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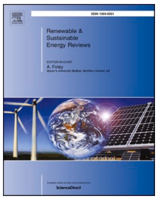

Agrivoltaics, a promising new tool for electricity and food production: A systematic review

J. Widmer [a,b,*], B. Christ [b], J. Grenz [a], L. Norgrove [a]

[a] *Bern University of Applied Sciences (BFH), School of Agricultural, Forest and Food Sciences (HAFL), Länggasse 85, 3052, Zollikofen, Bern, Switzerland*
[b] *Agroscope, Route des Eterpys 18, 1964, Conthey, Switzerland*

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ABSTRACT

Increased global demand for food and energy implies higher competition for agricultural land. Photovoltaic installations contribute to more sustainable solutions to satisfying energy requirements, however, they also require land. To address this dilemma, agrivoltaics has been proposed, combining energy and agricultural production on the same area. Our objectives were to review and synthesise the current agronomic knowledge on agrivoltaics and its future development possibilities. A systematic literature search was conducted in Web of Science on 17 December 2022, resulting in 54 articles that met the inclusion criteria and concentrated primarily on food production. Most studies focused on combining electricity generation with crop production. Vegetables, especially lettuce and tomato, were the focus of many papers. The success of a crop under an agrivoltaic system depends on many factors, yet mainly on location and season. Additionally, even light-demanding crops such as maize could be grown under certain conditions. Therefore, we propose to define an optimal daily light integral for each species, rather than a shade level. Given climate change, agrivoltaics may reduce inter-annual yield fluctuation by buffering the negative effects of both frost and high temperatures on crops, as well as reducing water consumption. Future research should focus mainly on berries and on plants whose production can be affected by high temperatures. Experiments on larger areas, over several years, and with solar panels allowing a separation of the light spectrum are needed to promote development of agrivoltaics without affecting crop yields.

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1. Introduction

In a context of climate change and a growing world population, agriculture is facing new challenges in producing food. On the one hand, global food production is expanding to meet increasing demand, while the global land area allocated has stabilised in recent years [1]. On the other hand, global warming of +1.5 °C is highly likely in the near future due to human activities and extreme weather events such as heatwaves, droughts, and heavy precipitation will become more frequent [2–4]. In 2015, the 17 Sustainable Development Goals were adopted by the member states of the United Nations [5]. The Paris Agreement ratified during the COP 21 aiming to limit global warming to +1.5 °C compared to pre-industrial levels [6]. In this context, the European Union pledged to reduce its greenhouse gas (GHG) emissions by at least 55 % by 2030, compared to 1990 levels, and to become climate-neutral by 2050 by achieving the end of net GHG emissions [7].

In addition, increase in world population, and rising living standards and industrialisation are driving global energy demand [8]. It is estimated that by the middle of the 21st century, global energy consumption will have doubled, of which 50 % could be for electricity alone [9,10]. To meet sustainable development goals and energy demand, the energy sector must be transformed by deploying low-emission energy sources and increasing the share of renewable energy [3,7]. Among renewable energies, solar energy is the most important exploitable resource [9]. It is estimated that more than 40 % of the renewable energy produced in the world in 2050 will come from photovoltaic installations [10]. Although today, solar installations occupy only a fraction of lands in the world, current scenarios show that their development may increase competition for lands and resources, especially with the agricultural

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* Corresponding author.
E-mail addresses: jocelyn.widmer@students.bfh.ch (J. Widmer), bastien.christ@agroscope.admin.ch (B. Christ), jan.grenz@bfh.ch (J. Grenz), lindsey.norgrove@bfh.ch (L. Norgrove).

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sector [11,12].

To address competition for land, it is possible to combine the installation of a solar photovoltaic (PV) plant with agricultural production on the same area [13]. This new production system was first devised and proposed in the 1980s to allow additional use of agricultural land [14]. This concept, known as agrophotovoltaics, agroPV, agrivoltaics, solar sharing or PV agriculture, depending on the country [15,16], is one of the new agricultural techniques under development where research has increased significantly in recent years [17].

Three types of agrivoltaics have been developed [18]. The first one consists in using the space between the crop rows to install solar panels (Interspersed PV arrays), while for the other two the PV modules are installed above the crops, either by replacing part of the greenhouse cover with panels (Greenhouse-mounted PV arrays) or by mounting them on an open-air structure (Stilt-mounted PV arrays). The solar panels can be installed in a fixed way on the structure (Static panels) or in a dynamic way (Dynamic panels) by modifying their inclination according to the sunshine and the management of the crops [19]. It is also possible to use photovoltaic cells that capture certain wavelengths of solar radiation to generate electricity. All these methods are based on the

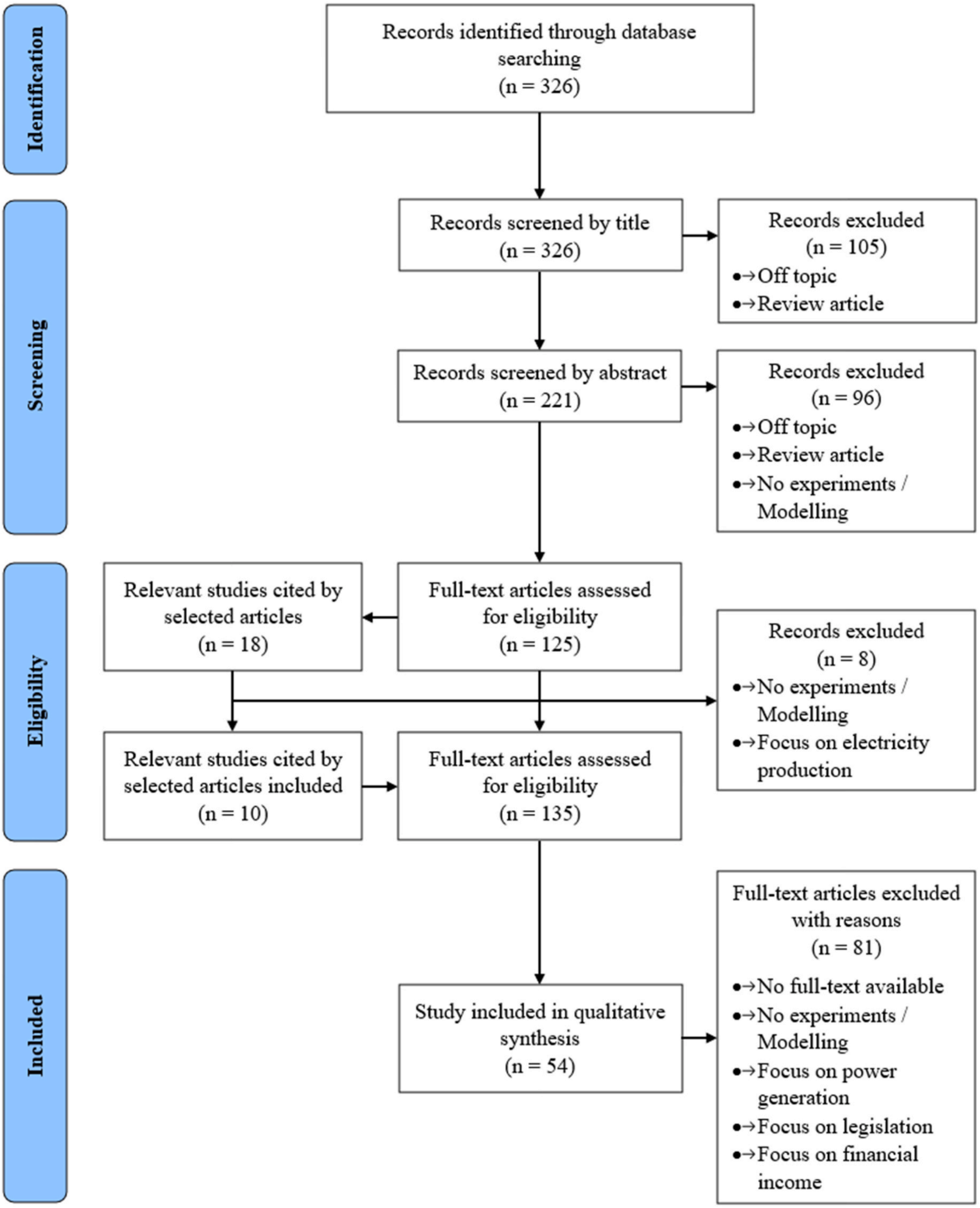

Fig. 1. PRISMA flow diagram detailing the screening, eligibility, exclusion and inclusion criteria after a keyword search using Web of Science. Other databases, such as google scholar, that include grey literature were not used as the focus of our study was on literature that had already been through a rigorous review process.

fact that plants use only part of the solar spectrum to grow and that they have an intrinsic level of light saturation beyond which photosynthesis stabilises [20,21].

Agrivoltaics is therefore a new production system that is developing worldwide and gaining interest. The study in Ref. [22] conducted a meta-analysis to review the evolution of yields of different crops under shade and to identify those with most potential for this system. A systematic review of electricity production and financial balance of the installations has been carried out by Ref. [16], as well as another by Ref. [23] on circularity and landscape experience of agrivoltaics. Yet little attention was given to the plant physiological and agronomic results of the experiments, except for the changes in microclimatic conditions under the infrastructure. Moreover, publications on this topic have proliferated since 2005, with more than 215 articles in 2020 [24]. Ample information is thus available on agrivoltaics, yet, to the best of our knowledge, no synthesis of the agronomic data has been done to date. This would be useful to guide future research. The aim of this study was to fill this gap by synthesising current agronomic data on plant cultivation and animal husbandry within agri-photovoltaic systems. The objectives were to identify and describe existing agrivoltaics and to evaluate the morphological, quantitative, and qualitative changes in plant production. In addition, animal husbandry was also evaluated considering production intensity and animal welfare.

2. Methods

2.1. Data inclusion criteria

A literature search was conducted in Web of Science on 17 December 2022 using the following search strings in the “topic” field: (agrivoltai* OR agri-voltai* OR "agrivoltai* system*" OR "agri-voltai* system*" OR agriphotovoltai* OR agri-photovoltai* OR agrovoltai* OR agro-voltai* OR "agrovoltai* system*" OR "agro-voltai* system*" OR agrophotovoltai* OR agro-photovoltai* OR agrisolar OR ″dual-use solar" OR "solar farming" OR "solar sharing*" OR "PV agriculture*" OR "dual land use*" OR "photovoltaic greenhouse*" OR "agricultur* photovoltai*" OR "greenhouse* photovoltai*" OR "flexible photovoltaic panel*"). The search was conducted using only English terms and no restrictions on language or document type were made. No time restrictions were applied. The initial search resulted in 326 publications.

2.2. Data exclusion criteria

The articles were evaluated by analysing them using the “Preferred Reporting Items for Systematic Reviews and Meta-Analyses” (PRISMA method [25]; Fig. 1), as is standard practice. The selection of articles was done as follows. In the first instance, only primary research articles were retained and those off-topic were eliminated. Opinion papers were excluded as they did not contain primary data. Articles on the development of solar panels, energy production or financial income were not retained as these were outside the scope of our work. Finally, articles that only mentioned modelling of agronomic results or did not include field experiments and measurements were discarded. A “backward snowball” [26] was also done by checking the reference sources of the captured papers, resulting in ten additional publications. Fifty-four publications were therefore used in the systematic review.

2.3. Data extraction

Data were extracted from the included studies according to the following variables of interest: (1) location; (2) Köppen-Geiger climate classification; (3) type of production (animal or plant); (4) species studied; (5) type of plant crops studied; (6) type of agrivoltaic arrays; (7) type of solar panels (static or dynamic/with or without solar spectrum separation); (8) agrivoltaic plant area; (9) shaded ground area; (10) treatments evaluated (factors, control, number); (11) and, response variables.

The response variables of importance that were compiled from the studies are (i) total plant production; (ii) marketable plant production; (iii) morphological changes in plants; (iv) change in chemical composition of plants (such as sugar, acidity, bioactive compounds); (v) plant development; (vii) animal production; (vii) animal welfare.

2.4. Data synthesis and analysis

All data were synthesised and analysed using Microsoft Excel® software. The variables of interest available in each article were compiled in a single table to be able to compare them and create the graphs necessary for their interpretation. Due to the wide application area of agrivoltaics and to facilitate the analysis of the results, the articles were first grouped according to the type of production and treated as discrete variables. For plants, they were further classified according to the different types of crops, such as cereals, vegetables, or perennial crops, for all response variables except for the part addressing changes in their chemical composition. Tomatoes and sweet peppers were classified as “vegetables”.

3. Results and discussion

3.1. Categorization and description of the general framework of studies

Agrivoltaics were all in the Northern hemisphere ($n = 50$; Fig. 2a). The map shows the development potential of photovoltaic plants according to the solar resource [27]. However, it does not accurately define whether conditions are optimal at a given site, as this also depends on the soil and climate factors of the location [16]. This may partly explain why installations are mainly located in Asia, Europe, and North America. It also seems likely that the development of agrivoltaics is predominantly in developed countries due to the cost of the installations. However, it is worth noting that there is no mention of an installation in Australia and that relatively few research agrivoltaics have been implemented in North America compared with the other two continents. Of the fifty-four studies found, 15 % were conducted in the United States ($n = 8$), 13 % in China and Italy ($n = 7$) and 11 % in the Republic of Korea and France ($n = 6$). Europe is the continent with the most studies with 44 % ($n = 24$) ahead of Asia (37 %) and North America (15 %). To the best of our knowledge, the studies published are representative of the current development of agrivoltaics around the world, which is taking place predominantly on these three continents.

Two-thirds of the research agrivoltaics ($n = 33$) were stilt-mounted PV arrays and fifteen were greenhouse-mounted PV arrays (Fig. 2b). Only two installations were interspersed PV arrays within crops [31,32]. These two studies were carried out with fixed solar modules positioned between rows of Tuscan kale (*Brassica oleracea* var. *palmifolia* DC.) or turmeric (*Curcuma longa* L.), considered as shade-tolerant [81] and partially shade-tolerant [82], respectively. Most of the installations had static solar modules ($n = 45$), and three stilt-mounted PV arrays were equipped with dynamic panels. One greenhouse-mounted PV array [33] and one stilt-mounted PV array [34] were composed of solar panels with solar spectrum separation.

Of the 50 agrivoltaics mentioned, only 37 had their total area indicated. The smallest was only 4 m^2 and was an experimental greenhouse partially covered by a photovoltaic panel [35]. The largest covered an area of 2.4 ha, is in Corvallis (Oregon, USA) and was part of a research project on animal husbandry in an agrivoltaic [36,37]. Almost two-thirds of the installations ($n = 23$) were smaller than 1000 m^2, 12 were between 1030 m^2 and 4410 m^2, while the second largest was 0.8 ha [38]. For 33 of the agrivoltaics, the shaded area on the ground was measured. The majority (79 %) shaded a ground area equal to or less than 40 % of the total surface. It has been reported that generally a coverage of up to 25 % of the area does not significantly affect plant growth and quality [17]. However, as soon as the ratio exceeds 50 %, it

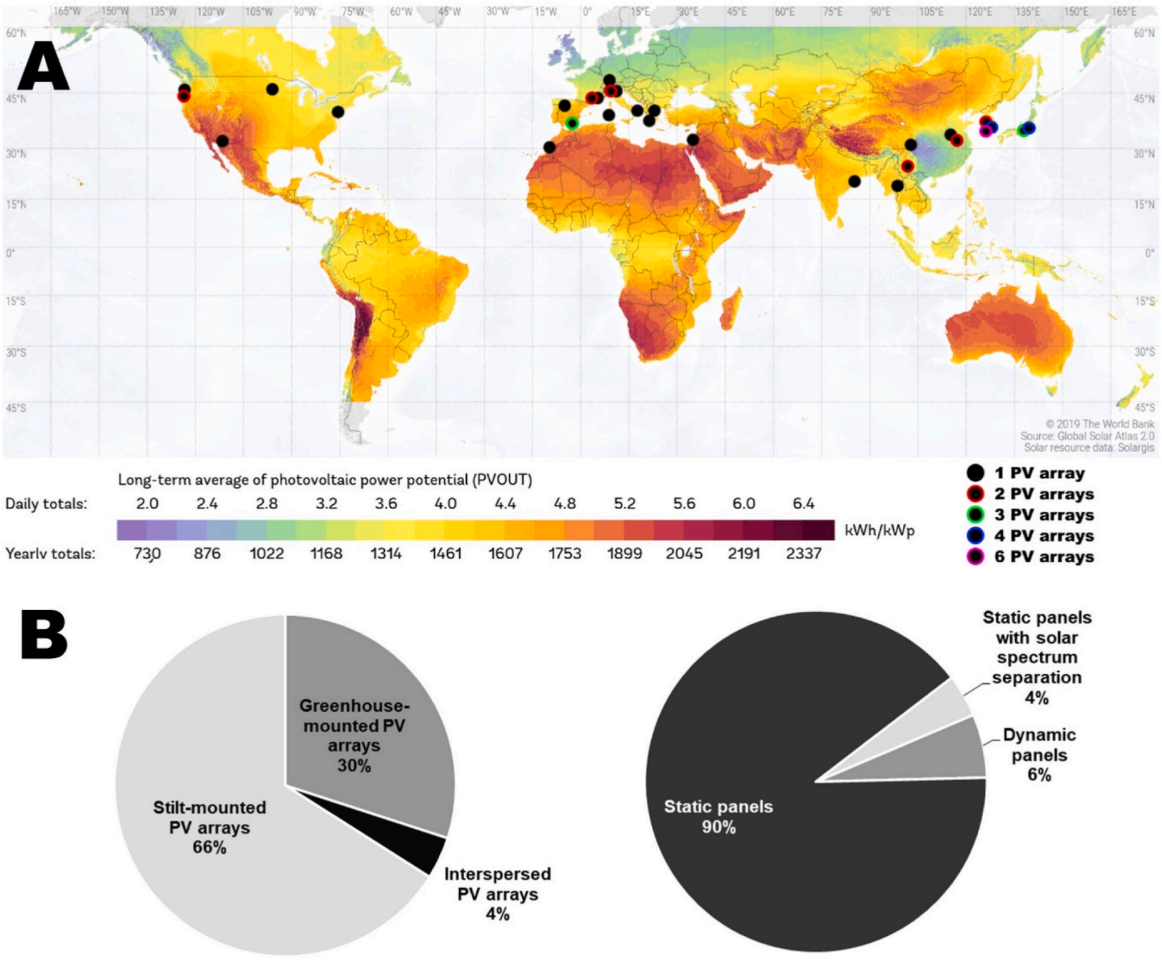

Fig. 2. Characteristics of the 54 reviewed studies on agrivoltaics. **a** Location of the agri-photovoltaic installations mentioned in the articles (different colour dots indicate whether several installations are located in the same region) on a map showing the photovoltaic power potential (The darker the colour, the higher the long-term average potential) (adapted from © 2020 The World Bank, Source: Global Solar Atlas 2.0, Solar resource data: Solargis [27]) **b** Type of agrivoltaic arrays and solar panels used (n = 54; [18,28–80], for codes, see reference list.

inhibits the growth of many plants. In two studies, the shaded area was equal to 75 % on a crop of grapes (*Vitis vinifera* L.) or turmeric [39,82].

Three of the 54 papers were related to livestock husbandry and evaluated the possibilities of rearing lambs [37] or dairy cows [40,41] in an agrivoltaic system. All other research projects were conducted with plants and sometimes several species were grown in the same project. Of 90 trials with plants, fifty-six were conducted with vegetables, mainly lettuce (*Lactuca sativa* L., n = 13) and tomato (*Solanum lycopersicum* L., n = 11), while 11 % and 10 % evaluated cereals or legumes, respectively (Fig. 3). However, few berries have been evaluated under agrivoltaics, although these crops seem to be the most promising, while cereals and legumes would be less suitable [22].

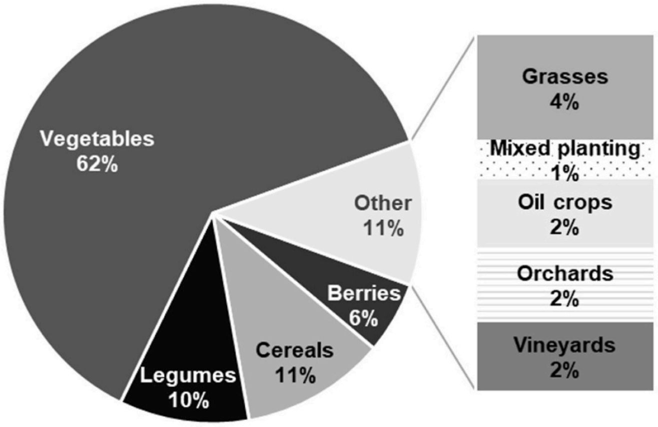

Fig. 3. Proportions of the different types of crops studied (n = 51, all except [37,40,41]). We use the term "vegetables" to include tomatoes and sweet peppers.

3.2. *Agronomic results in agrivoltaics*

3.2.1. *Solar sharing & animal husbandry*

The results obtained by Ref. [37] for lamb production under an agrivoltaic system showed that such an installation had no influence on the daily live weight gain of the animals. However, these results were obtained when the average dry matter production of the forage was higher for the open field. Yet, the quality of the forage under the PV system was better and was able to offset the lack of production. A decrease in forage quantity under solar panels was also observed by Ref. [42], while opposite results were obtained by Ref. [36]. This difference in forage dry matter production can be explained by distinct botanical composition as well as the soil and climatic conditions of each facility. Animal welfare and well-being was assessed and measured by visual observations of the animals' behaviour. Scores were awarded for various parameters such as grazing, rumination, idleness, hygiene, and animal activity. No changes in lamb behaviour were observed [37]. Dairy cows reared under solar panels did not show any changes in behaviour [41]. However, their peak activity was lower and was explained by the fact that the ruminants stayed under the panels during the hot period of the day. General herd hygiene was similar, while the body temperature of the cows kept under the PV system was significantly lower during the day [40]. Nevertheless, milk production, protein and fat content were similar in both herds. These results are surprising as an increase in air temperature negatively influences cow welfare and productivity by decreasing the amount of milk produced and altering its quality [83]. A difference in milk production and quality should therefore have been expected for the cows kept under solar panels. One explanation could be that the cows had access to the shaded area of the panels only for 22 days from June to September due to the time required for the grass to regrow between grazing [40]. The agrivoltaic installation therefore certainly did not influence the metabolism of the cows and long-term effects would probably have been observed if the cows had spent the whole season under the solar panels.

3.2.2. Solar sharing & crop production

3.2.2.1. Vegetables. With more than 23 % of the trials conducted, lettuce was the most researched vegetable (Table 1). This can be explained by the ease of management of this plant in cultivation, its rapid growth, and the low space requirement for its development.

In 11 out of the 13 studies, the fresh weight of lettuce was assessed. In general, the average weight was either significantly lower for lettuce grown under the panels or slightly higher (Table 1). In only one study, the fresh weight was significantly higher, with an increase of up to 87.6 % of the weight obtained in full sun with 18 % less light [47]. Conversely, yield decreases of 50 % of those obtained for the control were observed [46,48]. Depending on the season, differences in production were noticed for the same variety [47,50]. The dry weight was systematically lower for plants grown under agrivoltaics. Seasonal and varietal differences were also observed for this parameter [44,49,52]. According to the studies, the number of mature leaves per lettuce evolved in opposite ways. In a study conducted by Ref. [47],a significant increase in the number of leaves of lettuce grown under solar panels was observed, while [45] reported a decrease of up to 25 %. Furthermore [53], observed that the appearance of leaves was delayed for plants grown under an agrivoltaic installation, especially during the first three weeks after planting. Finally, the chlorophyll content was analysed in two experiments. The contents were either slightly higher [43] or significantly lower [49].

Tomatoes were the second most common vegetable evaluated with 11 studies (Table 2). Yield changes were not consistent across studies. A significant decrease in production was observed by Ref. [54] due to a 30 % decrease in PAR, while [55] obtained twice the total fruit production under solar panels with over 45 % less light. Average fruit weights followed the same trends, with an increase in weight for tomatoes harvested from plants grown under shade [56,57], while a decrease in weight and size was observed in other studies [58,59]. In two studies, marketable yield was not affected by the solar installation [58,59], while it was significantly higher for tomatoes grown in full sun in the trial conducted by Ref. [60]. These divergent observations could be partly explained by the varieties used, but also due to the changes in climatic and sunlight conditions under agrivoltaics [38]. Indeed, heat stress on tomatoes causes physiological and biological damage, including reduced flower fertility or abortion [84]. Conversely, it was shown that shading of tomatoes had a negative influence on yield [85]. This was also noted by Ref. [61], who observed a significant decrease in the production of plants grown under an agrivoltaic installation that reduced PAR radiation by 28.8 %. This difference becomes even more pronounced when this rate was increased to 46.6 % and 66.3 %. In the study conducted by Ref. [62], an increase in plant size, number of leaves, leaf area and chlorophyll content was noted in tomatoes grown under panels. This seems to indicate an adaptation of the plants to the production system. Conversely, a highly significant decrease in the number of flowers per square metre and in plant size was observed by Ref. [54]. Finally, fruit colouring was significantly influenced by the agrivoltaic installation, while firmness changed only slightly below 15 % shade [58,61].

In a two-season study conducted in Germany by Ref. [42], an increase in the aerial development of potato plants (*Solanum tuberosum* L.) grown under panels was observed compared to a full sun treatment. However, the results show a significant decrease in tuber yield of 18 % in the first year of cultivation, but a significant increase of 11 % in the second. Nevertheless, the yields obtained under the panels were above the national average in both years. The agrivoltaic installation has therefore made it possible to produce electricity without affecting the yield of the potatoes. In addition, the quality of the tubers was only slightly affected, with a similar marketable proportion between treatments. The same trends were observed by Ref. [64], suggesting that the potato is a suitable plant for agrivoltaics.

An increase in sweet pepper (*Capsicum annuum* L.) production and number of fruits per plant was also observed in crops grown under a solar array, without affecting the quality of the production [65,66]. Wild rocket (*Diplotaxis tenuifolia* (L.) DC.), cabbage (*Brassica oleracea* var. *capitata* L.), broccoli (*Brassica oleracea* var. *italica* Plenck) or celeriac (*Apium graveolens* var. *rapaceum* (Mill.) Poir.) did not show significant

Table 1

Yield and physiological response of lettuce (*Lactuca sativa* L.) to cultivation under solar panels, as measured at harvest (n = 13).

% PAR decrease compared to the control	Plant fresh weight (g)	Plant dry weight (g)	Leaf number	Average leaf length (cm)	Average leaf width (cm)	Leaf area (cm^2)	Chlorophyll content ($mg\ g^{-1}$)	Specific leaf area ($cm^2\ g^{-1}$)	Source
7.2	Hi ^{ns}	Lo *	Hi ^{ns}	Hi *	Hi *	Hi *	–	–	[35]
18–40	Hi *	–	Hi *	Hi *	–	–	–	–	[47]
20–50	–	Lo *	Lo ***	–	–	Lo ^{ns}/Hi $^{ns; ***}$	–	Hi ***	[45]
20–50	Lo *	–	–	–	–	–	–	–	[50]
30–50	Lo *	Lo *	Lo *	–	–	Lo */Hi *	–	Hi *	[44]
30–50	–	Lo ^{na}	–	–	–	–	–	–	[52]
30–50	–	–	Lo ^{na}	–	–	–	–	–	[53]
40–88	Lo */Hi ^{ns}	Lo $^{ns; *}$	Lo $^{ns; *}$	–	Lo ^{ns}/Hi ^{ns}	–	–	–	[46]
52–64	–	Lo *	–	–	–	Hi *	Lo $^{ns; *}$	–	[49]
55	Lo *	–	Lo *	Hi *	–	–	–	–	[48]
65–70	Hi ^{ns}	Eq	Lo ^{ns}	–	–	Hi ^{ns}	Hi ^{ns}	–	[43]
70	Hi ^{na}	–	–	–	–	–	–	–	[33]
70	Lo ^{ns}	–	–	–	–	–	–	–	[51]

Key: Lo and Hi indicate whether the data obtained on lettuce grown under solar panels are lower (Lo) or higher (Hi) compared to an unshaded control.
ns not significant (sig.), * sig. at $P < 0.05$, ** sig. at $P < 0.01$, *** sig. at $P < 0.001$, *na* no statistical analysis.
- no data.

Table 2

Yield and physiological response of tomato (*Solanum lycopersicum* L.) to cultivation under solar panels, as measured at harvest (n = 11).

% PAR decrease compared to the control	Yield (kg m^{-2})	Marketable yield (kg m^{-2})	Average fruit weight (g)	Fruit diameter (mm)	Plant height (cm)	Leaf number	Leaf area (cm^2)	Chlorophyll content (mg g^{-1})	Source
–	Lo ^{na}	–	–	–	–	–	–	–	[38]
–	Hi ***	–	–	–	–	–	–	–	[55]
–	Hi ^{na}	–	Hi ^{na}	–	Hi *	–	–	–	[56]
0	Lo ^{ns}/Hi ^{ns}	Lo ^{ns}/Hi ^{ns}	Lo *	Lo *	–	–	–	–	[58]
13–22	Lo ^{ns}	Lo ^{ns}/Hi ^{ns}	Lo $^{ns;\ **}$	Lo $^{ns;\ ***}$	Lo ^{ns}	Lo ^{ns}/Hi ^{ns}	–	–	[59]
25	Hi ^{na}	–	Lo ^{na}/Hi ^{na}	–	–	–	–	–	[57]
28.8–66.3	Lo ***	–	–	–	–	–	–	–	[61]
30	Lo **	–	–	–	Lo ***	–	–	–	[54]
35–40	–	–	–	–	Hi ^{ns}	Hi ^{ns}	Hi ^{ns}	Hi ^{ns}	[62]
50–59	Hi ^{na}	–	–	–	–	–	–	–	[63]
64	Lo *	–	–	–	–	–	–	–	[60]

Key: Lo and Hi indicate whether the data obtained on lettuce grown under solar panels are lower (Lo) or higher (Hi) compared to an unshaded control.
ns not significant (sign.), * sign. at $P < 0.05$, ** sign. at $P < 0.01$, *** sign. at $P < 0.001$, *na* no statistical analysis.
- no data.

differences in yield when grown under photovoltaic panels of w, sometimes over several cycles [67–70]. Conversely, a significant decrease in yield or biomass production was observed for garlic (*Allium sativum* L.), onion (*Allium cepa* L.), basil (*Ocimum basilicum* L.) or spinach (*Spinacia oleracea* L.) grown under a solar installation [34,71]. Finally, a crop of pak choi (*Brassica rapa* subsp. *chinensis* (L.) Hanelt) shaded at 100 % by panels was found to have up to ten times lower yields than the control in full sun [72].

3.2.2.2. Cereals. Surprisingly, a study conducted by Ref. [18] on maize (*Zea mays* L.) showed that this plant was tolerant of some shade, although it is typically considered to be shade-intolerant. A low density of solar panels increased biomass and yield (+5.7 %) compared with the control grown in full sun. Conversely, an increase in the density of the solar panels had a negative effect on biomass and yield. The higher yield at a low density of solar panels was explained primarily by optimising the light saturation point of the maize plus a reduction in soil water evaporation due to shading [18]. A similar increase in maize yield grown under agrivoltaics with a shading level of 21.3 % was also observed in the study of [73], yet a decrease in production at higher shading levels. No significant differences in maize plant size or yields were found by Ref. [71] in two consecutive years.

A study conducted by Ref. [74] on several farms and years showed that increasing shade led to a significant yield decrease of rice (*Oryza sativa* L.). This was partly due to the significant reduction in the number of panicles per plant. In contrast, the number of spikelets per plant as well as the grain weight were not influenced by the solar panels. A significant reduction in the yield of rice crops grown under three different agrivoltaics with a shading rate between 25 % and 32 % was also observed by Ref. [64]. In this study, the decrease in yields was due to a significantly higher thousand grain weight for all crops grown under full sun, as well as a significantly higher number of spikelets per panicle for two sites and panicles per plant for the third one. A significant decrease in yield between 9 % and 19 % was also observed by Ref. [71] in two consecutive seasons of rice cultivation under solar panels compared to the control.

A significant increase in the biomass of winter wheat (*Triticum aestivum* L.) plants grown under solar panels two years in a row was observed by Ref. [42]. Yield decreased significantly in the first season, while there were no differences in the following year. In addition, average grain weight was always significantly lower. Finally, yields and plant heights of two successive crops of rye (*Secale cereale* L.) were similar whether produced under a solar installation or in full sun [71].

3.2.2.3. Legumes and oilseeds. Few experiments were carried out with legumes or oilseeds under agrivoltaics. Nevertheless, it was observed that an increase in the level of shading of the solar panels negatively affected the yield of sesame (*Sesamum indicum* L.), mung bean (*Vigna radiata* (L.) Wilczek), red bean (*Vigna angularis* (Willd.) Ohwi & H. Ohashi) and soybean (*Glycine max* (L.) Merr.) in a field trial [73]. Depending on the species, a decrease in production ranging from 7 % (sesame) to 26 % (red bean) was observed when the shade ratio was 21.3 %. Yield reductions of 30 % (soybean) and up to 53 % (sesame) were observed when the shading of the solar panels was 32 %. A significant decrease in development and production of both sesame and soybean was also observed by Ref. [64]. For sesame, the decrease in yield was due to a significantly lower number of branches and seed weight, while for soybean it was due to a significantly higher ratio of seedless pods. No differences in the development and production of soybean or red bean in the first year of cultivation were found by Ref. [71], while all results were significantly lower in the second season. The poorer results obtained in the second cycle are likely linked to the climatic conditions of the trial and a series of heavy rains during the summer. Finally, in the study conducted by Ref. [75], an average decrease in production of 49 % was observed for green beans (*Phaseolus vulgaris* L.) grown under solar panels, as well as a significant decrease in marketable yield.

3.2.2.4. Berries, grape and tree fruits. A study by Ref. [76] evaluated the effect of three agrivoltaics with a roof solar panel coverage of 19.0 %, 30.4 % or 38.0 % on kiwifruit (*Actinidia chinensis* Planch.) over three years. No differences in leaf chlorophyll content were observed, while plant growth decreased with increasing shade level. The unshaded control always obtained the highest yields. However, at 19.0 % shading, there was no significant difference from the control (−2.6 % to −6.5 % depending on year; [76]). On the other hand, the more shaded treatments significantly reduced yield by at least 20 %.

The impact of a dynamic agrivoltaic system on a 'Golden Delicious' apple (*Malus* × *domestica* Borkh.) orchard was analysed by Ref. [77]. The objective of the study was to evaluate the impact of the installation on the plants over three seasons by maximising the electrical output of the panels (average global solar radiation interception was 50–55 %). Over the three growing seasons, phenology was never affected, being similar to the control. The specific leaf area (leaf area per unit leaf dry weight) was always significantly higher for plants grown under the solar panels, while flower production tended to be reduced. In the first two years, tree yields were negatively impacted by the agrivoltaic installation, with a reduction in production of 32 % and 27 %, respectively [77]. In contrast, in the last year of the experiment, the production was almost twice as high for the trees under the panels. This difference can be explained in part by a frost that occurred during the flowering of the trees, which caused a strong physiological loss of flowers in the uncovered control plots. In these conditions, the agrivoltaic installation therefore allowed the protection of the trees by limiting the drop in temperature of the plants.

In northern Italy, an experiment was conducted for three years to evaluate the production of grapes under solar panels shading 75 % of the crop [39]. The results show that production was systematically negatively impacted by the agrivoltaics, with a significant decrease in yield in the last two years of cultivation. In contrast, berry weight was always similar between the full sun control and the treatment. The difference in production is partly explained by a decrease in the number of berries developed per cluster under the panels.

An increase in yield and maximum weight of strawberries (*Fragaria x ananassa* L.) grown in greenhouses partially covered by PV panels was also observed [78,79]. The chlorophyll content of plants under the panels was consistently higher than that of unshaded strawberries and an advancement of the phenological development was also noted [78]. In addition, fruits were larger and firmer under the agrivoltaic system [79].

3.2.2.5. Changes in the chemical composition of crops. Several studies have analysed the chemical composition of plants grown under solar panels (Table 3). A significant increase in total anthocyanin and phenol content in blackberries (*Rubus fruticosus* L.) and raspberries (*Rubus idaeus* L.) grown under an agrivoltaic system with a 25 % shading rate was observed by Ref. [80]. On the other hand, a decrease in total phenol content was noted for wild strawberries (*Fragaria vesca* L.). A significant increase in fructose and glucose concentrations was observed for strawberries, while a significant decrease in glucose was noted for blackberries. Finally, changes in organic acid content were observed for all species. A significant decrease in total anthocyanins, phenols, and total soluble solids (°Brix) was measured for grapes grown under solar panels [39]. Significantly lower °Brix levels were also observed for tomatoes [54,59]. However, it was highlighted by Ref. [61] that 15 % of shade did not have a negative influence on the total soluble solids contained in the fruits of this plant. On the other hand, significant decreases in lycopene and β-carotene contents were observed [54]. Basil and rice crops showed significantly higher protein contents [34,74]. However, the increase of protein in rice has an undesirable effect on its taste and texture after cooking [74]. Finally [49], observed a significant decrease in ascorbic acid levels for three cycles of lettuce while [46] observed the opposite trend.

3.3. Study limitations and future research

Currently, research is increasingly focused on agrivoltaics, as shown by the growing number of studies conducted on this subject in recent years. However, it is difficult to compare the installations correctly because they are all different in terms of their design and the choice of solar panels used. In addition, the soil and climate conditions of a given location can greatly influence the results obtained, being favourable one year and limiting the next. At the crop level, another limitation is related to the numerous species studied, and even cultivars, as each variety has distinct optimal growing conditions and is therefore not influenced in the same way by the production system. Two-thirds of the studies were carried out with vegetables. There is therefore a lack of information on other crops, which currently makes it difficult to define which species would be most suitable for agrivoltaics.

Few agrivoltaic projects have been carried out with animals and data are lacking, making it difficult to assess the feasibility of such a system. However, the first results seem to show that animal husbandry in combination with electricity production is possible. Further studies must be carried out on longer rearing periods. In the first instance, research should focus on dairy farming, because of the thermal stresses that can reduce milk production, but also because of the large amount of agricultural land worldwide that is used to raise cows. The potential in this field, both for food and electricity, is important and could favour the development of agrivoltaics with animal husbandry.

Concerning crop production, the research was mainly focused on vegetables, especially lettuce and tomato. For these two plants, it has been observed that yields have evolved in opposite directions depending on the study, which clearly shows the difficulty of generalising the impact of an agrivoltaic installation on a crop. Moreover, plants that are currently considered to be shade intolerant, such as maize, could nevertheless be grown under solar panels with certain conditions. It should be noted that few experiments have been carried out with berries, although these would be promising as they are less sensitive to shade. In addition, there is currently a lack of knowledge about perennial crops with agrivoltaics. Future projects should therefore focus on these as a priority. Furthermore, it could be interesting to evaluate several cultivars of the same species on one site and over several successive years to confirm whether varietal differences exist. One of the main limitations of the study is the size of the agrivoltaic installations studied. More than two-thirds of the installations were less than 1000 m^2, which certainly limits the effect of shading on crops and the impact on yields. Finally, cultural conditions, such as climate or crop management, may introduce a slight bias in crop yields and limit the comparability of studies for the same species.

Few studies have been carried out to date with solar panels with a separation of the light spectrum. It could therefore be interesting to evaluate this technology, which limits direct shading of plants and allows the wavelengths necessary for photosynthesis to pass through. Finally, according to the results obtained in the different studies, it is not possible to define a general threshold limit of shading that plants can tolerate without negative impacts on yield. Indeed, the results depend

Table 3
Changes in the chemical composition of harvested crops grown under solar panels reported in some studies (n = 16).

Crop	°brix	pH	Total anthocyanins	Total phenols	Antioxidant activity	Protein content	Ascorbic acid content	Source
Basil	–	–	–	–	–	Hi *	–	[34]
Blackberry	–	–	Hi ***	Hi ***	Hi ***	–	–	[80]
Broccoli	–	–	–	n.s./Lo *	n.s.	–	–	[69]
Celeriac	–	–	–	–	–	n.s.	–	[68]
Grape	Lo *	n.s.	Lo *	Lo *	–	–	–	[39]
Lettuce	–	–	–	–	–	–	Lo *	[49]
Lettuce	–	–	–	–	–	n.s.	Hi *	[46]
Sweet Pepper	–	–	–	n.s.	n.s.	–	–	[65]
Raspberry	–	–	Hi *	Hi ***	n.s.	–	–	[80]
Rice	–	–	–	–	–	Hi *	–	[74]
Spinach	–	–	–	–	–	n.s.	–	[34]
Wild strawberry	–	–	n.s.	Lo *	n.s.	–	–	[80]
Tomato	n.s.	n.s./Lo *	–	–	–	–	–	[58]
	Lo *	n.s.	–	–	–	–	–	[59]
	Lo *	–	–	–	–	–	–	[54]
	n.s./Lo *	n.s.	–	–	–	–	–	[61]

Key: Lo and Hi indicates whether the data obtained on lettuce grown under solar panels are lower (Lo) or higher (Hi) compared to an unshaded control.
ns not significant (sign.), * sign. at $P < 0.05$, ** sign. at $P < 0.01$, *** sign. at $P < 0.001$, *na* no statistical analysis, - no data.

strongly on the species but also on the location of the crop, the design of the agrivoltaic array or the season. Therefore, it is better to define the optimum daily light integral (DLI) level for each species first and then adapt the agrivoltaics system accordingly.

Agrivoltaics have attracted the attention of investors and politicians alike, as they are seen as a means of developing larger areas for energy production. Debates have centred around the effects of agrivoltaics on landscape quality, biodiversity and crop yields. For example, in Switzerland, agrivoltaics were not licensable until July 2022. Agrivoltaics that replace plastic tunnels and greenhouses and thus do no additional “harm” to the landscape can be considered a compromise. Clearly our results uncover research gaps and the need to test "real" large scale agrivoltaics to be able to predict yield impacts with greater accuracy.

4. Conclusion

The global increase in demand for food, linked to population growth, requires an improvement in the productivity of agricultural land. In addition, demand for energy, especially electricity, will expand in the coming years, resulting in an increase in the area dedicated to solar installations. However, this development conflicts with agricultural production and competition for land will certainly occur. To remedy this, combining these two types of production on the same area was first suggested in 1982 under the term agri-photovoltaics. Research is developing around this theme and the first results are promising. Livestock and some crops, such as potatoes, seem to be adaptable to large areas. In addition, crops that require a lot of sunlight, such as tomato and maize, could still be grown under solar panels.

The success of a production depends mainly on the amount of PAR light the plants receive and their needs, as well as the varieties used within the same species. Furthermore, in the context of climate change, the effects of an agrivoltaic installation on crops should not be neglected neither. By modifying the climatic conditions directly at the level of the crop, it could, for example, make it possible to limit the impact of a frost or high temperatures on production. In addition, a reduction in water requirements for crops grown under solar panels, and therefore in the use of an essential resource that is likely to become scarcer, is a clear advantage of this new system.

The results of this study can be used in future research on agrivoltaics to find the most promising crops and develop the system worldwide. Initially, the experiments should focus on crops of importance in their geographical area and carry out projects on larger areas. Later, it would be interesting to carry out varietal trials over several cycles or seasons to evaluate cultivars under different growing conditions and find the most suitable ones. Finally, the installation of solar panels affects various crop growth factors in different ways and these multiple interactions should also be carefully considered. Currently, agrivoltaics are suboptimal from an agronomic point of view and are mostly in the experimental stage. There is a need to optimise crop and variety selection, water and nutrient management, and probably also crop protection.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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