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Research Article

Agrivoltaic Systems: Effect of Spacing Between Photovoltaic Panels on Yield and Water Productivity of Onions (Allium Cepa L. var. Galmi Purple) in Senegal

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Abstract

The integration of agrivoltaic systems into agricultural production has proven to be a way to reduce dependence on fossil fuels, improve the productivity of farmland, and reduce water consumption. In the Niayes region of Senegal, onions remain one of the most widely cultivated crops, but agricultural production in this region relies heavily on fossil fuels. This study, conducted in the village of Kalassane in the northern part of the Niayes region, evaluated the effect of agrivoltaic systems on the agronomic performance of onions. A completely randomized block design was used to test four agrivoltaic configurations: control plots without panels (CT), closely spaced panels (T1), and panels spaced 1.5 and 3 meters apart (T2 and T3, respectively). Analysis of variance revealed no statistically significant differences between treatments ($p > 0.05$) for any of the variables studied, namely the number of leaves, leaf length, leaf diameter, plant height, bulb diameter, bulb height, bulb weight, yield, and water use efficiency. Nevertheless, numerical variations were observed among the treatments: treatment T3 had the highest values for leaf length (54.37 cm), leaf diameter (1.33 cm), and plant height (61.17 cm) starting at 60 days after planting (DAT), and the lowest values for bulb weight (71.53 g), yield (32.77 t/ha), and water use efficiency (4.2 kg/m^3). Conversely, treatment T2 recorded the numerically highest yield (36.37 t/ha) and water use efficiency (4.63 kg/m^3), while the control (CT) recorded the highest bulb weight (83.6 g). The absence of a statistically significant reduction in onion agronomic performance under the various configurations tested suggests that agrivoltaic systems can be integrated into onion production in the Niayes region without compromising it, while offering the potential to reduce dependence on fossil fuels.

Keywords

Agrivoltaics, Yield, Water Productivity, Onion, Niayes, Senegal

1. Introduction

The sustainable intensification of agricultural production has become a critical global issue for ensuring food supply stability amid growing environmental and socioeconomic pressures. With the global population projected to reach 9.8 billion people by 2050 [1], it is essential to emphasize that the sustainability of agricultural production systems is a strategic imperative for meeting current food needs while preserving resources for future generations [2]. Furthermore, the impacts

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of climate change exacerbate these challenges, particularly through rising temperatures, which lead to increased water requirements for crops, and reduced rainfall, which limits water availability for rain-fed and irrigated agricultural production. In light of these constraints, the integration of emerging technological innovations appears to be a strategic lever for promoting the sustainable intensification of agricultural production [3]. Among these innovations is agrivoltaics, which has garnered growing interest from the scientific community to the point of becoming a major focus of research and innovation over the past decade [4]. Agrivoltaics is a dual-use land management technique that combines electricity generation and agricultural production on the same plot of land. In this system, photovoltaic panels are installed above agricultural crops. The results of numerous studies on agrivoltaic systems have shown a reduction in dependence on fossil fuels [5], along with reduced carbon dioxide emissions [6], reduced evapotranspiration due to shading [7], improved water use efficiency [8], and the creation of a microclimate that enhances soil moisture [9]. Furthermore, the electricity generated by photovoltaic panels can be used to power irrigation water pumping equipment, helping to improve the resilience of farms [10, 11]. However, varying reductions in yields have been observed in several crops grown beneath the panels, potentially due to shading. Marrou et al. [12] observed delayed growth followed by a decrease in wheat yield under partial shading, while Weselek et al. [9] reported yield losses of between 5 and 20% for winter wheat and potatoes. These results highlight the need to optimize the design of agrivoltaic systems in order to limit the decline in yield to an acceptable level without compromising agricultural production. Studies on optimization strategies for agricultural production include row spacing [13], photovoltaic field density [14], the installation height of photovoltaic panels [15], and their tilt angle [16]. The spacing between rows of panels is one of the most important configuration parameters in agrivoltaic systems. Variations in spacing can increase or decrease the amount of radiation available to crops, thereby affecting photosynthesis, which is precisely why this parameter was selected for this study. Furthermore, although vegetable crops have been the most extensively studied in agrivoltaic systems, the specific response of onion cultivation remains poorly documented, and this study aims to address that gap. Furthermore, in the Niayes region of Senegal, which is characterized by high horticultural production [17], onions play a significant role in the horticultural portfolio, with national production estimated at 421,464 metric tons, making onions the country's leading vegetable crop [18]. However, certain constraints inherent to the Niayes region impact the sustainable production of onions, notably the decline in the piezometric levels of the groundwater table as a result of its overexploitation and low recharge [19, 20]. Furthermore, agricultural production relies on irrigation and is primarily powered by fossil fuels [21], exacerbating climate impacts. However, it should be noted that the Niayes region has significant potential for the adoption of solar technologies, particularly in northern Niayes, offering favorable prospects for the development of agrivoltaic systems. Thus, integrating these systems into agricultural production could help reduce the risk of water stress in crops while generating renewable energy to power pumping and irrigation systems. This innovative approach could serve as a solution not only for enhancing the sustainability and resilience of agricultural production systems in the Niayes region, but also for addressing the challenges of the water-energy-food nexus [22, 23]. To the best of our knowledge, no experimental study on agrivoltaic systems incorporating vegetable crops in the Niayes region or more broadly in Senegal has yet been reported in the literature. This study therefore aims to evaluate the agronomic performance of the onion (Allium cepa var. Galmi purple), specifically vegetative growth, bulb yield, and water productivity. The results of this study will provide a scientific basis to guide the integration of renewable energy through agrivoltaic systems into agricultural production in the Niayes region.

2. Materials and Methods

2.1. Field Site

This study was conducted during the cold off-season from December 2023 to April 2024 in the village of Kalassane, located in the northern Niayes region of Senegal, as shown in Figure 1. The village is located at 15.905 °N and -16.413 °W in the Rao district of the municipality of Gandon in the Saint-Louis region. The Niayes region borders Senegal's northwestern coastline between latitudes 14°55' and 15°27' N and longitudes 16°50' and 17°07' W, extending along a narrow coastal strip 180 km long and 20 to 30 km wide, with a total area of 2,759 km^2 between the Dakar and Saint-Louis regions [24, 25].

The Niayes region is characterized by a hot, dry Sahelian climate with relatively low average rainfall, ranging from 350 to 450 mm/year [26]. The experimental site, for its part, is characterized by average daily temperatures ranging from 22.4 to 35.8 ℃, with maximum and minimum temperatures reaching 42.2 ℃ and 17.1 ℃, respectively. In addition, the average daily relative humidity ranged from 10.8 to 74.5%, while daily solar radiation reached a maximum of 45 MJ/m^2/day. These values were recorded and collected at the weather station installed on-site and pertain to the experimental period. However, no rainfall was recorded. Nevertheless, the entire Niayes region benefits from a microclimate favorable to vegetable crops such as onions, thanks to the influence of the maritime trade winds [27]. Soils in the Niayes region are poor and vulnerable to wind and water erosion [28], with low water-holding capacity in addition to problems with salinity and acidity in certain areas [29, 30]. Vegetable production is primarily irrigated using groundwater from the Quaternary Sand Aquifer (QSA).

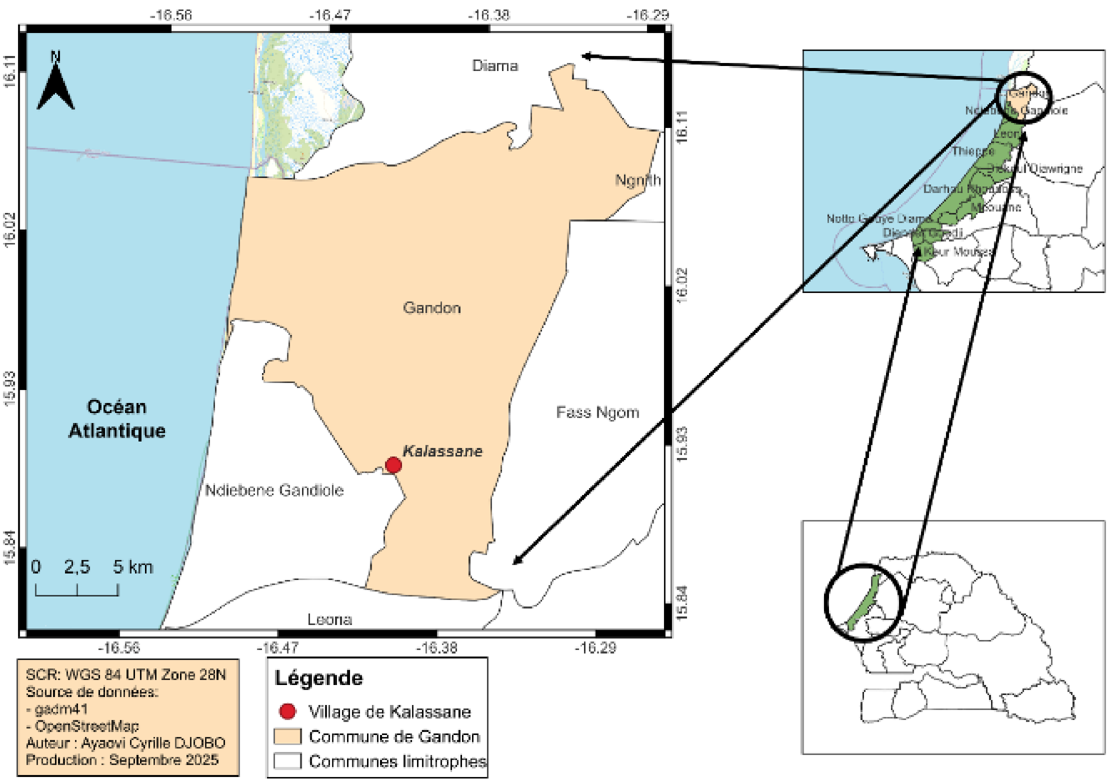

Figure 1. *Location of the field site.*

2.2. Plant Materials

The onion variety known as "Galmi purple" was used in this study. It is widely grown by farmers in the Niayes region during the cold off-season, particularly in the north. It is a short-cycle variety that can reach maturity in 120–130 days, with potential yields of up to 50 metric tons per hectare [31, 32]. Furthermore, in addition to its purple color, it is characterized by a very good ability to adapt to sub-Saharan conditions and a long shelf life, which can exceed six months [33, 34].

2.3. Experimental Design

The treatments were arranged in a completely randomized block design with three replicates and were randomly assigned within each block. Four agrivoltaic treatments were evaluated in this study: the control (CT) with plots without panels; treatment T1 with panels attached; treatments T2 and T3 with panels spaced 1.5 m and 3 m apart, respectively, as reported in Figure 2. Each plot measured 1.6 m^2 (1 m × 0.6 m). The blocks were spaced 4 m apart, while the spacing between plots within each block was 2 m. The photovoltaic panels in each treatment were oriented west-east with a fixed tilt of 15° toward the south and maintained at a height of 1.5 m above the ground at their lowest point

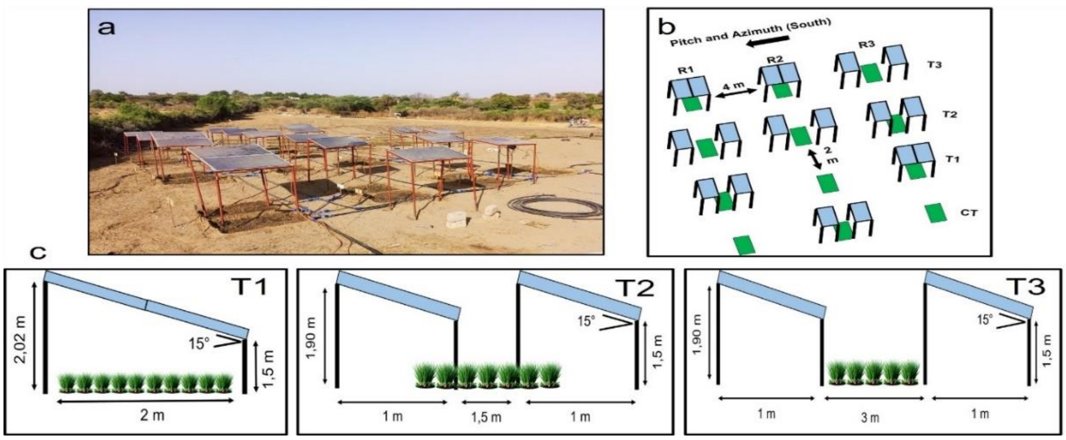

Figure 2. *(a) Setup at the field site, (b) Schematic drawing of the agrivoltaic system, and (c) Schematic drawing of the agrivoltaic treatments.*

2.4. Crop Management and Agronomic Practices

The onion seedlings were transplanted 63 days after sowing in the nursery, spaced 10 cm apart and 15 cm between rows, for a planting density of 560,000 plants per hectare. The BF2 solid fertilizer, a mixture of major macronutrients (NPK, MgO, CaO, SO_3) and micronutrients, was applied to all twelve plots on the third day after transplanting at a rate of 1 metric ton per hectare. The NPK 10-10-20 mineral fertilizer was applied in accordance with the technical guidelines for best practices in onion production in the Niayes region. Four applications were made at 20-day intervals starting from transplanting, each at a rate of 25 g/m ^{2}of NPK (equivalent to 250 kg/ha). Water was supplied using the gravity-fed furrow irrigation method, with a frequency of every 2 days. The volumes of water applied were determined based on the crops' gross daily water requirements, calculated from the reference evapotranspiration (ET0) estimated using the Penman-Monteith formula (FAO-56) (1) using climate data collected at the weather station, as shown in Table 1. Irrigation was stopped when 80% of the plants in each plot had lodged, and harvesting was conducted 15 days after irrigation ceased, i.e., on day 115 after transplanting (DAT).

Table 1. *Average values of climatic variables and total water supply by growth stage.*

Stage	Tmax (℃)	Tmin (℃)	Rhav (%)	Srav (W/m^2)	ET0cum (mm)	Wreq (m^3/ha)
Initial stage and growth	33,8	20,7	32,8	333	205,2	2062,5
Development and bulb formation	34,6	21,6	28,8	337,9	260,4	3625
Maturation and end	31,7	22,7	49,3	381,2	235	2687,5

Tmax: average maximum temperature; Tmin: average minimum temperature; Rhav: average relative humidity; Srav: average solar radiation; ET0cum: cumulative reference evapotranspiration and Wreq: total water requirements.

$$ET0 = \frac{[0{,}408\Delta\times(Rn-G)]+\left[\gamma\left(\frac{900}{T+273}\right)\times u^2(es-ea)\right]}{\Delta+\gamma(1+0{,}34u^2)} \quad (1)$$

Where: ET0: reference evapotranspiration (mm/day); Rn: total solar radiation (MJ/m ²day); G: soil heat flux (MJ/m ²day); T: average daily air temperature at a height of 2 m (℃); u2: wind speed at a height of 2 m (m/s); es: saturated vapor pressure (kPa); ea: vapor pressure at temperature T (kPa); Δ: slope of the saturated vapor pressure curve (kPa/℃); γ: psychrometric constant (kPa/°C); and 900: constant for a daily time step.

2.5. Data Collection

Growth parameters including the number of leaves per plant, leaf diameter and length, and plant height were measured 30, 60, and 90 DAT on five plants randomly selected from each plot. At harvest, the morphological parameters of the bulb, namely, diameter, height, and weight were measured on five bulbs randomly selected from each plot; onion yield and water use efficiency were also determined for each plot.

2.5.1. Growth Parameters

The number of leaves was determined by counting all the leaves on each selected onion plant, then averaging the count per plot and per treatment. Measurements of leaf length, leaf diameter, and plant height were taken using a graduated ruler and expressed in centimeters (cm). Leaf length was measured from the point of attachment to the tip of the longest leaf. Leaf diameter corresponds to the maximum diameter measured at the widest part of the longest leaf. Plant height was measured from the collar to the tip of the longest leaf.

2.5.2. Yield Parameters and Water Productivity

The diameter and height of the bulb (cm) were measured using a manual caliper: the diameter was measured at the widest point of the central portion, and the height was measured along the vertical axis from the root plate to the neck. Bulb weight (g) was determined using an electronic scale with a precision of ±1 g. Yield was estimated by weighing all bulbs harvested from each plot and dividing this weight by the harvested area. The average yield was then calculated for each treatment and expressed in metric tons per hectare (t/ha). Water use efficiency was calculated by dividing the total weight of the bulbs from each plot by the total volume of water applied, then averaged by treatment and expressed in kilograms per cubic meter (kg/m^3).

2.6. Statistical Analyses

The collected data were first checked for ANOVA assumptions (normality of residuals and homogeneity of variances) using the Shapiro-Wilk and Levene tests. A square root transformation of the raw data on the number of leaves per plant was necessary to satisfy the assumption of normality of residuals. Growth data were analyzed using a linear mixed model (LMM), with treatment, phenological stage (DAT), and their interaction as fixed effects, and block as a random effect. Yield data were subjected to a two-factor analysis of variance (ANOVA) (treatment and block). Tukey's test was applied to compare mean pairs when ANOVA revealed significant differences ($p < 0.05$). A principal component analysis (PCA) was performed on the growth and yield parameters to explore the covariation structure among the variables.

3. Results

3.1. Number of Leaves Per Plant

The number of leaves per onion plant did not differ significantly ($p > 0.05$) depending on the spacing between the photovoltaic panels at 30, 60, and 90 DAT, as shown in Table 3. Similarly, no significant difference ($p > 0.05$) was observed in the interaction between photovoltaic panel spacing and developmental stage, as reported in Table 2. However, treatment T1 had numerically the highest number of leaves per plant at 30 DAT (5.13) and 60 DAT (8.6). Furthermore, Figure 3 showed that the number of leaves per plant stabilized under treatments T2 and T3 at the 60 and 90 DAT, while CT and T1 showed a decrease.

Table 2. *Summary of the effects tested by the linear mixed model on onion growth parameters.*

Effect	Number of leaves	Leave length (cm)	Leave diameter (cm)	Plant height (cm)
Treatment	ns	ns	ns	ns
DAT	***	***	***	***
Bloc	ns	ns	*	ns
Treatment: DAT	ns	ns	ns	ns

*** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$; ns = not significant.

Table 3. *Effect of agrivoltaic treatment on onion growth parameters at different stages of development*.

DAT	Treatment	Number of leaves	Leave length (cm)	Leave diameter (cm)	Plant height (cm)
30 DAT	CT	4.67 a	22.73 a	0.53 a	25.27 a
	T1	5.13 a	23.77 a	0.63 a	26.53 a
	T2	4.93 a	24.27 a	0.63 a	26.63 a
	T3	4.33 a	23.77 a	0.6 a	26.2 a
60 DAT	CT	8.33 a	49.97 a	1.3 a	56.03 a
	T1	8.6 a	53.7 a	1.3 a	60.47 a
	T2	8.2 a	51.33 a	1.2 a	57.37 a
	T3	8.2 a	54.37 a	1.33 a	61.17 a
90 DAT	CT	7.53 a	45.2 a	1.33 a	50.33 a
	T1	7.33 a	51.17 a	1.5 a	57 a
	T2	8.27 a	48.2 a	1.37 a	54.27 a
	T3	8.07 a	52.87 a	1.53 a	59.6 a
	SE (±)	0.116	2.23	0.115	2.48
	CV (%)	7.15	7.31	15	6.35

Means followed by the same letter within the same column and at the same stage do not differ significantly according to Tukey's test ($p < 0.05$).

3.2. Leaf Length

The results in Table 2 showed no significant differences between the agrivoltaic treatments and their interactions with the developmental stage in terms of leaf length. Similarly, Table 3 shows that none of the treatments differed from the others at any developmental stage. The trend in leaf length showed that the agrivoltaic treatments had numerically higher values than the control treatment (CT) at all stages, as shown in Figure 3. Thus, treatments T2 at 30 DAT, with 24.27 cm, and T3 at 60 and 90 DAT, with 54.37 and 52.87 cm, respectively, recorded the highest values.

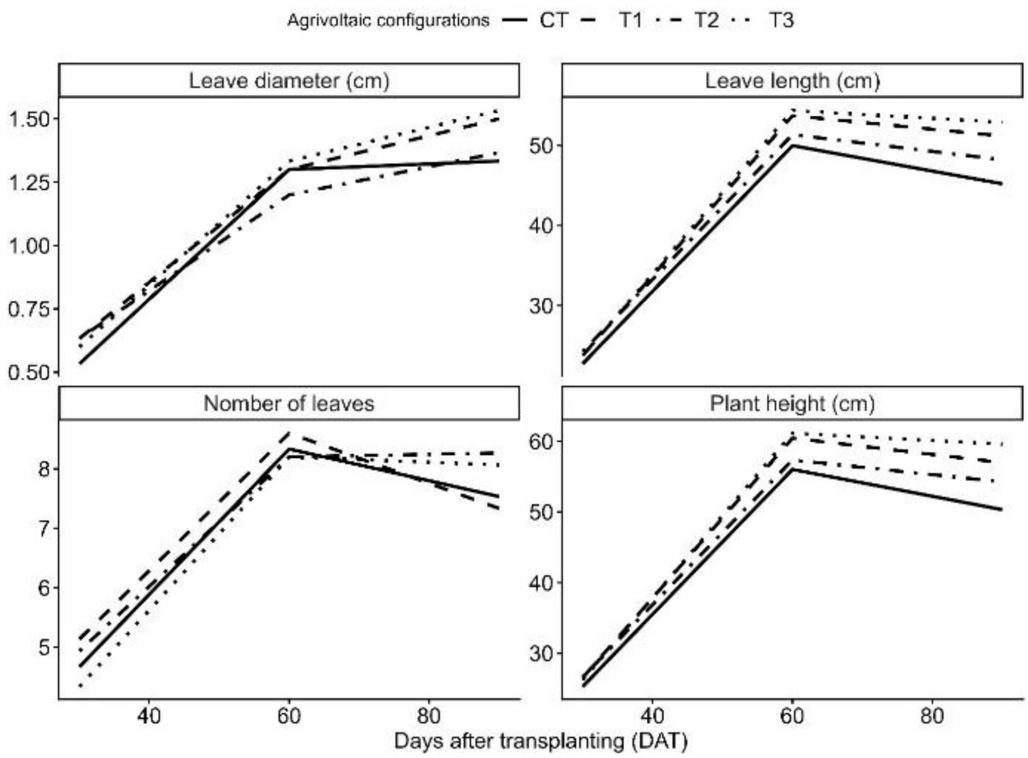

Figure 3. *Evolution of growth parameters of onion over time (days after transplanting) as affected by agrivoltaic configuration*.

3.3. Leaf Diameter

Table 2 shows that, unlike other growth parameters, the block effect was significant ($p = 0.03$), even though the treatment and the interaction with the developmental stage were not significant. Consequently, none of the treatments tested differed significantly from the others at any developmental stage, as reported in Table 3, even though Figure 3 showed different trends in leaf diameter depending on the treatment. Thus, crops under the agrivoltaic treatments showed a continuous increase in leaf diameter throughout the development cycle, whereas those in the control treatment (CT) maintained a relatively constant leaf diameter between the 60 and 90 DAT. At 90 DAT, the T2 (1.37 cm) and CT (1.33 cm) treatments had a leaf diameter slightly smaller than that of the T1 (1.5 cm) and T3 (1.57 cm) treatments.

3.4. Plant Height

As shown in Table 2, the interaction between treatment and growth stage was not significant for plant height. The results in Table 3 showed that the height of onion plants under the various agrivoltaic treatments remained statistically similar at each stage of development. However, Figure 3 shows that the growth curve for plant height followed the same trend as that for leaf length. The control treatment (CT) recorded numerically the shortest plant heights at all developmental stages, while treatments T2 (26.63 cm) at 30 DAT and T3 (61.17 and 59.6 cm) at 60 and 90 DAT, respectively, had the highest values.

3.5. Bulb Diameter

The results of the analysis of variance indicated that bulb diameter was not significantly affected by the various agrivoltaic treatments tested, as shown in Table 4. Onions grown under treatment T1 had numerically the largest bulb diameter (5.4 cm), followed by the control treatment (CT) with a diameter of 5.3 cm, while treatments with 1.5- and 3-meter spacing between the panels recorded smaller diameters of 5.13 and 5.07 cm, respectively.

Table 4. *Effect of agrivoltaic treatment on onion yield parameters and water productivity.*

Treatment	Bulb diameter (cm)	Bulb height (cm)	Bulb weight (g)	Yield (t/ha)	Water productivity (kg/m^3)
CT	5.3 a	4.9 a	83.6 a	33.5 a	4.3 a
T1	5.4 a	5.1 a	80.27 a	35.57 a	4.57 a
T2	5.13 a	5.13 a	73.87 a	36.37 a	4.63 a
T3	5.07 a	5.1 a	71.53 a	32.77 a	4.2 a
SE (±)	0.55	0.23	19.5	3	0.37
CV (%)	18.09	7.8	43.62	15.04	14.64

Means followed by the same letter within the same column and at the same stage do not differ significantly according to Tukey's test ($p < 0.05$).

3.6. Bulb Height

None of the treatments tested had a significant effect on bulb height, as shown in Table 4. Onion plants grown outdoors without photovoltaic panels (CT) had a slightly lower height (4.9 cm) than those grown under photovoltaic panels, which showed very similar values, ranging from 5.1 to 5.13 cm.

3.7. Bulb Weight

The control treatment (CT) had numerically heavier onion bulbs (83.6 g) than the agrivoltaic treatments, which had, in descending order, 80.27 g for T1, 73.87 g for T2, and 71.53 g for T3. However, this difference was not statistically significant at the 5% level, as reported in Table 4.

3.8. Bulb Yield and Water Productivity

Analysis of variance revealed no statistically significant differences ($p > 0.05$) between the effects of the various treatments tested on bulb yield and water productivity. For bulb yield, even though the values are statistically similar, the highest and lowest yields were recorded with treatment T2 (36.37 t/ha) and treatment T3 (32.77 t/ha), respectively, while the control treatment recorded a bulb yield of 33.5 t/ha. Regarding onion water productivity, Figure 4 shows that the trend was similar to that of bulb yield. Indeed, treatment T2 had numerically the highest water productivity at 4.63 kg/m^3, followed in descending order by treatment T1 at 4.57 kg/m^3, treatment CT at 4.3 kg/m^3, and treatment T3, which had the lowest water productivity (4.2 kg/m^3).

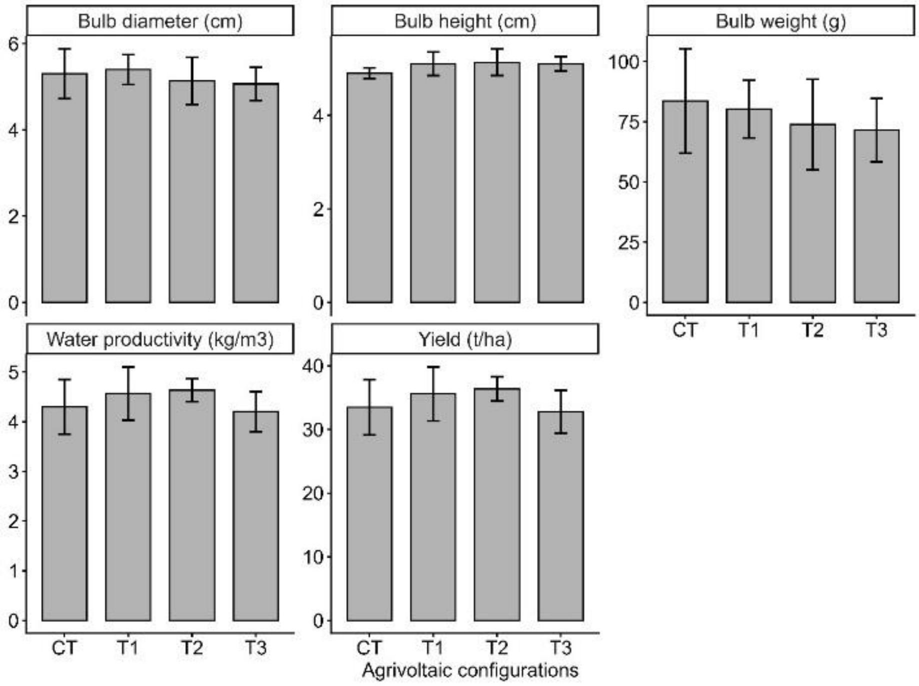

Figure 4. *Yield parameters and water productivity of onion as affected by agrivoltaic configuration.*

3.9. Principal Component Analysis

Figure 5 shows the results of the principal component analysis performed on the combined dataset of onion growth and yield parameters to summarize the overall agronomic profile of the various agrivoltaic treatments tested. The first two principal components (PC1 and PC2) accounted for 46.8% and 30.2% of the total variance, respectively, thus explaining 77% of the total variance in the dataset. The first axis (PC1) was primarily determined by growth parameters (leaf length, plant height, and leaf diameter at the 60 and 90 DAT) and bulb height on the positive side of the axis, while bulb weight and diameter were on the negative side. The second axis (PC2) was primarily associated with bulb yield, water use efficiency, and the number of leaves 30 DAT on the positive side of the axis, as well as leaf diameter 60 DAT, which was on the negative side. Treatment T2 was associated with the highest values for yield, water productivity, and the number of leaves per plant at the start of the growing season (30 DAT). Treatment T1 occupied an intermediate position in terms of growth parameters at 30 DAT and bulb height. Treatment T3 was associated with higher values for advanced growth parameters (60 and 90 DAT), particularly leaf length, plant height, and leaf diameter. The control treatment (CT) was clearly distinct from the agrivoltaic treatments along axis 2 and was closely aligned with the morphological variables of the bulb, particularly diameter and weight.

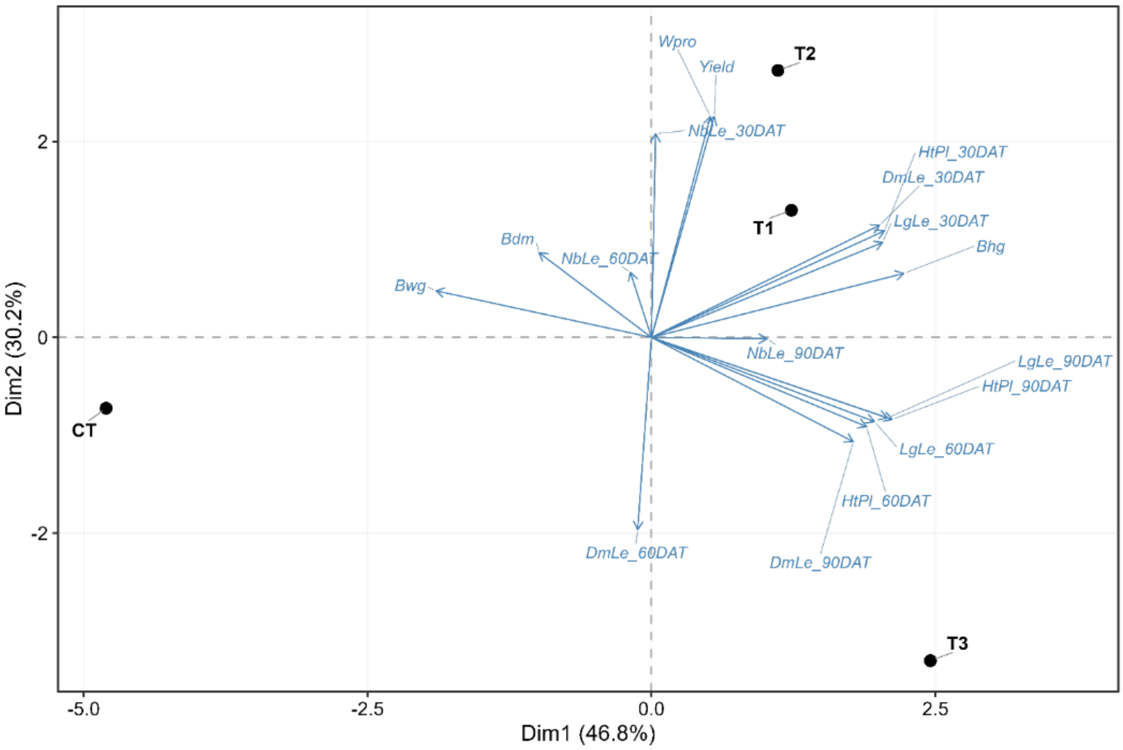

Figure 5. *Principal Component Analysis (PCA) of onion growth and yield parameters as affected by agrivoltaic configuration: biplot of variables and individuals (treatment means). NbLe: number of leaves; DmLe: leaf diameter; LgLe: leaf length; HtPl: plant height; Bwg: bulb weight; Bdm: bulb diameter; Bhg: Bulb height; Wpro: water productivity.*

4. Discussion

4.1. Dynamics of Onion Vegetative Growth Under Agrivoltaic Systems

The absence of statistically significant differences ($p > 0.05$) among the various spacing distances between the test panels (CT, T1, T2, and T3) in terms of the number of leaves per plant, leaf length and diameter, and plant height at all growth stages (30, 60, and 90 DAT) suggests similar growth of the onions regardless of the shading level. Similar results have been reported regarding the absence of significant differences in the growth of lettuce crops grown under panels compared to lettuce grown in open fields [35]. According to these authors, this absence is likely due to a morpho-agronomic adaptation of the crops. Furthermore, the three agrivoltaic treatments consistently exhibited greater plant heights and leaf lengths than the control (CT) throughout the entire growth cycle, with a more pronounced numerical advantage at 60 and 90 DAT. These results highlight a tendency for leaves and plants to elongate in response to shading. This effect reflects a shade-avoidance mechanism, a response triggered by changes in the red-to-far-red ratio under agrivoltaic structures. This response activates the phytochrome pathway and stimulates cell elongation at the expense of pseudostem thickening [36]. These authors described a similar response in bunch onions grown under black or silver nets providing 35-50% coverage. However, according to the authors, this elongation does not necessarily indicate an increase in biomass or harvestable yield, hence the need to interpret this response as an indicator of light stress rather than a sign of agronomic vigor. Furthermore, this response of leaf elongation under shaded conditions is not specific to onion cultivation but has been widely documented across agronomic trials involving all plant species. Indeed, Renno and Di Marino [37], in their systematic review of 82 experimental agrivoltaic trials, reported an increase in plant height of approximately 8.6% in thyme under a 56% reduction in photosynthetically active radiation (PAR) in Greece, and an increase in specific leaf area in lettuce under partial shading in France. This elongation was interpreted as an acclimation response to reduced solar radiation rather than as a stress response. However, in this study, the growth response of the crops under agrivoltaic treatments was not linear; the most shaded treatment (T1, with nearly total shading) did not result in the most pronounced growth. The values for plant height and leaf length, for example at 90 DAT (57 cm and 51.17 cm, respectively), remained intermediate between those of T2 (54.27 cm and 48.2 cm) and T3 (59.6 cm and 52.87 cm), even though T3, which was less shaded than T1, had shown the most pronounced elongation in the study. This lack of a strict gradient between the level of shading and the morphological response can be explained by the heterogeneous distribution of solar radiation under the different agrivoltaic treatments, which could modulate crop response. Indeed, under T3, the 3-meter spacing between the panels creates a wide inter-panel corridor, allowing a large portion of the crops to receive direct radiation close to that of an open field for much of the day, while the remaining portion receives less direct radiation, thus creating two microenvironments under the same treatment. This heterogeneity in the spatial distribution of daily radiation which is more pronounced under T3 than under T2 (with a narrower inter-panel aisle) or T1 (no aisle) explains the magnitude of the response in leaf and plant elongation under the different agrivoltaic configurations.

4.2. Morphological Characteristics of the Bulb

None of the bulb's morphological characteristics including diameter, height, and weight, varied significantly among the agrivoltaic treatments tested, suggesting that these variables are not very sensitive to the effects of shading. In contrast, bulb weight showed a gradual decreasing trend from the control treatment to the least shaded treatment: CT (83.6 g) > T1 (80.27 g) > T2 (73.87 g) > T3 (71.53 g), representing a 14.5% decrease between CT and T3, even though this difference is not statistically significant. This result can be explained by the physiology of bulb formation in onions. Indeed, even though the bulbification process is triggered by the photoperiod, its completion subsequently depends on the availability of carbon assimilates for filling the fleshy scales. Thus, when available light decreases, the plant produces less energy through photosynthesis and directs this energy preferentially toward leaf development rather than bulb enlargement [38]. Nevertheless, in this study, the most shaded treatment (T1) had larger bulbs than the partially shaded treatments (T2 and T3). This could be explained by the heterogeneity in the spatial distribution of radiation under the panels, which may have impacted bulb filling.

4.3. Bulb Yield

Bulb yield did not differ significantly among the various agrivoltaic treatments tested. However, the values obtained do not follow a linear trend with respect to the shading gradient. In fact, the highest bulb yield was recorded with treatment T2 (36.37 t/ha), followed by T1 (35.57 t/ha), then CT (33.5 t/ha), and finally T3, which had the lowest yield (32.77 t/ha). The results of this study are unique in that they show both an increase (T2 +8.6% and T1 +6.2%) and a decrease (T3 –2.2%) in bulb yield under agrivoltaic systems compared to the open-field control treatment (CT). These results both contrast with and corroborate those reported in the literature from agrivoltaic trials on onion cultivation. For example, Moreda et al. [39] in Spain recorded a 6% decrease in onion yield under solar panels compared to the open-field control. Similar results were reported in South Korea by Jo et al. [40], who observed an average 14% reduction in onion yield (Allium cepa, var. Honmaru) over two growing seasons in an agrivoltaic system that reduced PAR by 30% compared to the open-field control. Similarly, Randle-Boggis et al. [41], after testing several vegetable crops under a fixed-panel agrivoltaic system, also recorded a reduction in onion yield (Allium cepa, "Creole Red" variety in Tanzania and "Pinoi Red" variety in Kenya) of 15.9% and 20.7%, respectively, compared to open-field cultivation, in a hot, semi-arid climate similar to conditions in the Niayes region. This discrepancy between the results of this study and those reported in the literature could be explained, in part, by several factors, including variety (Galmi purple versus Honmaru, or Creole red versus Pinoi red), water regime, and the soil and climatic conditions at the experimental site. This corroborates the conclusion drawn from the systematic review of agrivoltaic trials by Renno and Di Marino [37]. According to the authors, the response of yield to shading depends heavily on the local climate; hot, arid to semi-arid, and Mediterranean climates more frequently show neutral to moderately positive responses to moderate shading, whereas temperate or cool climates consistently show yield reductions at the same level of shading. Thus, the moderate level of shading in treatment T2 may have promoted favorable microclimatic conditions (mitigation of heat and evaporative stress) that could compensate for or even exceed the loss of photosynthetic radiation. Furthermore, this difference can be explained by the agrivoltaic configuration implemented in the overall design [42, 43]. Indeed, in an agrivoltaic system with fixed east-west-oriented panels as in this study, Dupraz et al. [44] demonstrated that, in this type of configuration, the amplitude of the daily light/shade fluctuation experienced by crops depends directly on their position relative to the row and on the spacing tested. Thus, crops under treatment T3 spend the vast majority of midday in full sun and experience significant shading very early in the morning and at the end of the day, resulting in a greater amplitude of daily solar radiation fluctuations than under the other agrivoltaic treatments. Conversely, in the T1 configuration, which had a numerically higher yield than T3, shading is more intense on average, and the amplitude of daily light-to-shade fluctuations is lower, with diffuse radiation predominating rather than sharp transitions. To this end, Marrou et al. [45], in the agrivoltaic trial in Montpellier with an east-west orientation, demonstrated that continuous coverage by photovoltaic panels reduces the daily temperature range of crops and lowers soil temperature, without significantly altering air temperature or the vapor pressure deficit. Thus, the growth rate of crops under this homogeneous configuration was not reduced compared to open fields, except during the initial phase. In this study, the stability of the microclimate under T1 throughout the day appears to have at least partially compensated for the reduction in the total amount of radiation available for photosynthesis, while eliminating the amplitude of the daily fluctuation that hindered crop growth under T3. These yield results confirm the trend observed during vegetative growth under the various agrivoltaic treatments, where, in a heterogeneous microclimate, the crops appear to preferentially redirect their energy toward vegetative growth (leaf elongation) at the expense of bulb filling. Thus, T3 had onion seedlings with numerically the greatest plant height and leaf length but also numerically the lowest bulb weight and yield. Furthermore, the yields obtained under agrivoltaic treatments in this study are of the same order of magnitude as those reported in the literature for onion production in Senegal, despite slight differences. For example, Tarpaga et al. [46] reported an average yield of “Galmi purple” onions in Senegal of 20 t/ha. Furthermore, Diouf et al. [47] obtained a yield of approximately 32 t/ha in the Senegal River Valley, while Sane et al. [48] reported a yield of 35 t/ha in Kalassane.

4.4. Water Productivity

The water productivity results for onions followed the same hierarchical trend as the yield, with T2 (4.63 kg/m^3) > T1 (4.57 kg/m^3) > CT (4.3 kg/m^3) > T3 (4.2 kg/m^3), and no statistically significant differences were observed among the treatments. This result is expected, given that irrigation rates were kept identical across the four treatments. Thus, in this study, water productivity directly reflects variations in bulb yield rather than a difference in water consumption reduction. The low water productivity observed in the T3 treatment could be explained by the coexistence, within the same plot, of crops located in a semi-sunny area and others in a shaded area, resulting in uneven evaporative demand within the same treatment. Thus, crops in the partially sunny area experience evapotranspiration levels similar to those of open-field crops (CT), without benefiting from the thermal buffering effect that continuous shading can provide. This prevents more efficient water use and consequently lowers the average water productivity of the treatment. However, at the system level, Ali Abaker Omer et al. [49], in their systematic review of 33 agrivoltaic studies, reported that improved water-use efficiency under agrivoltaic systems (generally ranging from 20 to 47%) is associated with a reduction in evapotranspiration and soil temperature of 1 to 4 ℃. These results corroborate those of this study, in which this thermal buffering effect was observed with treatments T2 and T1 but only to a very limited extent under T3, where the coexistence of two microclimates limited the extent of this effect. However, the water productivity of onions recorded in this study under photovoltaic panels (4.2–4.63 kg/m^3) is comparable to that reported by Sane et al. [48] in Kalassane (3.41–4.83 kg/m^3), although the average observed in this study is higher than that reported by those authors (3.93 kg/m^3).

In summary, the results of this study suggest, on the one hand, that onion production under agrivoltaic systems in the Niayes region is feasible and could be beneficial from an agronomic standpoint. Indeed, the agronomic performance of onions under these systems is statistically similar to that of the control and is even superior in some cases, although this increase is not statistically significant. These results corroborate the assertion by Santra et al. [50] that onions are a crop well-suited to and adaptable to agrivoltaic systems in arid environments. Furthermore, these results indicate that, in the context of the Niayes region, it is not primarily the level of shading that determines the agronomic performance of onions under agrivoltaic systems, but rather the daily range of variation between full sun and shade experienced by the crops, which depends on the spacing between the panels in an east-west-oriented system. However, further research including long-term monitoring of microclimatic variables and the amount of photosynthetically active radiation received, as well as multi-year and seasonal replicates would be necessary to confirm or refute these results.

5. Conclusions

This study on onion cultivation, notably the Galmi purple variety, highlighted two key findings. First, the potential of agrivoltaic systems to support vegetative growth comparable to that of crops grown in full sun without reducing yield, as often reported in the literature. Second, the daily spatial variability of shading influences the crop's response. Furthermore, statistical analysis showed no significant difference between the agrivoltaic treatments tested in this study for growth, yield, and water productivity ($p > 0.05$). However, T2, corresponding to a spacing of 1.5 m between panels, recorded the numerically highest values for yield and water productivity. In contrast, T3, corresponding to a spacing of 3 m between panels, had numerically the lowest values for yield and water productivity. The agronomic performance results recorded for onions under the different agrivoltaic configurations suggest that these systems could be used in vegetable production in the Niayes region, particularly for onion cultivation. Within the scope of this study, and although it is a pioneering effort with certain limitations, the results show that agrivoltaic systems could represent a promising solution for irrigated production in the Niayes region, where managing water availability (declining groundwater levels) is a genuine socioeconomic challenge. Nonetheless, it is important to highlight the limitations of this study, notably the lack of microclimatic data under different agrivoltaic configurations, the limited duration of growth parameter monitoring, and the small number of experimental plots. Thus, additional trials spanning several years and different growing seasons would provide a better understanding of the impact of different agrivoltaic configurations on the performance of the tested crops. Furthermore, this would reduce the risk of underestimating or overestimating the advantages and disadvantages of crops grown under photovoltaic shading.

Abbreviations

DAT	Days After Transplanting
ET0	Reference Evapotranspiration
PAR	Photosynthetically Active Radiation
PCA	Principal Component Analysis
QSA	Quaternary Sand Aquifer

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Author Contributions

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Lamine Diop: Conceptualization, Methodology, Writing – review & editing

Baboucar Sane: Methodology

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Data Availability Statement

The data supporting the outcome of this research work has been reported in this manuscript.

Conflicts of Interest

The authors declare no conflicts of interest.

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Biography

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Research Field

Ayaovi Cyrille Djobo: Irrigation, water resources management, agrivoltaics

Lamine Diop: Irrigation, water management, climate-smart irrigation, agrivoltaics, water–energy–agriculture interactions, agricultural water demand under climate change, integrated water resources management

Baboucar Sane: Aquaculture, nutrition, optimization of fish growth