes, and shading protects them, which increases the harvest, especially in the very hot region of Southern Africa. Therefore, it is crucial to validate crop model simulation results, and this was done by comparing the simulated results with other similar studies from around the world, as given in Table 2. In this comparison, it is seen that indeed simulation studies tend to predict a drop in harvest, whereas experiments show improved crop growth, which highlights the aforementioned constraints of crop model simulation. Future experimental studies will be essential to paint an accurate picture of exactly how tomato crops behave in an agrivoltaics setup in Botswana.

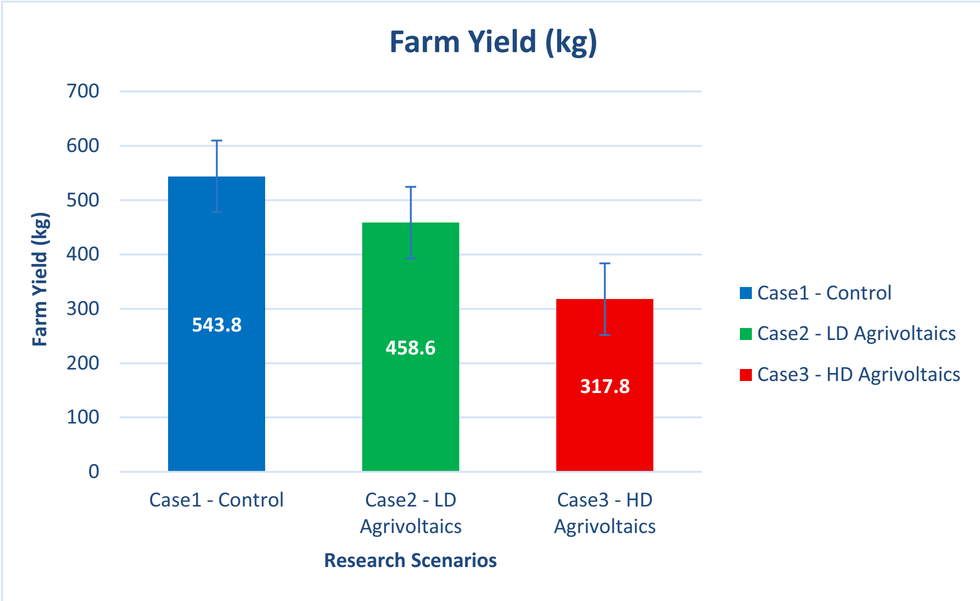

FIGURE 7 | Tomato yield.

TABLE 2 | Validation—How the crop yield compares in our current study versus other studies.

Article/study	(Barron-Gafford et al. 2019)	(Sekiyama and Nagashima 2019)	(Dinesh and Pearce 2016)	The current study
Type of research (Place/Crop model)	Experiment (Arizona)	Experiment (Japan)	Simulation (STICS)	Simulation (STICS)
Crop studied	Tomato	Corn	Lettuce	Tomato
Change in crop yield (Compared with control)	+75%	+6%	−22%	−18%
Why that yield?	Alleviation of heat stresses & extreme weather protection	Protection from excessive sunlight & moisture retention through reduced evaporation	Simulation is limited; crop models cannot account for all the synergetic benefits of colocation	Limitations of crop model simulation. Increased yield expected in an experimental study

3.2 | PV Energy Output

As expected, the PV electricity generated from the high-density farm (Case 3) was higher than in the low-density scenario. An annual PV output of 22.1 MWh was generated in Case 3, whereas Case 2 generated 37% less energy at 13.9 MWh. It is noticeable from Figure 8 that the monthly generation is reasonably consistent throughout the year, even in the winter months, which means that these solar systems can be relied upon all year round. The sacrifice in tomato harvest that was discussed earlier may be compensated for by the electricity generated. The researchers used the LER metrics to determine the exact value accrued from this dual land use.

3.3 | Land Use Efficiency of Agrivoltaics

Crop and solar simulations have shown that the addition of PV modules to a tomato farm reduced the harvest of tomatoes while also resulting in the generation of electricity. The LER results in Figure 9 show that LER > 1 in both cases; hence, both agrivoltaics setups are concluded to present a more effective use of land. In Case 2, the land use efficiency was increased by 15% and by 8% in Case 3. Hence, the low-density agrivoltaics scenario (Case 2) has proven itself as the best option for maximising the efficiency of land use. The LER metrics can be a key tool to justify investment in agrivoltaics. On top of this, it is also important to consider the economic viability of the investment, as it was proven from the studies by Rabasoma et al. (2024).

4 | Conclusions

Two agrivoltaics scenarios together with the control were designed and simulated using the STICS crop model and PV*SOL software. It is concluded from the simulations in this study that shading reduced the yield of tomatoes. The use of agrivoltaics

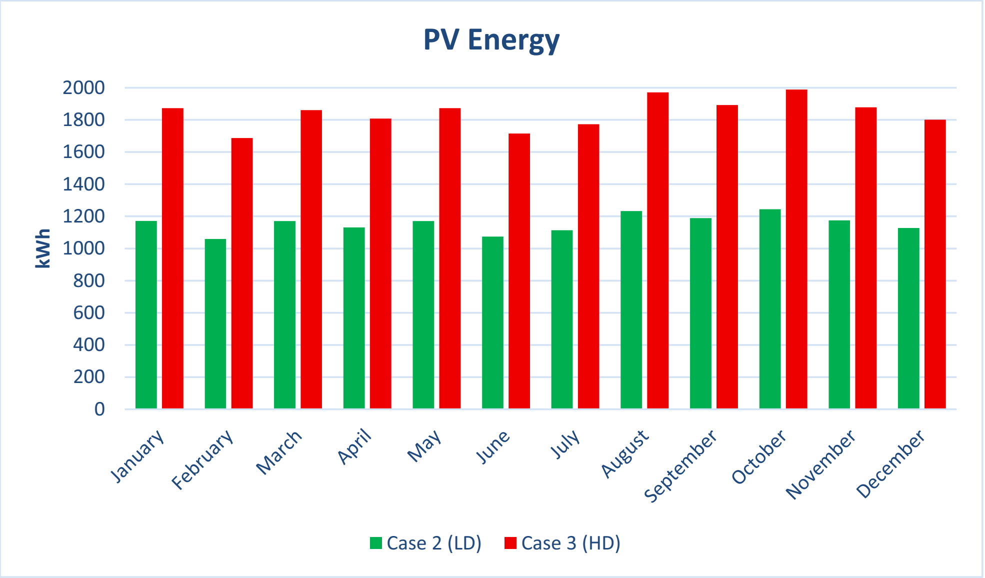

FIGURE 8 | PV electricity generated.

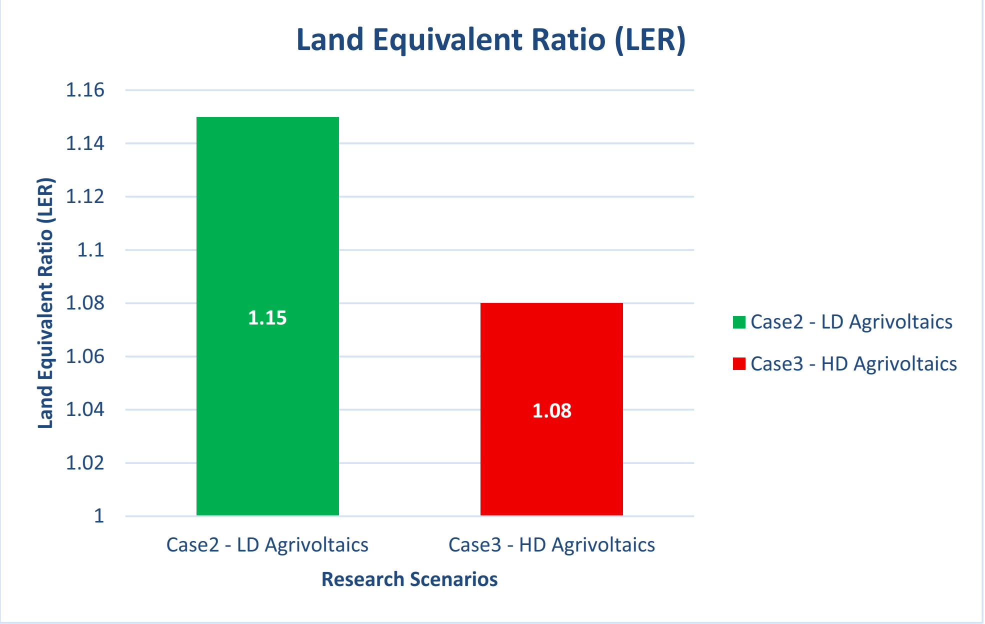

FIGURE 9 | Land equivalent ratio (LER).

resulted in a 16% reduction of harvest for Case 2 and an even worse 42% drop in tomato harvest for Case 3. Even though crop yield was reduced in the agrivoltaics cases, PV electricity was also generated, a total of 22.1 MWh per annum and 13.9 MWh per annum for high-density and low-density agrivoltaics, respectively. A significant loss in PV generation of at least 10% was expected due to increased soiling of the solar panels, which is caused by agricultural activities.

The dual land use through agrivoltaics presented an opportunity to diversify farm income from tomato production only. The two agrivoltaics scenarios in Cases 2 and 3 are concluded to present a more effective utilisation of the farmland than the control, as they both have a LER that is greater than 1. Case 2 has been calculated to be the best design because its land use efficiency was increased the most (15%), thus the most value was extracted from the farm in this case. All in all, this study has proven that agrivoltaics can be successfully implemented in the hot and dry climate of Botswana. This is a multi-pronged solution that can improve the farming of shade-tolerant crops, electrify off-grid rural communities and present alternative revenue streams for the farm.

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The authors have nothing to report.

Ethics Statement

The authors confirm that the paper presents the results of their own research, which has not been published elsewhere.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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