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A review of research on agrivoltaic systems

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ABSTRACT

The expansion of large-scale photovoltaic (PV) power generation is essential to global efforts to mitigate climate change. A constraint to such PV development is its extensive space requirements, complicated by increasing competition for land driven by population growth and rising food demand. Agrivoltaic systems, which integrate crop production and PV power generation, offer a potential solution to the land economy problem. In this article, we present the results of a systematic review of agrivoltaic research backed with relevant analysis, discussion, and directions for future research. In total, 98 studies were appraised. Among them, 48 dealt with specific applications, while 50 were preoccupied with the scale of PV production. Fourteen of those 50 inquiries examined small-scale (<100 kW) PV systems. The remaining 36 addressed medium-to-large-scale facilities (over 100 kW), with 26 oriented to installations exceeding MW in capacity. Apart from originating mainly in the northern hemisphere, research characteristically focusses on engineering issues – either configuration, or factors influencing power yield. Currently lacking is a comprehensive financial performance model for agrivoltaic systems. Further, very little investigation has been directed to large-scale (>1.0 MW) facilities which integrate livestock grazing. These later issues constitute important gaps in our knowledge because the regions around the world with the greatest potential for PV power generation are typically those where grazing is prominent.

1. Introduction

Land is a vital asset, not only for any economy based on agriculture but also for critical ecosystems parameters such as CO_2 capture, biodiversity, water cycle regulation, etc [1]. The assertive growth of photovoltaics creates potential conflict between food production and electricity generation in the use of land [2,3]. Power development intensifies competition for resources, especially within the agricultural sector which currently accounts for 12% (1.6 billion ha) of land globally for the cultivation of crops [3,4]. Often, suitable areas for PV installations, which perform optimally with long daylight hours and minimal cloud cover, are devoted to primary industries [5]. Countries which are densely populated, with limited flat areas, will face difficulty in trading off their agricultural estate to install purely solar farms or other renewable energy facilities such as wind turbines. The impasse will be accentuated by the expected 1.15% per annum increase in global population [6].

Adequate nourishment of the world's people remains a challenge because of the redeployment of land previously devoted to food or fibre production [7]. To illustrate, prior efforts to use croplands for producing biofuels such as ethanol drove up the cost of food, which principally impacted the poor and contributed to hunger [8,9]. All these negative aspects of conflicting land use have highlighted the importance of finding the right balance of crop, livestock and energy production.

Agrivoltaics involves a compromise between agriculture and PV development [10]. The system, known also as “agrophotovoltaics” in Germany [11], “solar sharing” in India [12], and “PV agriculture” in China [13], provides mutual benefits across the food-energy-water nexus [14,15]. Improved access to useable water can be achieved around PV facilities, along with the diversion of the same water for PV surface cleaning and irrigation. The curtailment in water extracted for irrigation can also support improvements in environmental outputs and input cost management [16].

With the aim of explaining the keynotes of contemporary agrivoltaic research, the plan now is to establish the methods used in the inquiry, and to present, as primary ‘results’, a descriptive, statistical overview of the field. Subsequent analysis addresses two central themes on the research frontier, namely, the impacts of PV installations on farming,

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and problems in implementing this new approach which promises radical change in systems of primary production. A discussion section follows, which deliberates the benefits and constraints of agrivoltaics. An outline of future study directions and a formal conclusion round off the account.

2. Methods

To examine peer-reviewed articles and grey literature on agrivoltaic applications [17,18], we undertake a systematic literature review. It presumes a protocol-driven approach to mark out potential investigative opportunities [19]. By design, it limits researcher bias [20], ensuring rigorous and transparent identification, synthesis, and assessment of all available evidence in order to generate a robust, empirically-derived answer to a designated question [21,22]. The review methodology is summarised in Fig. 1.

2.1. Sources of information

The PRISMA (Preferred Reported Items for Systematic Reviews and Meta-Analysis) protocol was used as the framework for inquiry [23]. The databases co-opted were ScienceDirect, Nature, the Web of Science, Scopus, IEEE Xplore, Springer Link, Taylor and Francis, and Google Scholar. In selecting the documents, the scope assumed is agriculture and livestock grazing under PV installations with principal indicators being the quality and quantity of crops grown under a PV array and the relative contributions of primary produce and energy output to total revenue on an agrivoltaic farm. Keywords were “agrivoltaic* or agro-photovoltaics*”, “solar sharing*”, “PV agriculture*” and “dual land use*”. A comprehensive search from 2011 (the year the first paper about agrivoltaics was published) to late January 2022 identified peer reviewed articles and grey literature (including technical reports). As illustrated in Fig. 1, the initial search produced 2,055 potential documents.

2.2. Screening

The 2,055 were imported into EndNote® reference management software. They were then uploaded and duplicates removed through the screening of titles, abstracts, and keywords (Fig. 1). This step eliminated 549 duplicates. A full-text screening was conducted of the remaining 1,506 references. In this process, a further 832 were put aside because of irrelevant titles and abstracts, their not being in English, or their abstraction from agrivoltaics. The final number of papers selected was 674.

2.3. Eligibility criteria

The criterion filters used in this systematic review are shown in Fig. 1. They require that: a full-text of the reference be available for assessment; that the said reference focus on electricity generation integrated with food production; and be written in English. Reviews from academic journals and conference articles were admitted. Articles not in full-text and not discussing agrivoltaic or agrophotovoltaics were excluded. In this process, 576 titles were discarded from the previous 674; the outcome was the inclusion of 98 articles.

2.4. Data extraction and synthesis

Each of the 98 selected documents was coded based on the following criteria: authorship, year of publication; publication types; journal/conference names; publishers or institutions; access types; types of

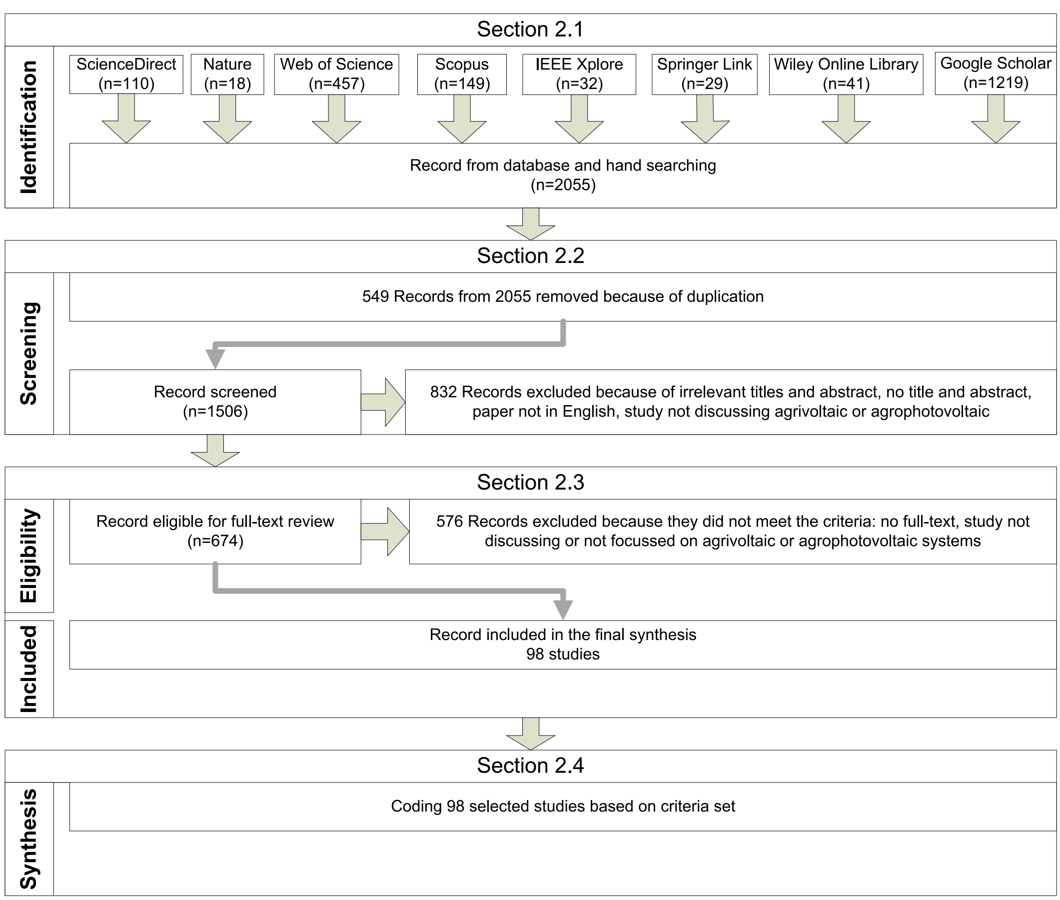

Fig. 1. Search criteria and protocol of the systematic literature review.

agricultural activities; and countries. This step enabled clear a progression through: the presentation of results by means of a descriptive overview; analysis of key aspects of agrivoltaic development; discussion of the emerging technology; and an account of the research field and frontier.

3. Results: a descriptive overview

The most efficient overview of the selected literature emerges from a chronological assessment, an account of publication sources, and delineation of the range of agrivoltaic research.

3.1. Chronological pattern of publications

The timeline of papers selected for this review, 2011–2022, is shown in Fig. 2. Almost 81% were published within the last five years: 31% materialized in 2021, 10% in 2020, 14% in 2019, 16% in 2018, and 10% in 2017. Ten papers were published in 2017, of which five reported well-established agrivoltaic trials including: a system in Chile; the University of Arizona Agrivoltaics project in the United States; an AgriVoltaic project in Malaysia; the Shanghai Science and Technology Commission project in China; and the Montpellier SupAgro in France [11,14,24–26]. In 2018, 16 articles were produced, 12 of which reported research projects commenced prior to 2018. More than half the literature identified was authored by 16 research groups (96 authors in total). Four research groups [14,27,28], [29–39] are working in the United States; two [11,40–45] and [46,47] in Germany; and two [48–52] in Italy. However, in most countries, only one group is working on agrivoltaics; e.g., in France [53–57]; India [58–62], China [25,63,64], Malaysia [26,65,66], Pakistan [67,68], South Korea [69,70], Japan [10,71] and in Australia [72,73]. Of the focal 98 documents, 45 (46%) were published by Elsevier.

3.2. Publication sources

Further dissection of the 98 documents shows that 86 (88%) were peer-reviewed articles, eight (8%) were conference papers, and four (4%) were poster presentations (Fig. 3). The articles were found in 59 different journals, of which 19 published more than one paper on the topic. Featuring seven relevant articles, *Applied Energy* was the largest single source of information. Of papers published in ISI journals, 46% (45) of the 98 are of Q1 rank.

3.3. Range of publications

In this sub-section, publications are categorized on several key features: the geographic distribution of research endeavour; the scale and economics of agrivoltaics; operational considerations and practical influences, and policy-related matters (Fig. 4).

3.3.1. Geographic distribution of agrivoltaic research

The study settings of agrivoltaic research, overlaid with the distribution of global horizontal irradiation (GHI), are presented in Fig. 5. Warmer colours indicate higher solar radiation intensity. Usually, GHI is adequate for agrivoltaics in latitudes of less than 45° and in areas close to the equator [74] such as the Saharan countries, Australia, the Arabian Peninsula, Mexico, Central America, northern Chile, South Africa, and the United States Southwest. However, GHI alone does not indicate optimum conditions. They depend additionally on local agricultural factors such as climatic elements, soil condition, and the availability of water for irrigation. As reflected in Fig. 5, these issues explain why not all agrivoltaic facilities identified in this review are situated in sunbelts. Specifically, most research was carried out in the United States and Germany, with respective totals of 25 and 11 papers (of the 98) published. A number of small scale (34.4 kW) trials have been conducted in Japan since 2004 [75], three commercial projects (800, 1294, and 3230 kW) have been patented as 'Agrovoltaico' in Italy [48], and one research plant (194 kW) was constructed in Southern Germany in 2016 by the Fraunhofer Institute of Solar Energy Systems (Fraunhofer ISE) [11]. A small-scale site has been established in Arizona, United States, as part of the Biosphere 2 research facility. China is already installing large-scale (544 kW) agrivoltaic systems on a commercial basis [13].

3.3.2. Scale of PV and land use economics

Among the 98 papers, only 50 mention the size of the agrivoltaic facility: 36 address medium-to large-scale PV systems (over 100 kW) and, as shown in Fig. 6, 14 report on small-scale facilities (under 100 kW). Within the first group of 36 studied, 26 exceed 1 MW in capacity. Guerin [73], while reporting on a conventional ground-mounted PV system, assessed the suitability of installing large-scale, solar power stations on agricultural land. He examined case-by-case and site-to-site benefits versus negative impacts depending, among other factors, on local soil type, water availability, topography, access to the electricity grid, the number of sunny days expected each year, and the soil's cropping or stocking potential. Guerin [72] opined that the decision to utilize agricultural land for a PV farm relies on the presence of good solar resources, access to the grid, a market for the electricity generated and a viable business case for the land and property in question. Papers

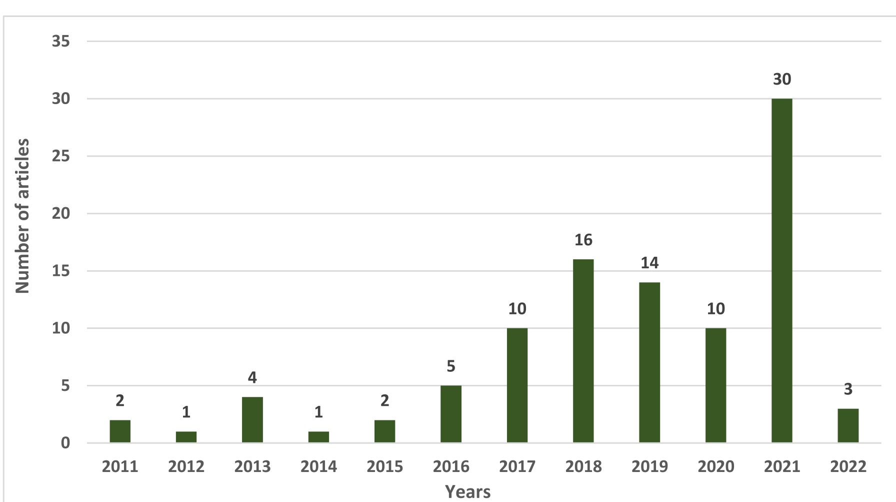

Fig. 2. Distribution of publications on agrivoltaic systems by year, from 2011 to 2022.

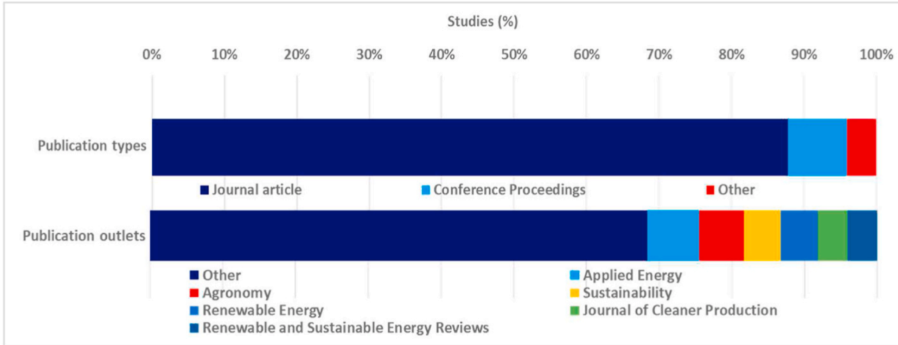

Fig. 3. Percentage distribution of publication types and outlets.

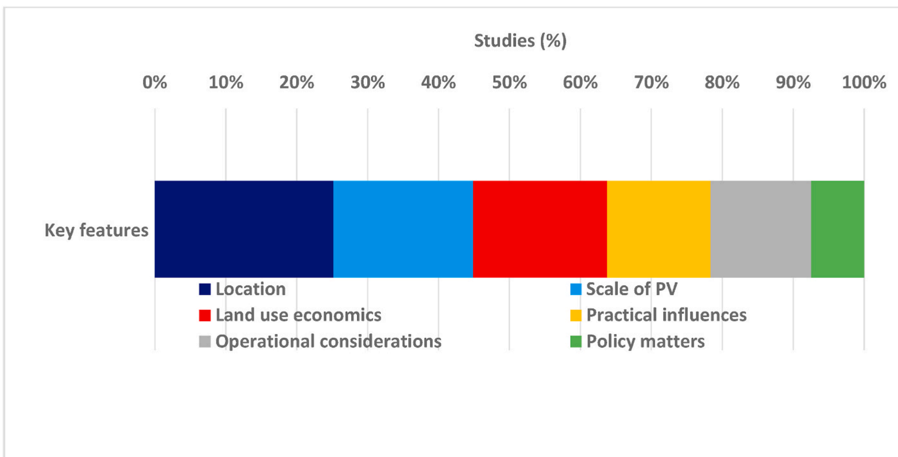

Fig. 4. Publication mapping based on six key features affecting agrivoltaic applications.

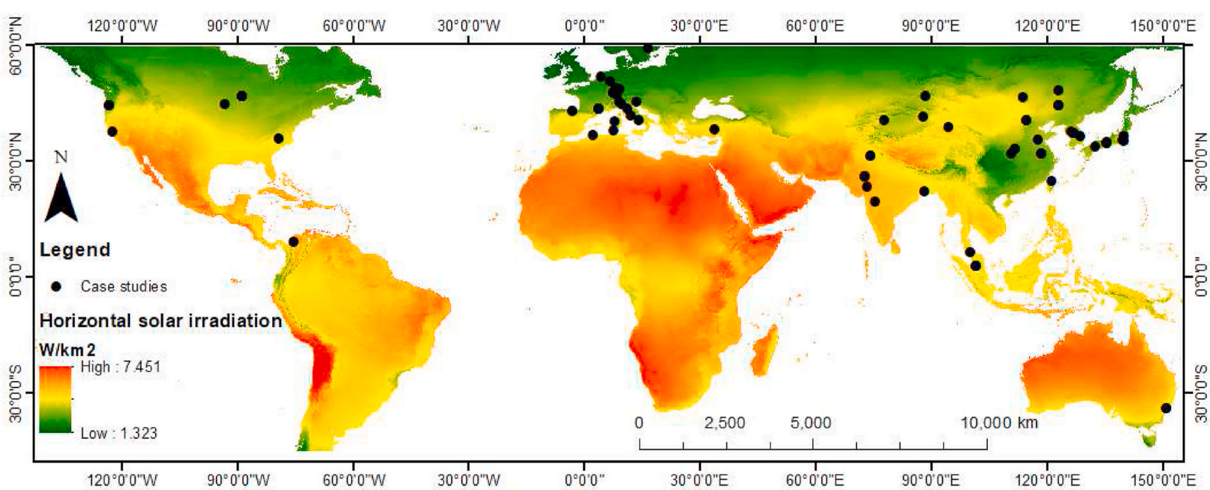

Fig. 5. Global horizontal irradiation map [76] showing 49 agrivoltaic projects referred in the 98 publications, as of late January 2022.

appraising PV farms larger than 1 MW focus on issues such as evaluation of the technical potential of utility-scale operations, techno-economic price-performance ratio calculations, land utilization and comparative financial analysis of growing crops under a PV array [39,42,77]. Among the 98 documents, 48 dealt with the land use economics of agrivoltaic systems invoking levelized cost of electricity (LCOE), net present value (NPV), internal rate of return (IRR), and payback period analyses [49,62,78,79] (Fig. 4).

3.3.3. *Operational considerations and practical influences*

Following per Figs. 4 and 36% of the papers (of the 98) discuss working considerations, such as the effect of irradiation distribution [36,80], shading [29,48,81], and microclimatic factors bearing on crop growth under a PV array [28,37,56,82]. Three contributions [29,55,83] deliberate water use and rain harvesting, different crop models, and photosynthesis and evapotranspiration in the crops growing under installations.

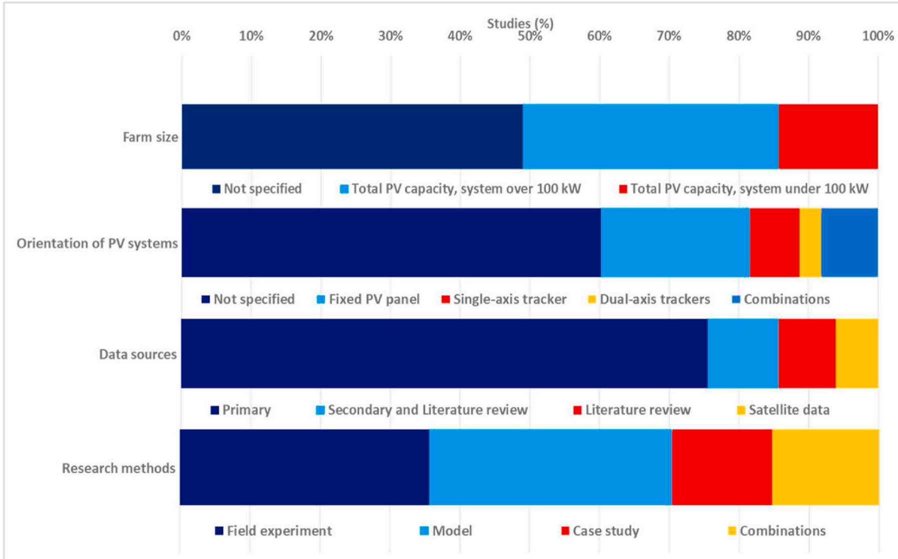

Fig. 6. Percentage distribution of reviewed studies exhibiting various analytical approaches.

As also shown in Figs. 4 and 37% of the projects (37) investigate various practical influences involved in combining the production of primary commodities and electrical output. Among them 9% (9) looked into microclimatic factors, 13% (13) addressed the suitability of plants, and 8% (8) concerned water usage. Certain papers (12%; 12) which discuss operational considerations also highlight such practical points.

Fig. 6 demonstrates that most studies (60% of the 98) did not address the solar orientation of the PV itself. Among those which did pursue the topic, 22% (22) incorporated analysis of fixed-axis systems, 7% (7) addressed a single-axis tracker, 8% a combination of systems, and 3% assessed a dual-axis tracker. Four research endeavours [11,46,47,84] explored the potential and opportunities of agrivoltaic systems, and relayed citizens' perceptions of this technology based on workshops, literature research, expert discussions, and modelling through Causal Loop Diagrams (CLDs).

Regarding data sources, 76% of the 98 research pieces were based on primary, and the remaining 24% on secondary, data. Apropos methods, 36% adopted field experiments, another 35% implemented modelling, 14% relied on case studies, and the rest (15%) combined all these approaches.

3.3.4. *Policy matters*

Of nearly 100 documents canvassed, 19 mention policy matters. Most emanate from the United States (6), Germany (4), and Japan (4). They discuss quality assurance, crop selection, land management, price, subsidies, feed-in-tariffs (FiTs), power purchase agreement (PPA) and allied themes [42]. The means by which government policies affect agrivoltaic implementation remain an important but neglected feature. Public support is vital to this budding technology because it encourages acceptance among farmers, thereby stimulating production [31,35]. To achieve this, it is important to communicate evidence of policy's effectiveness as it was found that the perceived effectiveness of a policy to promote its goal is a strong predictor of public support [85].

4. Analysis: impacts and implementation of agrivoltaics

4.1. *The impact of PV installations on cropping and grazing*

The impact of PV arrays is most readily analyzed through a systematic appraisal of situational factors affecting agricultural production, and topics surrounding the application of PV in cropping and livestock management.

4.1.1. *Situational factors influencing agricultural production*

The situational factors researched within agrivoltaic systems include: (1) air temperature; (2) humidity; (3) wind speed; (4) wind direction; (5) soil temperature; (6) soil moisture; (7) crop temperature; and (8) vapour pressure deficit (VPD). As demonstrated in Table 1, 14 separate references concentrate on these aspects, along with photosynthetically active radiation (PAR). Each is treated in detail in the subsequent text.

In France, Marrou et al. [57] did not spot any noteworthy difference in the mean daily readings of *air temperature* between an agrivoltaic trial and an open control plot. However, Weselek et al. [11] in Germany recorded a drop in air temperature under PV shades compared with open conditions. This anomaly might be due to the direct effects of the ground clearance of the panels [37] and the shading patterns below the array. While, irrespective of the season, some researchers have found similar mean daily air temperature and *humidity* under direct sun exposure and under PV panel shades [56], others have observed significant disparity in these parameters [37]. In analyzing the discrepancy, the configuration of the subject agrivoltaic system should be noted. Ones studied by Marrou et al. [56] had a higher ground clearance than those reported by Adeh et al. [37]. The inadequate clearance for airflow in the latter application hindered natural convection, leading to rises in air temperature and humidity under the panels. It is likewise important to notice that the mean *wind speed* was significantly different at all ground clearance levels, and the distribution of *wind direction* was random at all heights [37]. However, Marrou et al. [56] reported no significant difference in wind speed at a reference height of 2 m from the ground level.

Possible modifications in soil condition (mainly, to temperature and moisture) resulting from agrivoltaic installation has been detected. In one study, due to changes in *soil temperature* upon shading, a significant reduction in the leaf emission rate of lettuces and cucumbers became apparent three weeks after planting [56]. The daily average soil temperature beneath the PV systems was found to fall significantly as compared with full sun exposure [56]. Marrou et al. [55] showed that soil temperature was more affected than air temperature by shading. In Italy, Amaducci et al. [48] observed that, in all years canvassed, mean soil temperature was lower under Agrovoltaico than in full light (FL) conditions. Armstrong et al. [86] observed that soil temperature cooled under the PV arrays during the summer and between the PV arrays during the winter.

Another problem related to *soil moisture* arises from the high runoff from the panels, causing uneven water circulation with variable moist

Table 1
Situational factors influencing agricultural production in an agrivoltaic system.

Situational factors	Impacts	References
Air temperature	- Mean daily air temperature was found to be similar both under direct sun exposure and under PV panel shades, irrespective of the season. - Significant differences in mean air temperature are caused by the panels. - Air temperature around agrivoltaic installations is found to be significantly lower, as compared with stand-alone PV systems due to presence of crops.	[28,37,56,82]
Humidity	- Mean daily humidity was found to be similar for both direct sun exposure and under PV panel shades, irrespective of the season. - The daily variation in humidity during summer was decreased under PV systems. - Significant differences in relative humidity were observed as a result of growing crops under PV systems, regardless of height of ground clearance.	[37,56,86]
Wind speed	- Plant growth under PV panels was significantly impacted by wind speed, regardless of height of ground clearance. - Larger agrivoltaic systems could change the wind speed profile.	[37,56,82]
Wind direction	- Crop growth under PV systems caused significant differences in wind direction, irrespective of the height of ground clearance.	[37,82]
Soil temperature	- As a result of variations in soil temperature, noteworthy disparity in the leaf emission rate in cucumbers and lettuces were found three weeks after planting.	[48,55,56,86]
Soil moisture	- Acute incongruity and localized gradients in soil moisture were observed resulting from an uneven shade pattern of agrivoltaic systems.	[14,37,82]
Crop temperature and growth rate	- Crop temperature did not change considerably under shading and the growth rate was found similar under PV installations compared with conventional agricultural activities.	[56]
Vapour pressure deficit (VPD)	- During the growing season, VPD was always 0.52 + 0.15 kPa lower in an agrivoltaic system compared with a conventional setting.	[14,36,56]
Photosynthetically active radiation (PAR)	- For tomato production 50% of incoming solar radiation should be PAR. - Available PAR on shaded ground was noticed to be drastically lower than in an unshaded condition.	[25,59,61,64,71]

patches between the lower panel edge and the sheltered area [83]. Although overflow during heavy rainfall might lead to soil erosion and the formation of gullies [83], this problem only occurs in early development when the soil is uncovered, or scarcely covered, by vegetation. Radiation leaving the soil under the array is modified to long wave (with a little short wave) by the reflection from the back side of the modules. Those dynamics affect the soil evaporation rate, thereby influencing soil temperature [80]. In a study in the United States, extreme variation in soil moisture was spotted because of the heterogeneous shade patterns of the PV system causing asymmetrical temperature distribution [37].

Only one article discusses *crop temperature* under PV systems. Marrou et al. [56] observed that it did not change significantly in the shade, and the *growth rate* was similar in all treatments. The difference between the amount of moisture in the air and how much the air can hold when it is saturated (VPD), is analyzed in three articles. For example, Barron-Gafford et al. [14] found VPD to be consistently 0.52 ± 0.15 kPa lower in an agrivoltaic system than in conventional farming.

Irradiation distribution is a critical factor for agrivoltaics, such that five articles cover the topic. They note that crop growth is significantly influenced by light intensity and sunshine hours [25,53,54]. Lettuce could be produced normally under PV shading without affecting conversion efficiency [57,64]. Five papers address sunlight hours and *PAR* (the portion of the light spectrum (400–700 nm wavelengths) utilised by plants for photosynthesis). Kaneko et al. [87], in estimating tomato yield, advised that 50% of incoming solar radiation is PAR. Available PAR on shaded ground was found to be notably lower (84.5–127 mmol $cm^{-2}\ s^{-1}$) than in open sun conditions (243–1296 mmol $cm^{-2}\ s^{-1}$) [59, 60]. Santra et al. [61] write that the greatest photosynthetic photon flux density (PPFD) (1295 mmol $m^{-2}\ s^{-1}$) was monitored near noon in unshaded areas, while the lowest (24 mmol $m^{-2}\ s^{-1}$) was found during the morning underneath the PV array.

4.1.2. Agrivoltaics in cropping and livestock grazing

From a total of 62 agricultural activities identified in the literature, 29 represent intensive horticulture, 25 broad-acre cereals and legumes, six perennial pastures, and just two are associated with livestock grazing. As an original contribution, Table 2 now cross-references the situational factors and PAR as they impact these four agricultural subsectors in an agrivoltaic context. No single paper evaluated all nine situational factors previously cited. Three crops were linked with seven factors, one crop with six, another crop four, and five other crops were analyzed based on three factors. More detailed analysis follows of the findings of the 98 selected articles.

Intensive horticulture utilizes temperature-controlled environments (as in a greenhouse) to culture plants on an intensive scale to increase productivity and reduce the risk of weather or other external factors [96]. Certain plants like bottle gourd, cucumber, grape, lettuce, and tomato can adapt well to the imposition of PV panels. Lettuce production was investigated in seven studies which accounted for all factors except wind speed and soil moisture [24,25,29,55–57,91]. Dinesh and Pearce [29] report that the plant grown beneath an array was not materially affected by shading, allowing the same area of land to produce both food and electricity successfully. Valle et al. [24], measuring lettuce productivity per land area under a trackers-based PV array, find comparability between the agrivoltaic and full sun conditions. Tomato production occupied five enquiries; however, only one situational factor, namely soil temperature, was considered [10,25,27,71,93]. Cucumber growing attracted three articles which reviewed all factors except wind speed, wind direction, and soil moisture [55–57].

Broad acre (broad hectare) is a term used to describe farms or industries engaged in the production of grains, oilseeds, and other crops produced on a large scale [97]. It has also been engaged in conjunction with PV systems, as reported in nine of the 98 papers under review. These inquiries were associated with seven situational factors, not including wind direction and soil moisture [40,53,56,57,64,70,72,90, 94]. For example, Dupraz et al. [53] observed that, for monoculture wheat crops in a conventional PV array, the radiation before 9 a.m. and after 3 p.m. in the day (which represents significant energy during the summer) is not suitable for crop production. Amaducci et al. [48] undertook a long-term simulation, which compared the yield of maize (a broad-acre cereal and legume crop) under agrivoltaic conditions with that in the open field. It highlighted that, while the agrivoltaic yield is slightly lower when water is non-limiting, it is higher in situations of drought stress. Otherwise, five studies focused on bean cropping and three situational factors (air temperature, humidity, soil temperature) and PAR were analyzed [57,59,60,70,94].

Perennial pastures, cultivated for livestock feed, rely on herbaceous plants which have a life span of more than one year. Grasses and

Table 2
Situational factors which impact cropping and livestock grazing.

No	Subsectors	Type of activity	Microclimate factors								Photosynthetically Active Radiation (PAR)	References
			Air temperature	Humidity	Wind speed	Wind direction	Soil temperature	Soil moisture	Crop temperature	Vapour Pressure Deficit (VPD)		
1.	Intensive horticulture	Bottle gourd	No	Yes	Yes	No	Yes	No	No	No	No	[88]
2.		Cabbage	No	No	No	No	No	No	No	No	No	[25]
3.		Cantaloupe	No	No	No	No	No	No	No	No	No	[27]
4.		Carrot	No	No	No	No	No	No	No	No	No	[89]
5.		Cucumber	Yes	Yes	No	No	Yes (-)	No	Yes (+)	Yes	Yes	[55-57]
6.		Chiltepin	No	No	No	No	No	No	No	No	No	[27]
7.		Cumin	No	No	No	No	No	No	No	No	Yes	[59]
8.		Eggplant	No	No	No	No	Yes	No	No	No	No	[25]
9.		Ginger	No	Yes	Yes	No	Yes	No	No	No	No	[88]
10.		Ginseng	No	No	No	No	No	No	No	No	No	[90]
11.		Green pepper/ red pepper	No	No	No	No	No	No	No	No	No	[89]
12.		Grape	No	No	No	No	No	No	No	No	No	[30, 84]
13.		Isabgol	No	No	No	No	No	No	No	No	Yes	[59]
14.		Ivy gourd	No	Yes	Yes	No	Yes	No	No	No	No	[88]
15.		Jalapeño	No	No	No	No	No	No	No	No	No	[27]
16.		Lady finger	No	Yes	Yes	No	Yes	No	No	No	No	[88]
17.		Lettuce	Yes	Yes	No	Yes	Yes (-)	No	Yes (+)	Yes	Yes	[24, 25, 29, 55-57, 91]
18.		Mushrooms	No	No	No	No	No	No	No	No	No	[25, 92]
19.		Misai kucing	No	No	No	No	No	No	No	No	No	[65]
20.		Onions/ Welsh onion/spring onion	No	No	No	No	No	No	No	No	No	[25, 90, 93]
21.		Pakchoi	No	No	No	No	No	No	No	No	No	[25]
22.		Pumpkin	No	No	No	No	No	No	No	No	No	[89]
23.		Salad	No	Yes	No	No	Yes	No	No	No	No	[40]
24.		Shallot	No	No	No	No	No	No	No	No	No	[25]
25.		Spanish esparcet	No	No	No	No	No	No	No	No	No	[94]
26.		Strawberries	No	No	No	No	No	No	No	No	No	[93]
27.		Taro	No	No	No	No	No	No	No	No	No	[89]
28.		Tomato	No	No	No	No	Yes	No	No	No	No	[10, 25, 27, 71, 93]
29.		Watermelon	No	No	No	No	Yes	No	No	No	No	[89]
30.	Broad-acre cereal and legume copping	Alfalfa	No	No	No	No	No	No	No	No	No	[93, 94]
31.		Aloe vera	No	No	No	No	No	No	No	No	Yes	[59]
32.		Aromatic and officinal herbs	No	No	No	No	No	No	No	No	No	[94]
33.		Barley	No	No	No	No	No	No	No	No	No	[94]
34.		Corn (maize)	Yes	No	No	No	Yes	No	No	No	No	[40, 48, 89]
35.		Cotton	No	No	No	No	No	No	No	No	No	[93]
36.		Chickpea	No	No	No	No	No	No	No	No	No	[94]
37.		Dokudami	No	No	No	No	No	No	No	No	No	[90]
38.		Oat	No	No	No	No	No	No	No	No	No	[40, 94]
39.		Egyptian clover/ crimson clover/ white clover/ red clover	No	No	No	No	No	No	No	No	No	[94]
40.		French bean /mung bean/moth bean /cluster bean /broad bean	Yes	Yes	No	No	Yes	No	No	No	Yes	[57, 59, 60, 70, 94]
41.		Garden pea	No	No	No	No	No	No	No	No	No	[94]
42.		Garlic	No	No	No	No	No	No	No	No	No	[25]
43.		Guarpatha	No	No	No	No	No	No	No	No	No	[60]
44.		Lavender	No	No	No	No	No	No	No	No	No	[94]
45.		Lentil	No	No	No	No	No	No	No	No	No	[94]
46.		Millet	No	No	No	No	No	No	No	No	No	[94]
47.		Potatoes	No	Yes	No	No	Yes	No	No	No	No	[40]
48.		Rape/ rape-seed	No	Yes	No	No	No	No	No	No	No	[40, 94]
49.		Spelt	No	No	No	No	No	No	No	No	No	[94]
50.		Sunflower	No	No	No	No	No	No	No	No	No	[94]
51.		Tea/java tea	No	No	No	No	No	No	No	No	No	[66, 92, 95]
52.		Turmeric	No	Yes	Yes	No	Yes	No	No	No	No	[88]
53.		White lupin	No	No	No	No	No	No	No	No	No	[94]
54.		Wheat/ buckwheat /Wheat / durum wheat	Yes	Yes	Yes	No	Yes (-)	No	Yes (-)	Yes	Yes	[40, 53, 56, 57, 63, 72, 90, 94]
55.	Perennial pasture	Perennial rye-grass	Yes	Yes	Yes	No	No	No	No	No	No	[94]
56.		Lemongrass	No	No	No	No	No	No	No	No	No	[51]
57.		French grass	No	No	No	No	No	No	No	No	No	[94]
58.		Rye	No	No	No	No	No	No	No	No	No	[40, 94]
59.		Sonamukhi	No	No	No	No	No	No	No	No	No	[60]
60.		Sheep pasture	Yes	Yes	Yes	Yes	No	Yes	No	Yes	Yes	[36, 37]
61.	Livestock grazing	Goat	No	No	No	No	No	No	No	No	No	[72, 73]
62.		Sheep	No	No	No	No	No	No	No	No	No	[72, 73]

Note: 'Yes' (with grey colour fill) and 'No' refer to factors considered and not considered in the paper, (+) refers to positive impact, (-) refers to negative impact. For sources, see final column.

legumes are generally sown together: this combination enhances the quality of the forage and soil fertility [98]. Adeh et al. [37] mention that the agricultural benefits of pasture and energy co-location could reduce land competition and conflict in extensive cultivation operations. The sources reveal several common meadow types which flourish in moist conditions on agrivoltaic farms. They comprise perennial rye-grass [94], lemongrass [51], France grass [94], rye [40,94], sheep pasture [37,48], and Sonamukhi [60].

Grazing of livestock on agrivoltaic farms is a popular dual land use option, especially since it has the additional benefit of controlling vegetation growth [99]. For a single-use solar farm, if the height of the mounting structures of the PV systems is close to ground level, vegetation can be an obstacle to sufficient irradiation, resulting in a shading effect on the panels. To overcome this difficulty, grazing of livestock such as cattle and sheep in solar farms has been attempted, but a mounting system will need to be designed to accommodate the animals' size.

Studies on sheep pasture gravitate around seven situational factors and exclude soil temperature and crop temperature. The two research articles which discuss the integration of PV power and livestock grazing centre on goats and sheep in Australia and did not take in any situational factors [72,73]. In the case study by Guerin [72], the location selected for the facility was based on local, state, and federal government requirements, as well as the potential yield of the land for grazing and crop production. Livestock, such as sheep and goats, could curb the need for vegetation removal and maintenance, and control erosion, while supporting both food and energy production [72,73].

The presence of agrivoltaic systems does not affect stock density but can provide shelter for grazing beasts. However, consideration needs to be given to the choice of livestock. Andrew et al. [100] found that lower herbage mass available in solar pastures is offset by higher forage quality, resulting in similar spring lamb production to that in open fields. Sheep are favoured since they are small enough to pass easily between rows of modules and not damage equipment [73]. Thought could be given to the feasibility and costs of raising the lower edge of the panels above the average height of sheep. Grazing of larger animals such as cattle will require the mounting system to be higher to accommodate their size.

For existing and purely solar farms, the PV plant might not favour grazing applications due to insufficient height clearance. Nonetheless, grazing and cropping would be possible within an associated transmission line easement and outside the immediate array area. Grazing co-benefits have been achieved on other projects with minimal impact on PV systems: for example, Japan has successfully diversified its grid by integrating solar PV in unoccupied spaces around livestock sheds [72].

4.2. Issues in the implementation of agrivoltaic systems

Leading research on implementation of PV systems revolves around power generation capability and issues which occur when integrating the production of farm commodities and electricity.

4.2.1. Power generation

As indicated in Table 3, PV power generation is mainly influenced by solar insolation, the tilt and azimuth angle of the array, ambient temperature, and dust accumulation. While irradiance refers to instantaneous incident power from the sun (units in kW/m^2), *insolation* is the energy received over of time (units in kWh/m^2). Two articles focus on the effect of solar insolation on PV power generation. Although some cell materials use diffuse insolation (coming from scattered light reflected from atmospheric particles), direct insolation is usually more effective for electricity generation [36,80]. Light received at any specific site is affected by the location of the sun, daytime length, clouds and other interference in the sky [101]. Research shows that agricultural yield is improved under amorphous silicon (a-Si) and cadmium telluride (CdTe) solar panels compared with mc-Si (crystalline silicon) ones [80]. For both a-Si and CdTe arrays, revenue from crops amounts to 35% of total farm revenue, while the figure is 30% for mc-Si equipment. Recently, Cho et al. [102], over a five-month period, investigated power generation in agrivoltaic facilities based on mc-Si, bifacial and transparent modules of comparable specifications These authors found daily averages of 25.2 MWh, 21.6 MWh, and 25.7 MWh energy output, respectively.

Table 3
Power generation issues in agrivoltaic systems.

Issues	Impacts	References
Insolation	- Although some PV cell materials use diffuse insolation well, usually direct insolation is more effective for electricity generation.	[36,80]
Tilt and azimuth	- The performance of PV panels is influenced by their orientation and tilt, which affect the amount of producible energy. - Maximum radiation is intercepted by the PV module with the least incident angle of sunlight.	[30,51,58,64]
Ambient temperature	- PV efficiency diminishes at a rate of approximately 0.5% as air temperature increases by 10 °C. - In a simulation study, during daytime in core growing seasons, PV panel temperature in agrivoltaic systems was found ~8.9 + 0.2 °C cooler than in dedicated PV farms.	[14,29,36,80]
Dust accumulation	- Electricity generation reduces with increasing dust accumulation, the accumulation rate being a function of the size of dust particles and density of the dust deposited.	[30,39,58,60, 72,80,88,89]
Existing solar farm	- Height of ground clearance, distance between pillars, and crop height are major concerns of the solar farm.	[72,73]

The amount of energy generated by PV panels is influenced by their *tilt and azimuth*. Careful adjustment of an array's tilt angle (relative to the horizontal ground surface) and its azimuth (its east to west bearing) can maximise interception of incoming radiation. In the northern hemisphere, the rule in placing panels is that they must face true south (and in the southern hemisphere, true north), so that they can receive as much direct radiation as possible throughout the day. Orientation is based on the solar azimuth angle, which is zero at solar noon, negative in the morning, and positive in the afternoon. While a single-axis tracking system has a fixed tilt angle, a dual-axis PV module automatically adjusts array tilt and azimuth to ensure that the panel closely follows the incoming irradiance. Fixed-axis PV facilities compromise somewhat between the tilt and azimuth to optimise the power output over the whole year. Three articles discuss the effect of tilt and azimuth angle on PV performance. Scognamiglio [51] reports that fixing an optimum azimuth angle depends on the latitude of the installation site. Other researchers found that position of the sun can be determined in respect of the height angle and azimuth [103] and that effective solar radiation received by the PV modules increases with a decrease in incident angle of the sunlight [64]. On one hand, the orientation and position of the PV array affect the extent of electricity generation; on the other, they influence plant growth rates through their control of the amount of crop-available irradiation. Therefore, in setting the tilt and azimuth angle in agrivoltaic installations, crop-available irradiation should be carefully considered.

Ambient temperature is affected by wind speed, though speed has no direct impact on PV performance (Table 3). Significant variation in surface temperatures across modules has been recorded with a change in ambient temperature. Four articles point to its effect on PV installations. Under high irradiance, module surface temperature is found to be five to 8 °C higher than ambient temperature [80]. Rahman et al. [104] report that 27% more power is produced if the PV module is properly cooled: the higher wind speed, the more the cooling will be apparent. Only one scientific publication analyzes the effects of PV panel temperature on power generation and electrical efficiency specifically for agrivoltaic use. Barron-Gafford et al. [14] remark that panel temperature in daytime throughout the major growing season was ~8.9 + 0.2 °C cooler than that of conventional solar farms, leading to an enhancement in PV operations.

Dust accumulation is one of the vital issues in electricity generation [30,39,58,60,72,80,88,89]. Agriculturally-related maintenance works can negatively impact power output since they will increase deposition on the PV surface [46]. It diminishes transmittance of the top glass cover which, in turn, reduces performance [89]. Hence, periodic cleaning of the module is necessary, especially in regions with low rainfall or extended dry periods [29]. Unsurprisingly, dust on the PV surface decreases with an increased tilt angle [29]. Solar tracking systems are found to lower the dust effect by 50% [105]. Power output is reduced by approximately 50% as a result of six months' dust collection over a PV module [105]. Notably, Rahman et al. [104] observe that daily power output falls by 7.70 W and efficiency drops by 1.47% with the accrual of just 0.012 gm of dust on every square centimetre of PV surface.

As crop and livestock activities need PV installations to be at a certain height, current conventional design practice for PV might have to be re-engineered to accommodate these applications. PV support structures, which influence solar power generation, can restrict the type of agricultural machinery used in their vicinity [36,48,51,72,73,106–108]. There must be overhead clearance under the array and enough space between support pillars to allow the passage of traditional farm equipment. At least 4–5 m clearance is required for cereal harvesting with large combines [11]. Dupraz et al. [53] thus recommend mounting the array 4 m above ground. Regarding spacing, the aforesaid authors and Valle et al. [24] recommend pillars 6.4 m apart. Alternatively, in small scale agrivoltaic farms, both ground clearance and spacing can be reduced. Adeh et al. [37], in their application, measured only 1.1 m of ground clearance at the lowest point and the distance between arrays was 6 m. From another stance, according to Weselek et al. [11], at least 2% of the designated land will be occupied by the pillars of the support structure which, in turn, would slightly limit crop production. Othman et al. [109] comment that the percentage of heat stress occurrences was greatest at 1.22 m height during peak sun and moderate sun (afternoon), in case of the plants (*Orthosiphon Stamineus*) under heat stress of 10° to 15 °C above the ambient temperature.

4.2.2. Integration of agricultural and energy production

As depicted in Table 4, issues which jointly influence both agricultural production and a PV system are the rainwater harvesting, plant suitability, livestock grazing, and shading.

Rainwater availability and harvesting are recognized within eight papers as among the key issues affecting agrivoltaic installations. Given optimum design, rainwater harvesting and electricity production could potentially deliver sustainable agriculture through self-watering and self-powered farming [60]. Simulation has shown that rain distribution is mostly uneven with 0° tilt angle, and least irregular with panels either facing towards, or opposite, the wind direction. The angle of incidence of rainfall is also noticed as a key factor [11,83,91].

Harvesting is improved by attaching suitable catchment channels along the edges of the PV arrays. Runoff can be stored in rain barrels and tanks, and used for PV top surface cleaning or to supplement irrigation as per crops' requirements [60]. In India, installations reportedly secured 150,000 L annually from a 105-kW facility, enough to provide irrigation of about 37.5 mm on 0.404 ha of land [59]. Parkinson and Hunt [110] tracked the prospect of rain-fed irrigation in agrivoltaic farms in groundwater-stressed regions. The authors predict global retention of 150 km^3 of groundwater by means of rainfed operations.

The *suitability of plants* for agrivoltaic applications is of continuing concern in the literature [11,25,29,30,63,109] (Table 4). Those with high net photosynthetic levels [24,25,48,81,88,89,91], and high tolerance to shading are the best suited [53]. Marrou et al. [55] advise that evapotranspiration drops because of reduction in light exposure under PV arrays. However, the authors found that the effect is crop-specific, and evaporation is also driven by the crop shading percentage. For example, the effect is significant for lettuce, since it influences the evaporation rate, while the opposite holds for cucumber. Conversely, annual yields of species like forage crops, herbaceous plants and leaf vegetables (cabbage and lettuce) can be maintained or even increased, since they are well adapted to shade conditions [57]. Marrou et al. [55] conclude that appropriately selected crops in an agrivoltaic system can improve water use efficiency and help check water losses in dry climates. Apart from those already identified [72,73], there are other potential risks in the integration of *livestock grazing* under a PV array, the animals' health and welfare being obvious concerns.

Table 4
Issues affecting interfacing aspects of an agrivoltaic systems.

Issues	Impacts	References
Rainwater harvesting	- About 150,000 L of rainwater can be harvested per year from a 105-kW PV system, which is enough to supply irrigation of about 37.50 mm water on 0.404 ha of land. - Rainwater harvesting systems can provide water for cleaning deposited dust on PV modules.	[58–60,83]
Suitability of plants	- Plants with high net photosynthetic levels and high tolerance to shading are the most suitable. - Production of forage crops, herbaceous plants and leaf vegetables can be maintained or even increased since they are well adapted to shading.	[11,24,25,29,30,48,53,63,81,88,89,91,109]
Livestock grazing	- Risk of damage to solar panel by animals and *vice versa*.	[47,72,73]
Shading	- Crop-available irradiation reduced by about 15–40% due to a PV array corresponds to 'moderate shading' for crop production. - Lettuce is a suitable crop for the agrivoltaic systems since it can shade-tolerate up to 30%.	[29,48,81]

Shading thus emerges as a critical issue. Available irradiation under agrivoltaics is reduced by about 15–40% (Table 4), said to be 'moderate shading' for crop production [48,53,56]. With 30% shade tolerance, lettuce growing is one of the most suitable enterprises [56]. Elamri et al. [91] found a slight delay in the development of lettuce under PV shading. Crop-available radiation can reach as much as 60–85% of open-sun conditions through a reduced module density [38,41,53], though this outcome will be less significant in smaller facilities. Research suggests that, in a growing season, irradiation intensity over a land area of 0.093 m^2 under the modules must not fall below 50% [29]. Most crops need strong or moderate light to grow under PV systems. In shading above 50%, some plants are found to be restrained from achieving their maximum rate of photosynthesis [89]. Shading can bear positively on water harvesting and retention. It can lead to stable yields in arid regions, where there are negative effects of high solar insolation and excessive water shortages [48]. The counter-case is that plants under the panels will not be exposed directly to rain which could increase dust deposition on leaves and decrease photosynthetic effectiveness [29,38,39,53,88]. This problem is particularly detrimental in tea plantations in that it affects leaf quality.

Marrou et al. [57] point out that the impact of shading on yield is plant-specific and linked to different mechanisms of how varieties adapt. As shade pattern and micro-meteorological conditions under agrivoltaic facilities vary, seasonal crop yield will also depend on whether cultivation occurs in spring or summer [54,57]. Shade-tolerant plants are characterised by a large total leaf area, an altered leaf orientation, and a custom-made morphology with longer, wider, and thinner, but fewer leaves. These attributes enable the plants to endure low light [89,111]. Shade-tolerant varieties such as alfalfa, arugula, Asian greens, broccoli, cassava, chard, collard greens, hog peanut, kale, kohlrabi, lettuce, mustard greens, parsley, scallions, sorrel, spinach, sweet potato, taro, and yam have been found suitable for agrivoltaics [29]. Conversely, there are other many commercial crops including cabbage, corn, cucumber, pumpkin, rice, tomato, turnip, and watermelon which are shade-intolerant and need profuse daylight to grow. Those which can grow under moderate light include cauliflower, beans, carrots, coriander, onions and pepper. Mushrooms, notably, perform comparatively well in dark places [25,92]. Table 5 summarizes examples of shade-tolerant crops which offer substantial potential in agrivoltaic situations.

5. Discussion: benefits of, and constraints to, agrivoltaic development

Informed by the foregoing results and analysis, this discussion proposes a wide-ranging review of the pros and cons of agrivoltaic farming, arranged in terms of the efficiency of water and land use, possibilities for income diversification, financial issues, social benefits and environmental outcomes.

5.1. Water use efficiency

The efficiency of water usage in crop production does not appear seriously affected by the construction of an agrivoltaic system [73]. Researchers have assembled evidence of favorable interactions in the shading provided by PV modules in areas affected by water scarcity [56,57]. Marrou et al. [57] write that lettuces and cucumbers cover the soil very quickly under the panels. The soil water gradient and soil water potential (the difference between drainage and uptake) in these crops were found to be relatively lower under agrivoltaic systems, leading to an improved final harvest. Some authors posit that mitigation of the direct irradiation through shading decreases soil evaporation rates and thus enhances water saving [48]. Elamri et al. [91] remark that water use for irrigation can be reduced by 20% through tolerating a 10% reduction in plant yield or, instead, a slight extension of the harvesting cycle. The reason behind the reduction in crop yield is the effect of altered microclimatic conditions under the PV shades.

There are indications that the integration of PV onto farms can enhance efficiency because water inputs for cleaning solar panels and dust suppression can be reused for irrigation [88]. Other studies have reported changes relating to water collection below the modules [37,55,91]. For instance, it was perceived that efficiency improved with lower radiation intensity for citrus grown under shade conditions [27]. In a simulation model of maize production, Amaducci et al. [48] comment upon low soil evaporation and better average crop yield on a non-irrigated, agrivoltaic farm. Marrou et al. [55] tender that, under a PV array, crops' actual evapotranspiration decreases by 10–30% when accessible light is between 50 and 70% of full-sun exposure. This reduced evapotranspiration in turn improves water use efficiency [117]. Conversely, a potential issue posed by the shading of a PV installation is the altered water distribution under the panels [37,53,83], which can, in turn, alter the local water balance.

The water balance of dry, non-arable lands under PV shading has been observed to improve crop production. In one case, the rainwater harvested through a 105-kW agrivoltaic installation in the Central Arid Zone Research Institute of Jodhpur, India was reported to improve its land equivalent ratio (LER) by up to 1.62. LER is a concept which describes the relative land area required under sole cropping (monoculture) to produce the same yield as would occur with intercropping (polyculture) [59,60]. Agegnehu et al. [118] show that the total yield of wheat and beans increases linearly with LER, signaling a potential improvement in farm finances.

Adeh et al. [37] claim that the water use efficiency (WUE) of a solar-fully covered (SFC) area is 49.65 kg biomass/m^3 of water and that for a control area is 11.59 kg biomass/m^3 of water. That is, spaces underneath the PV modules are 328% more water efficient than gap or control areas, suggesting greatly enhanced plant biomass or grain production. This estimate holds for the summer growing season (May–August 2015). Since access to water is likely to recede in many regions based on predicted future climatic conditions, agrivoltaic farming should become more attractive and could help tackle the worldwide demand for food and fibre [83].

5.2. Land use efficiency

Advocates of agrivoltaics suggest that PV arrays should be configured as integrated building blocks in the landscape to complement existing ecological functions [26,53]. Large flat areas are desirable, since they lower installation and maintenance costs. Sites need to be well exposed to the sun, as well having access to electrical reticulation facilities [51]. Dual-use has the potential to improve land use efficiency and real estate value [73,77]. Agrivoltaic systems also should offer the means to help with land scarcity challenges in densely-populated countries, hilly regions and on small islands [89]. Yet, there are several challenges. To explain, installations can be harmful for crops if they provide too much shadow (more applicable for static configurations) and increased humidity due to decreased evaporation from shading which can introduce diseases and/or parasites [73]. The capital cost of PV systems and the disruption to farming operations caused by infrastructure are also possible constraints to wider uptake [29,55].

5.3. Income diversification

A well-designed agrivoltaic facility can solve several issues of land use competition while providing income and employment opportunities in rural areas [26,30,65,93,119] and in fragile ecosystems [60]. It produces a diversified income stream from sales of farm produce and electricity as joint products. Financially, the combined crop and energy output from an agrivoltaic system can enhance land productivity by up to 70% [11].

An integrated cropping and energy system should not require major change in farmers' business models. Instead, it could improve on-farm input use and, from wider perspectives, reduce public spending on energy and offset greenhouse gas emissions [73,92]. A study of the placement of agrivoltaic facilities in grape vineyards submits that dual-use could attract tourists through recreational day tours on food and energy farms, increasing income opportunities for vignerons [30]. Currently, many landowners have incorporated agri-tourism into their business model, as in fruit picking and wine tasting. The introduction of solar on a property could attract environmentally-oriented visitors.

Table 5
Shade-tolerant crops for potential use in agrivoltaic systems [25,29,89,111–116].

Major commercial shade-intolerant crops	Shade-tolerant-crops		
	Full shade	Moderate light	Low light
Cabbage, corn, cucumber, pumpkin, rice, tomato, turnip, and watermelon	Alfalfa, arugula, Asian greens, broccoli, cassava, chard, collard greens, hog peanuts, kale, kohlrabi, lettuce, mustard greens, parsley, scallions, sorrel, spinach, sweet potatoes, taro, and yam	Beans, carrots, cauliflower, coriander, green peppers, and onions	Mushroom

Despite such enthusiam, Amaducci et al. [48] advocate a complete (economic and environmental) sustainability assessment to ascertain a farm's readiness for diversified income options.

5.4. Financial issues

Discussion of financial issues associated with agrivoltaics involves consideration of revenue generation and accumulation of costs in the production of farm goods and electricity.

5.4.1. Revenue factors

Within any PV system, the level of revenue relates primarily to the density of the array. Dinesh and Pearce [29] indicate that income from cropping under both half and full density configurations is always lower than planting in full sun. Full density treatment requires optimization of the panels' configuration for electricity production. The distance between two strips is kept to 1.6 m, making an average of 50% of the incident radiation available to the crop. Half density treatment is obtained by removing one strip of a full density PV panel. The 3.2 m thus existing between two strips lets an average of 70% of incident radiation through to the crop. When the total revenue (derived from crop production and power generation) is considered, the outcome exceeds that forthcoming from the single land use scenario. This gain highlights the trade-off between crop yield and electricity generation.

An Indian contribution by Patel et al. [88] details the income from a 3 MW solar power installed on 7 ha of land also used for producing turmeric, ginger, bottle gourd, lady finger, and ivy gourd. The total solar power generated, as well as the auxiliary consumption (irrigation of the water pump, light, and an office computer for monitoring solar software) from 2012 to 2017 produced annual averages of 4,738,304 kWh and 6,515 kWh, respectively. The average net power supplied to the grid was 4,731,789 kWh. Attracting US$ 0.23 per kWh based on the Gujarat state solar policy, it delivered an average income of US$ 155, 473/ha/year. The total average income from all five crops was recorded as US$ 3,505/ha/year. Hence, 98% was obtained from selling the solar electricity generated. Malu et al. [30] quote total income of US$ 56, 954/ha/year for agrivoltaic grape production farm in Nashik, Maharashtra, India. The average solar power generated was 259,826 kWh/year. To calculate the revenue obtained, the authors used a receipt of US$ 0.08 per kWh, based on the average retail electricity price in India, resulting in a total of US$ 51,341/ha/year. Grape production provided an income of US$ 3,507/ha/year; total farm income was US$ 54, 848/ha/year. With a PV array installed across a vineyard, annual revenue is multiplied by over 15 times. In any year, 94% of the total income is obtained from the sale of the solar electricity [30]. If the price of electricity is increased to US$ 0.23 per kWh, the income from solar energy becomes comparable with the findings of Patel et al. [88].

In Michigan in the United States, electricity generation from a half density agrivoltaic farm was recorded at 390 kW/ha, while that of a full density one amounted to 720 kW/ha. Revenue from lettuce production from a half density, stilt-mounted array was reportedly US$ 17,000/ha/year and that from solar electricity at US$ 80,000/ha/year, the latter providing 82.5% of total farm income [29]. Clearly, the percentage contributed by energy would be higher with a full density configuration.

The levelized cost of electricity (LCOE) depicts the net present cost of electricity production over the lifetime of a power plant. Whereas the revenue and cost of *food* production are excluded in estimating the LCOE of agrivoltaics, the nominal price of the annual land lease is included [42]. From Germany, Schindele et al. [42] reported that the LCOE for agrivoltaic farms is 38% higher than that of an ordinary, ground-mounted solar PV installation, the respective values being US$ 0.0992/kWh and US$ 0.0721/kWh. Their study also noted that an agrivoltaic farm producing organic potatoes recorded a solar electricity yield of 1,284 kWh/year. Based on a rate of US$ 0.0992/kWh, the total income from solar energy was US$ 70,981/ha/year, while that from crops was US$ 12,809/ha/year. Given these figures, the energy component is 85% of the total income of the farm, consistent with the literature cited above. In another study in Michigan, the co-location of PV and rabbit farming was found to augment overall site revenue by 2.5–24% above the projected electricity revenue [120]. It should be noted that the percentage of income from the sale of solar energy from these agrivoltaic farms cannot be directly compared, since location influences the solar uptake of PV systems and, therefore, the total energy output.

The financial data generated in previous studies have been amalgamated in Table 6. The revenues have been normalized by converting the currencies presented in the publications to US$ based on the currency exchange rates of the year of publications. For example, the revenue mentioned in Schindele et al. [42] (published in 2020) was converted from € 59,329/ha/year to US$ 70,981 at a rate of 1.1964 effective during the period. As against purely revenue calculations, overall return on asset use (i.e. financial yield) has not been a major concern in the literature.

5.4.2. Cost factors

Looking first *beyond* agrivoltaics, the structural and maintenance costs of an on-farm integrated system appear higher than those of a conventional solar arrangement. A German study constructed a comparative scenario of the cost structure including capital expenditures for installation (CAPEX) as well as operational costs (OPEX) of the two types of installation. For agrivoltaics, cost-increasing factors (e.g. higher labor and planning expenses) outweigh the cost-reducing factors (e.g. no fencing required). The conclusion was that, although OPEX is similar, overall CAPEX is 30% higher for agrivoltaic systems [121]. Roy and Ghosh [80] address this initial investment by separating costs under two headings: the engineering procurement and commissioning (EPC) cost, and the land cost. The authors record an EPC cost of US$ 1.3×10^6 per MW combined with an approximate land cost of US$ 5,000 per acre, the latter varying from place to place.

The adoption of agrivoltaics thus implies substantial investment considering its long-term application. A life cycle analysis for a PV system with no dual-use has revealed a payback period of fewer than five years, even in low solar flux locations [122]. A 2021 study finds that the initial cost of an agrivoltaic system is returned in nine years while, in the case of ground- and roof-mounted solar, the periods are eight and six years, respectively [49]. Depending on the crop, another inquiry estimated the payback period of agrivoltaics in tomato, broccoli, and mushroom cropping to be between four and eight years [92]. Majumdar and Pasqualetti [38] state that approximately 50% of the investment in buying agricultural land could be returned within two years if a traditional farm were enhanced with agrivoltaic apparatus. Accordingly, successful adoption of PVs can result in potentially large economic benefits. However, few investigations interrogate the economics of integrating crop and energy production. Further comprehensive work on long-term financial outcomes is vital to the success of such systems.

Table 6
Financial data of several agrivoltaic farms.

References	Revenue from solar electricity (US$/ha/year)	Revenue from agricultural production (US$/ha/year)	Percentage of solar electricity revenue
Patel et al. [88]	155,473	3,505	98%
Malu et al. [30]	51,341	3,507	93.6%
Dinesh and Pearce [29]	80,000	17,000	82.5%
Schindele et al. [42]	70,981	12,809	85%

5.4.3. Economic feasibility

To determine the feasibility of an agrivoltaic system, a business model must ensure that the high CAPEX is justifiable. Consideration needs to be given to both the agricultural and power production. Relevant agricultural variables include types of crops farmed, cropping seasons, land preparation practices, harvest quantity in reference to farm size, agro-processing activities, post-harvest management, the local market for the products (or self-consumption), and likely market prices for selling outputs and purchasing non-farm inputs. For solar generation, key factors include the cost of the plant (for installation, and operations), the level of electricity production, and selling prices (surplus selling and self-consumption) [78]. Once the capital outlay is fully understood, additional data on crop yield changes, water use efficiency, ground cover effects on PV panel temperatures, and working and maintenance expenses are needed to assess the lifetime revenue and cost effects given different scenarios [123]. For instance, in arable farming, agrivoltaic systems with higher generating capacity are economically profitable. Smaller installations appear feasible in conjunction with permanent and special crops under favorable preconditions [124].

Another important factor is whether the business model will incorporate sustainable practices like self-consumption of the electricity generated. Such energy is most valuable when self-consumed since this pathway directly reduces external power purchases. One study shows that, in the first year of operation, 41% or 101.2 MWh of the output of an agrivoltaic system was consumed locally by the farming community [45]. A report by Germany's Fraunhofer Institute for Solar Energy Systems (Fraunhofer ISE) states that, at a commercial electricity price of between US$ 0.1674/kWh and US$ 0.1914/kWh and a LCOE around US $ 0.1076/kWh, savings between US$ 0.0598/kWh and US$ 0.0837/kWh can be realized [124]. Usually, agricultural activities are concentrated during those months with higher solar radiation and, hence, higher electricity production and usage. During this time, it is expected that the self-consumption rate is increased, easing mismatch and congestion in the grid and raising farm revenues due to the difference between selling and buying prices of electricity [50].

An important external factor bearing on the economic feasibility of an agrivoltaic system is any relevant public policy. For example, in Japan, the FiT system, a country-wide support for renewable energy (RE) electricity deployment, was introduced in July 2012. It enables recovery of investment in RE electricity, through fixing the energy price for 10–20 years [95]. In Germany, between 2004 and 2010, ground-mounted PV plants were assisted via the Renewable Energy Act (EEG), also involving a price-based FiT [42]. The revenue generated by a PV farm is highly dependent on shifting commodity markets. Businesses can negotiate electricity prices through a PPA. Based on an American study of 232 contracts, the average utility-scale PPAs range from US$ 0.02/kWh to US$ 0.04/kWh [125]. The Agua Caliente solar project, the largest PV power plant in Arizona, sells it entire output under a 25-year PPA to a California-based utility company, Pacific Gas and Electric [39]. These policy mechanisms could similarly be applied to agrivoltaic businesses to help reduce risk and secure electricity sales for long-term economic gain.

5.5. Social benefits

Significant social benefits from agrivoltaic farms arise from new jobs, community income and potential tax revenues [92]. As one illustration, employment opportunities were created for 215 people from four villages in the Aravali foothills of north Gujarat state in India [88]. Micro-entrepreneurship (mostly among women) was encouraged as market networks for processed food were expanded. All these factors combine to reduce migration of the rural community to urban areas. In term of potential revenue, government receipts could increase through taxation from such enterprises to promote greater social welfare [71, 92]. A sector-wise social impact scoping (SSIS) has been conducted to explore the detailed impact of this emerging integrated technology [95].

This method can be taken further to examine the appeal of agrivoltaics per medium of their potential and realized social impacts [92]. Wide acceptance offers a way to improve energy security, as demonstrated in a Japanese project by Irie et al. [95]. Long-term benefits of agrivoltaic initiatives (as in mitigating climate change), not always perceived by the public, should be made more familiar through workshops and social awareness [51]. The efficacy of arrays should not be judged by any immediate loss of potentially productive farming land; rather, their overall contribution and impact are the main parameters [73]. Malu et al. [30] reveal that, if PV panels were installed at a density of 1,344/ha, an entire Indian grape farming region of about 34,000 ha could provide up to 16,000 GWh of solar power per annum, sufficient to provide electricity to 15 million people with almost no disruption to grape production.

5.6. Environmental outcomes

The environmental outcomes of an agrivoltaic system are subject to local peculiarities of the landscape, native ecology, types of crops and the geographical location of the facility. An account by Leon and Ishihara [71] of tomato cultivation, carried out in a PV greenhouse, argues that CO_2 emission is lowered by up to 12% on agrivoltaic facilities compared with traditional field practice. These authors recorded the total LC$-CO_2$ emissions in a conventional system as 232 t/ha, and in the agrivoltaic setting at 205 t/ha. This reduction could have ensued from the use of PV-generated electricity for irrigation, otherwise accomplished by burning fossil fuels. Conventional PV installations commonly leave land barren under the panels. Interestingly, Amaducci et al. [48] have mentioned an increase in the physical size of maize crops under the shade of a PV system as against production under full sun, both subject to drought stress. The inquiry implied that the agrivoltaics improve plant resilience to climate change [48]. They consequentially have potential to be an important component of climate-smart agriculture [71, 88].

Large-scale (over 100 kW) solar farms have both short- and long-term impacts on land, plants, animal life, and geo-hydrological resources which affect climate change, human health and well-being [126]. Scognamiglio [51] discovered that the influence in terms of land transformation and use becomes higher with a rise in the size and number of PV systems, leading to significant concerns about landscape conservation and possible losses of ecological balance. Specifically, the key issues of environmental stress include fauna and flora management, fire risks, visual impact, soil, water and dust management, waste treatment and resource use [72]. Like conventional PV farms, the lifetime of an agrivoltaic facility is 25 years [49]. In decommissioning, although the steel structures can be fully recycled, the expired PV modules will generate tonnes of e-waste [73]. Additionally, the toxic materials associated with panels are a worry if not handled and disposed of properly, because they can threaten the environment and public health [127].

6. Future research prospects

A vibrant and expanding literature around agrivoltaics encourages future research. Threads gathered from the foregoing review concern economic and financial issues, appropriate crop selection, PV infrastructure configuration, dealing with dust, and openings in social inquiry.

6.1. Economic and financial issues

As indicated, limited study has attended the economic and financial implications of combining farming and energy production. Financial viability has been assessed only for a few selected crops. Most analysis has concentrated on short-term outcomes, with little resort to discounted cash flow (DCF) analysis as a normal precursor to investment decisions. Just like a hydro-electric power station, an agrivoltaic system requires a large capital outlay, has a long-term investment horizon and involves deprecation and eventual disposal of equipment with little to no financial reversion presently possible. The degradation of PV due to exposure over time and the resulting decrease in energy generation are important allied considerations. Additionally, a framework to evaluate financial performance based on the configuration of each individual agrivoltaic farm is required to ensure that both agriculture and energy outputs are optimised. The capital investment to construct the system could be paid back within a time frame of fewer than five years [38,92,122]. To this end, it is essential to identify the solar dynamics of the project to organize its design and configuration for maximum power [128]. To optimise economic output from agricultural production, comprehensive analysis and modelling of long-term financial outcomes in a range of (crop and livestock) applications is essential. Other factors (as next discussed) which impact the agricultural outputs of an agrivoltaic farm will almost certainly influence the layout and thereby the capital cost.

6.2. Selection of suitable crops

The microclimatic condition of PV systems is a significant and complex adjunct to the effectiveness of agricultural practices. Despite their dependence on various situational factors, shade-tolerant plants offer the most viable options. Matters of note include irradiation capture efficiency, the light saturation point, damage from ultraviolet irradiation, the evaporation rate, and crop temperature. Limited research has tapped the relevant interrelationships. To facilitate the selection of crops capable of adapting, there is a need for workable modelling of the microclimate beneath the PV array under different orientations and positioning. Moreover, the best conditions for plant growth in terms of duration and timing of shading periods demand attention. Much of this proposed inquiry will be empirical and idiographic, based on the expansive geography of agriculture around the world. Our review further uncovers a lack of in-depth research into the agronomic aspects of an agrivoltaic system. To obtain maximum benefits, factors aside from those shown in Table 1 should be investigated through simulation and field experimentation.

6.3. PV infrastructure configuration

Appropriate PV infrastructure is a central aspect which requires further improvisation for agrivoltaic applications. Careful, site-specific design should be adopted to erect panel structures. One consideration is the avoidance of reflection from valley bottom installations to nearby hillsides. Another is to specify lightweight materials to minimize wind stress on the overall structure. Small panels are desirable to lessen shading on the ground. Research focus should be on developing more efficient bifacial PV panels capable of allowing the same amount of light to enter from both sides. A useful option would be the greater availability of semi-transparent PV modules. This technology has already been widely applied in greenhouse facilities [129]. A recent study presented a computational, digital-twin framework to track and optimise the flow of solar power through agrivoltaic systems, a move particularly useful for bifacial panelling [130]. An advanced micro-controlled stepper motor could be adopted automatically to adjust the tilt of solar panels and optimally to track the sun's movement. As evident throughout this review, PV installation alters microclimatic conditions for crop growth as well as hindering accessibility for agricultural operations. Therefore, a critical area of study is to evaluate the minimum requirement for ground clearance of panels to lessen their influence on a farm's microclimate, as well as for safe use of machinery. For agrivoltaic facilities on a hillside, soil erosion can be mitigated by the planting of hedges or perennial biomass crops between the stilts.

6.4. Dust accumulation

Intensive work is necessary to resolve technical and economic impediments to the glass-cleaning techniques currently available. Future initiatives could explore cost-effective and efficient self-cleaning glass coating and the viability of energy-efficient robots for panel maintenance. This line of inquiry would offer attractive external economies beyond primary industry since it could apply to other domestic and commercial PV applications.

6.5. Social research

Significant to the adoption of a given technology are public perception and attitudes towards its utility and benefit. A social license to operate is vital for wider implementation in that land use issues are characteristically related to communities of farmers and pastoralists. There can be a lack of social acceptance at the local level, particularly when potential loss and/or immediate consequences are feared [131]. While dual land use seems to deliver greater profits, landholders might be unwilling to adopt agrivoltaics because of the supposed constraints on future farming activities (i.e. loss of flexibility) and the risk of decline in crop quality. More research is required to assess farmers' perceptions of PV farms and tentative solutions to possible conflicts. The safety concerns of agricultural field workers under a PV system have also been overlooked in previous research. Comprehensive investigations are needed to devise standard operating procedures (SOP) to ensure employees' welfare.

7. Conclusions

The competition for land in recent times has been exacerbated by human demographic and economic expansion. Around 12% of the globe's land surface is used for crop production. With limited available land, negative effects include pressures on biodiversity and rising food prices. However, on the positive side, people are challenged to innovate to increase productive efficiency. As such, this systematic review has uncovered an extensive literature developed over the last 10 years concerning PV systems, a technology which introduces dual land use through agricultural and solar energy production.

Our investigation focused on factors which govern agrivoltaic production, as well as issues in its implementation and the benefits of the approach. Participating farmers are shown to have an opportunity to diversify their income stream. Integrated farming and energy production can create positive economic, social, and environmental externalities and provide feasible and realistic solutions to the growing competition for land resources. However, challenges arise from both components of the agrivoltaic system. In terms of agricultural output, the key issues are the impacts on crop growth of shading, and microclimatic conditions under the array. Even moderate shading can potentially lead to severe loss in harvest and quality. For solar power generation, the main points include reduced output due to dust accumulation from agricultural activities and potential damage to panels from livestock interference. Along with the necessary capital expenditure, these recognized problems could suggest why farmers and pastoralists might be slow to adopt this technology, thus retarding its widespread application.

Several priority areas exist for future research on agrivoltaics. First, successful implementation will require a framework for evaluating financial performance. It will allow the best system to be designed to maximise income for farmers and pastoralists. Second, a comprehensive assessment of potential crops and grazing enterprize using agrivoltaics in different localities and circumstances around the world needs to be compiled. This work should also consider methods or technologies to eliminate dust accumulation. Third, we seek a better understanding of how landholders, farmers and other key stakeholders perceive constraints to the wider adoption of agrivoltaics. Finally, viable recommendations for policy-makers should be developed, so that appropriate incentive and regulatory initiatives can be used to enlarge agrivoltaic applications with the aims of increasing farm income and reducing greenhouse gas emissions from the burning of fossil fuels.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.rser.2022.112351.

Supplementary Material

An MS Excel spreadsheet contains a summary of the systematic literature review.

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