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Circularity and landscape experience of agrivoltaics: A systematic review of literature and built systems

I. Sirnik [a,*], J. Sluijsmans [b], D. Oudes [a], S. Stremke [a]

[a] Wageningen University & Research, Environmental Sciences Group, Landscape Architecture Chair Group, PO Box 47, 6700 AA, Wageningen, the Netherlands
[b] Wageningen Environmental Research, Team Regional development & Spatial Use, Droevendaalsesteeg 3, 6708PB, Wageningen, the Netherlands

A R T I C L E I N F O

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A B S T R A C T

Reducing greenhouse gas emissions is a global challenge. Innovative agrivoltaic systems that combine agriculture and solar energy production is one set of the solutions to reduce these emissions. While circularity is a pressing issue in agriculture and landscape experience in solar energy production, these issues have received little attention in relationship to agrivoltaics. This study examines aspects of circularity and landscape experience in built agrivoltaic projects reported in scientific literature and recently constructed agrivoltaic projects in the Netherlands. Understanding circularity and landscape experience in agrivoltaics contributes to enabling agriculture transitions and increasing public acceptance.

Peer-reviewed literature was used to examine which aspects of circularity and landscape experience were addressed in 16 international agrivoltaics cases. Critical performance indicators were used for circularity and spatial properties for landscape experience. Furthermore, a systematic analysis of ten Dutch agrivoltaic cases was conducted by examining their visibility, accessibility, patch configuration and agricultural land-use beneath the agrivoltaic system.

The results show that *contribution to regional economy and vitality of the rural area* is the most frequently mentioned circularity indicator, which is found in 82% of the international cases and 60% of the Dutch cases. Low visibility and low accessibility of agrivoltaic systems were found in the majority of Dutch agrivoltaic cases. Limited attention to landscape experience was found in the studied literature. This study provides valuable recommendations for research, farmers and policy makers for advancing transitions towards circular agrivoltaic power plants that pay more attention to landscape experience.

1. Introduction

Climate change has become a severe threat to humanity. If concentrations of greenhouse gases in the atmosphere continue to rise, the risks facing humanity and the Earth in general will increase significantly [1]. Many countries have agreed to limit global warming to 1.5 °C compared to pre-industrial levels [2]. Consequently, the Dutch government aims to reduce greenhouse gas emissions in the Netherlands by 55% compared to 1990 [3]. In addition to climate change, global population growth also increases the demand for energy and food [3]. One of the solutions to mitigate the challenges posed by climate change and food security is agrivoltaics [4].

'Agrivoltaics' refers to the combination of electricity production, using photovoltaics (PV) and agriculture on the same area of land [5]. While monofunctional solar power plants (SPP) are often criticised for creating land use competition with food production [6], agrivoltaics is considered to be multifunctional [7]. Globally, agrivoltaics have grown exponentially in terms of installed capacity in recent years, reaching 2800 MW in 2020 from an initial 5 MW in 2012 [8]. Multiple classifications for agrivoltaics have emerged in recent years. Willocks et al. [9] have proposed that the way land is used beneath the PV arrays can be used as a defining parameter for the classification of agrivoltaics. Accordingly, they distinguish between 'rangevoltaics' (PV arrays with livestock beneath) and 'agrovoltaics' (PV arrays with crops beneath). Another classification has been proposed by Sekiyama & Nagashima [10], dividing agrivoltaics into three classes: (1) conventional

Abbreviations: AVPP, agrivoltaic power plant; CPICA, critical performance indicators of circular agriculture; PV, photovoltaic; SPP, solar power plant; TRL, technology readiness level.

* Corresponding author.
E-mail address: igor.sirnik@wur.nl (I. Sirnik).

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stilt-mounted systems, (2) PV arrays placed between the agricultural rows and (3) greenhouses with PV arrays placed on the roofs. Another classification is the Deutsches Institut für Normung standard with number DIN SPEC 91434:2021–05 [11]. Classes are first defined according to the type of agricultural production and, second, to energy production. This research combines the definitions for agrivoltaics provided by the Deutsches Institut für Normung standard [11] and Willockx et al. [9]. The agrivoltaic systems considered in this study are installations that consist of PV arrays installed over crops designated for food production. Agrivoltaics with livestock beneath are included if the agrivoltaic power plant (AVPP) is designated for grazing with economic revenue. In this research, 'agrivoltaic system' is defined as the technical hardware installation with PV arrays and an AVPP as the ensemble of agrivoltaic system and the land underneath and in-between PV arrays.

The primary focus of the growing body of literature on agrivoltaics is on optimising the synergy between agricultural yield and electricity production [12]. At the same time, societal considerations on circularity are starting to influence policy and research agendas for agriculture [13], and issues related to landscape change and experience those agendas of SPP [14]. However, in the field of agrivoltaics – the combination of agriculture and solar power plants (Fig. 1) – little scientific attention is thus far being paid to circularity and landscape experience. Both circularity and landscape experience have the potential to become significant factors in the public acceptance of agrivoltaics and, consequently, the timely implementation of local projects.

With regard to circularity, circularity and circular economy are concepts that lead towards sustainable systems. Circular economy aims to generate economic and social prosperity and protect the environment by preventing pollution and facilitating sustainable development [15]. There are 114 definitions for 'circular economy' [16]; the concept is both vague and wide-reaching [17]. The circularity of food production systems is commonly denoted as circular agriculture [15]. 'Circular agriculture' is used for analysis in this research. It assists in ensuring four goals: (1) economic sustainability, (2) the conservation of biodiversity, (3) environmental sustainability and (4) social sustainability (i.e. providing food security, eradicating poverty and improving health and living conditions) [15]. These four goals form part of the ten indicators of circular agriculture (CPICA) introduced by Dagevos & de Lauwere that are used in this study [18].

With regard to landscape experience, AVPPs, similarly to 'conventional' SPPs, change the landscape, and this is often met with low public acceptance [19]. A 'landscape' is defined as: "*an area, as perceived by people, whose character is the result of the action and interaction of natural and/or human factors*." [20]. The implementation of agrivoltaics affects how users (e.g. inhabitants, farmers, tourists) experience a landscape. Different from conventional SPPs, agrivoltaic systems often use higher

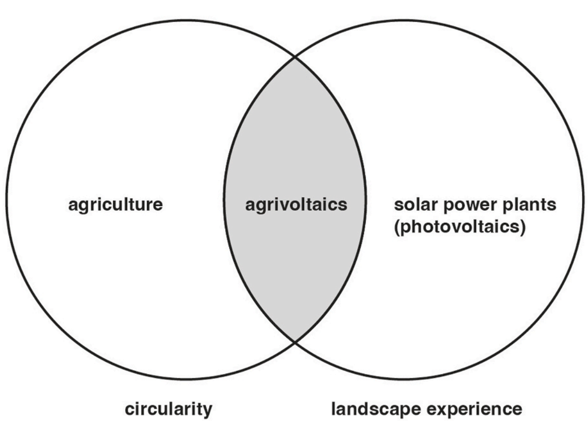

Fig. 1. The link between agriculture and circularity, solar power plants and landscape experience, as well as between circularity/landscape experience and agrivoltaics.

elevated structures to allow access for agricultural machinery. Although the land use combination of agriculture and PV may be favourable in terms of the public acceptance of agrivoltaics, these elevated and often permanent structures may affect landscape experience and, consequently, detract public acceptance [21]. Landscape change, the accompanying landscape experiences and low public acceptance may restrain the application of agrivoltaics [5]. Several studies have investigated agrivoltaics and its effects on the environment and landscape. Gomez-Casanovas et al. [22] studied the benefits of agrivoltaics for mitigating climate change. Other papers investigated the shading properties of agrivoltaics on crop production (for example [23]) and rain water harvesting in agrivoltaic systems [24]. Mamun et al. [4] investigated microclimate conditions underneath PV arrays. However, there is an overall lack of studies that examine the landscape experience of agrivoltaics (for example [21]).

Public acceptance of agrivoltaics can be influenced by their circularity and effects on landscape experience, but these factors have hardly been studied before. This research therefore aims to explore how circularity and landscape experience are addressed in agrivoltaics, supported by an overview of agrivoltaic cases from around the world and a more detailed study of cases in the Netherlands. This research answers two research questions: (1) Which aspects of circularity and landscape experience are addressed in the international literature on agrivoltaics? (2) What are the key technical properties and aspects of circularity of built agrivoltaic systems in the Netherlands, and how are landscape users' experiences addressed?

2. Methods and materials

A systematic review was used to identify and analyse literature on circularity and landscape experience of agrivoltaic cases [25]. This methodology limits research bias [26], presumes a protocol-driven approach to mark out potential investigative opportunities [25] and is explicit and reproducible [27]. Peer-reviewed literature and conference proceedings – both peer-reviewed and not – were used to study international cases. A more detailed insight in circularity and landscape experience of agrivoltaic cases was examined by a case study in the Netherlands [28]. The Netherlands was selected due to the recent rapid implementation of agrivoltaics, the availability of detailed national datasets, such as landscape openness and attractiveness, and the opportunity to study the cases in the field during the COVID-19 pandemic.

2.1. *Literature review of circularity and landscape experience of agrivoltaics*

Two databases were used to search for peer-reviewed literature and conference proceedings: Scopus and Web of Science. In the search query, specific keywords were used to identify relevant literature. The specific keywords were distributed into three clusters according to the topic of the research: 'Agrivoltaics', 'Landscape experience' and 'Circularity' (Fig. 2). The search was conducted for publication title, abstract and keywords. To focus our research on circularity and landscape experience, two search queries were used for each database. The first search query contained the keywords from clusters Landscape experience and Agrivoltaics, and the second query contained the keywords from the clusters Agrivoltaics and Circularity (Fig. 2). The next literature selection was subject to the following conditions: (1) the agrivoltaic case had been built, (2) the publication had been peer-reviewed or was a conference proceedings – either peer reviewed or not, (3) the publication was in English and (4) was published before January 31, 2022.

The identified international agrivoltaic cases were situated exclusively in the Northern Hemisphere (Fig. 3). The highest number of agrivoltaic cases was reported for North America (7), followed by Asia (6) and Europe (3). In South America, Africa and Australia, zero agrivoltaic cases were found in the studied literature.

The absence of literature on agrivoltaic cases in the Netherlands in

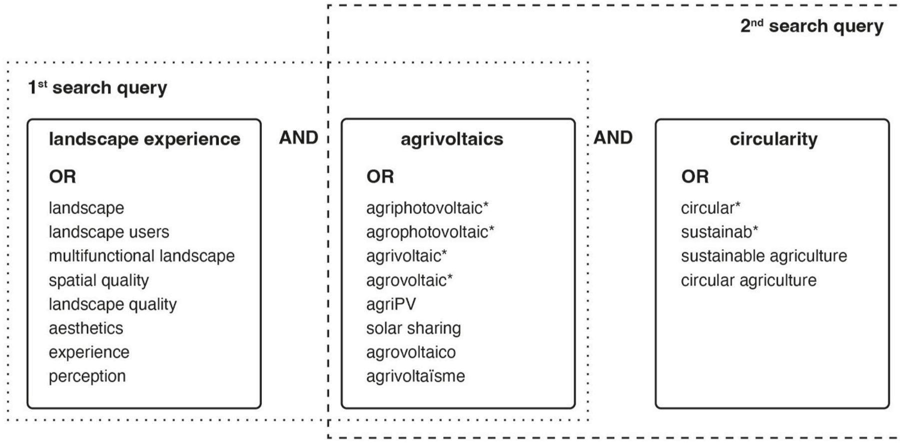

Fig. 2. Keywords used for the two search queries in Web of Science and Scopus.

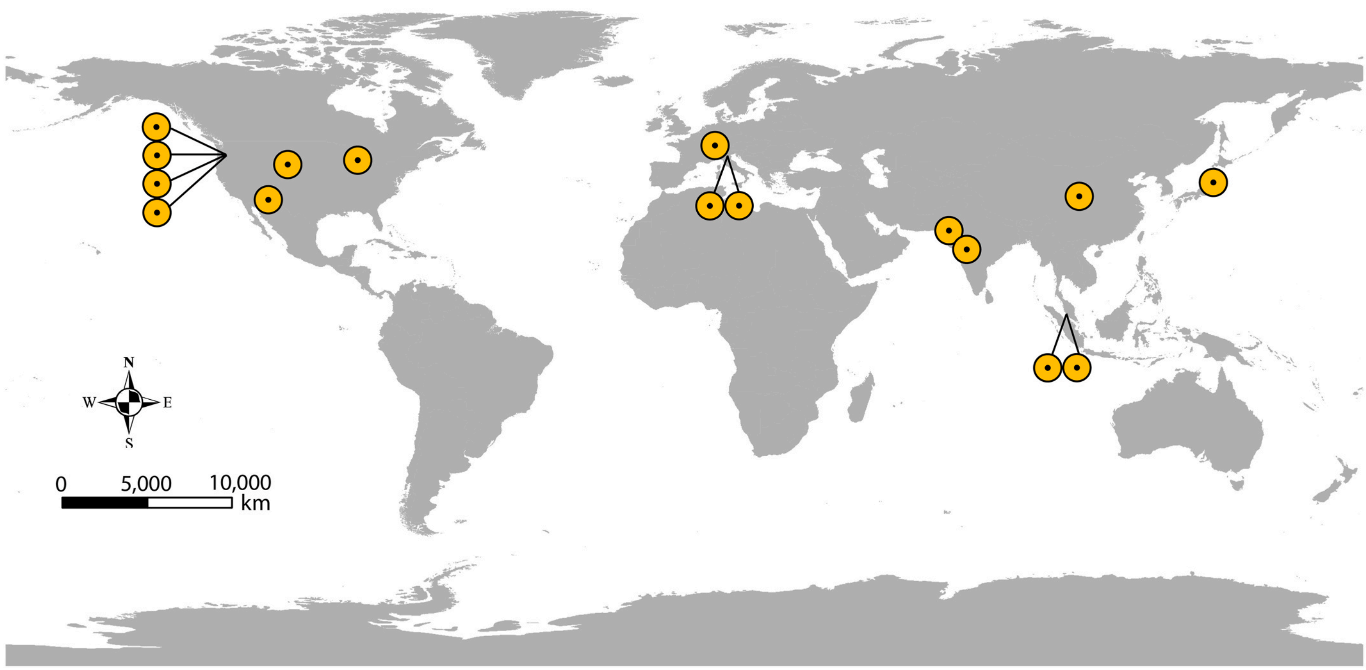

Fig. 3. Locations of international agrivoltaic cases studied in this research, depicted with orange circles. Source of Basemap: Efrainmaps [29].

both databases led to a search for grey literature of Dutch cases. An initial search was performed for two magazines: Solar Magazine [30] and PV Magazine [31]. Both magazines focus on renewable energy solutions worldwide and on solar energy projects in the Netherlands. The grey literature used for the research of Dutch agrivoltaic cases is listed in the Appendix. Further research was conducted using Google search engine [32], using the key term 'The Netherlands' with the combination with the keywords listed in the Agrivoltaic cluster (Fig. 2). The grey literature sources are clustered for each Dutch agrivoltaic case and are provided in the Appendix.

2.2. Introduction to the agrivoltaic cases in the Netherlands

Dutch agrivoltaic cases (Fig. 4) were selected according to the following criteria: (1) the agrivoltaic case should be described at least in one publication, (2) it should be built and characterised with a technology readiness level classification (TRL) of at least four, and (3) it should be in line with the agrivoltaics definition presented earlier in this research. The minimum TRL of four was employed to identify agrivoltaic cases of which the landscape integration and experience could be examined. TRL four refers to a built "small scale prototype" [33]. The agrivoltaic cases were named according to the toponym of the nearby urban settlement.

Nine out of ten agrivoltaic systems were located on agricultural land; only Etten-Leur was situated on non-agricultural land, adjacent to the A58 motorway (Fig. 5).

Dutch agrivoltaic cases showed high variability in terms of technical details (Table 1). For each agrivoltaic case, data pertaining to the location, year of construction, surface, TRL, height, patch type and orientation of the PV arrays was collected. Location and year of construction were retrieved from the literature. If the surface area of the AVPP was not found in the literature, it was calculated by means of GIS tools, using satellite or photogrammetry imagery. The TRL was assessed according to the completed project level [33]. If the height of the agrivoltaic structure was not reported in the literature, it was determined through field work and available imagery. The orientation of the PV arrays was retrieved from literature and available imagery. The patch type was assessed using spatial analysis [38]. Additional data on

Fig. 4. Map of the Netherlands with Dutch agrivoltaic cases, depicted with yellow circles. Source of the base map: PDOK [34].

Fig. 5. Imagery of studied Dutch agrivoltaic cases. Scale of the images varies. Images were retrieved from various sources [34–37].

accessibility of the Dutch cases was retrieved by short interviews with agrivoltaics farmers and developers.

Table 1 shows that all agrivoltaic cases were built after 2019. The surface area of the AVPPs ranges from 0.02 ha (Boekel) up to 9.50 ha (Lochem). The average TRL is 6.1, however, only two cases reach TRL 9. The height of the agrivoltaic systems varies from 1 m (Stadskanaal) to 3 m (Babberich, Wadenoijen and Etten-Leur). Half of the agrivoltaic cases uses an east to west orientation, while the other half are oriented towards the south. A high variability in landscape openness levels was identified. Openness is defined as the amount of space perceivable to the landscape user [41]. The openness classification used in this research was adopted from Weitkamp et al. [39]. The landscape of the Babberich case demonstrated the lowest level of openness (0.20 ha). Haren, Stadskanaal and Sint-Oedenrode present the only agrivoltaic cases in landscapes with openness levels above the average value of openness (60.2 ha). The plots hosting the agrivoltaic systems showed relatively high attractiveness. The classification for attractiveness was adopted from Lankhorst et al. [40]. The average attractiveness value of the landscapes with agrivoltaic cases is 7.1, with the highest value for attractiveness being 10 and the lowest 0. The attractiveness values of the host landscapes showed relatively low variability, ranging from 6.0 (Sint-Oedenrode) to 9.0 (Broekhuizen) (Table 1).

Further field research reveiled that two cases changed from agricultural to non-agricultural land uses beneath the PV arrays. In Etten-Leur, sheep continued to graze, but not for economic production. In Haren, crops were ceased to be grown beneath the PV arrays, but were cultivated between them. Both cases were kept in the study because their description in the studied literature matches the definition of AVPP as defined in the introduction.

2.3. *Analytical framework*

The study of landscape experience and circularity in the agrivoltaic cases required a comprehensive analytical framework. The framework was developed deductively, using literature, and is divided into two parts: circularity and landscape experience.

2.3.1. *Circularity*

This research makes use of the critical performance indicators of circular agriculture (CPICA) to define aspects of circular agriculture in agrivoltaic cases [18]. The CPICA are: (1) *soil preservation*; (2) *closing nutrient cycles*; (3) *reduction of greenhouse gases and ammonia*; (4) *sustainable energy*; (5) *maintenance of biodiversity*; (6) *nature conservation*; (7) *animal welfare*; (8) *animal health*; (9) *using residual flows from the food industry*; and (10) *contribution to regional economy and vitality of the rural area*. The CPICA have been used in several studies, such as a proposal for circular agriculture towards the year 2030 [17] and in a study about circular business models and circular agriculture in agricultural practices [18]. In this research, we omitted the indicator *sustainable energy* (4) because agrivoltaics by definition provide sustainable energy [42]. The level of circularity for each agrivoltaic case is estimated through the number of the identified CPICA.

2.3.2. *Landscape experience*

In this research, four spatial properties of agrivoltaic cases were studied to identify aspects of landscape experience: accessibility, visibility, patch configuration and agricultural land use beneath PV arrays. Accessibility, visibility and patch configuration are the spatial properties adopted from a similar study that addresses landscape experience of SPPs [38]. Land use beneath PV arrays was chosen due its impact on landscape experience [43].

2.3.2.1. Accessibility. The accessibility of the agrivoltaic cases affects the landscape experience of users. This part of the spatial analysis was inspired by the study of Oudes & Stremke [38], where the authors analysed the accessibility of SPP cases. Their method was translated to agrivoltaic cases, and the following options for accessibility of agrivoltaic cases were used: accessible, open upon request and inaccessible.

2.3.2.2. Visibility. Visibility describes whether a landscape user can observe an AVPP from a certain location [44,45]. Visibility can be modified by adding landscape elements [46,47]. In this research, we distinguished between three levels: visible, partly visible and invisible [45]. In our spatial analysis of agrivoltaic cases, the location of the landscape user was defined with a buffer of 10 m around the perimeter of the AVPP. The 10 m buffer was defined to consistently study visibility, independent of the presence of infrastructural elements such as roads or walking paths.

2.3.2.3. Patch configuration. The shape of the patch occupied by PV arrays affects the landscape experience [48]. The relationship between the original plot and the agrivoltaic system's PV modules leads to different spatial configurations, which are identified as 'patch types'. Spatial analysis of patch type was conducted on SPPs in a study by Oudes

Table 1
Key technical and spatial features of the Dutch agrivoltaic cases. TRL varies between 1 and 10, where 1 stands for 'Basic research, principles postulated and observed but no experimental proof available' and 10 for 'Full commercial application, technology available for consumers'. In the orientation category, E stands for east, S stands for south and W stands for west. Openness classification was adopted from Weitkamp et al. [39] and attractiveness from Lankhorst et al. [40].

Name of agrivoltaic case	Generaldata		Technical details				Host landscape properties	
	Location of agrivoltaic case	Year of construction	Area of agrivoltaics system (ha)	TRL	Height of structure (m)	Orientation	Open-ness (ha)	Attractiveness
Babberich	51°53′57.35″N 6° 7′33.95″E	2020	3.20	8	3	E-W	0.2	7.7
Wadenoijen	51°52′21.76″N 5°21′6.76″E	2021	1.20	6	3	E-W	49.0	7.3
Broekhuizen	51°29′15.03″N 6° 9′17.87″E	2020	0.11	5	2.5	S	16.5	7.8
Sint-Oedenrode	51°34′50.83″N 5°25′36.56″E	2020	0.13	6	2.1	E-W	205.3	6.0
Boekel	51°36′40.52″N 5°42′3.80″E	2020	0.04	6	2.1	S	13.6	7.0
Haren	53°10′55.06″N 6°37′30.68″E	2021	2	9	1.80	S	79.3	7.2
Someren	51°26′33.83″N 5°39′58.05″E	2021	0.03	4	2.5	E-W	48.4	6.4
Stadskanaal	52°59′40.60″N 7° 2′57.48″E	2021	0.14	4	1	E-W	143.7	7.3
Lochem	52° 9′54.60″N 6°23′27.84″E	2021	9.50	4	2.5	S	33.6	7.1
Etten-Leur	51°33′44.00″N 4°39′26.18″E	2020	3	9	3	S	12.2	7.4

& Stremke [38]. The same method and classifications were translated into a spatial analysis of AVPP patch types in this research. Three types of patch configurations were classified in Dutch agrivoltaic cases: responsive, irresponsive and split. The 'responsive type' PV patch mimics the shape of the plot in how the original parcellation structure remains recognisable. The coverage of the original plot is relatively high (65–90%). 'Irresponsive patch type' is self-referential and results in space being left over within the plot. The coverage of the original plot is between 50 and 75%. The 'split type' is characterised by the matching shape of the PV patch to the plot; the coverage of the original plot is low (25–50%).

2.3.2.4. Agricultural land use underneath PV arrays. The selection of crops in the agricultural landscape affects landscape experience [43]. Consequently, the landscape experience of AVPPs is affected by the kind of agricultural land used beneath the PV arrays. Agricultural land use was categorized using ten agricultural sectors, in this research (1) arable farming, (2) bulb growing, (3) tree nursery, (4) fruit growing, (5) greenhouse horticulture, (6) outdoor vegetable production, (7) dairy farming, (8) poultry farming, (9) pig farming and (10) other livestock farming [49,50].

3. Results and discussion

The results are presented and discussed in four parts. The first two sections (3.1 and 3.2) focus on the findings with respect to the international agrivoltaic cases. The third and fourth section (3.3 and 3.4) focus on the agrivoltaic cases in the Netherlands.

3.1. Circularity in international agrivoltaic cases

From the nine studied critical performance indicators for circularity, seven were found in the international literature on agrivoltaic cases (Fig. 6). The CPICA *contribution to regional economy and vitality of the rural area* was identified in 13 out of a total of 16 agrivoltaic cases. *Animal welfare* was found in three agrivoltaic cases, and the remaining CPICA were identified in one or zero agrivoltaic cases.

The findings show that *contribution to regional economies and vitality of rural areas* presents the most significant component of circularity in international agrivoltaic cases. Several agrivoltaic cases illustrated the

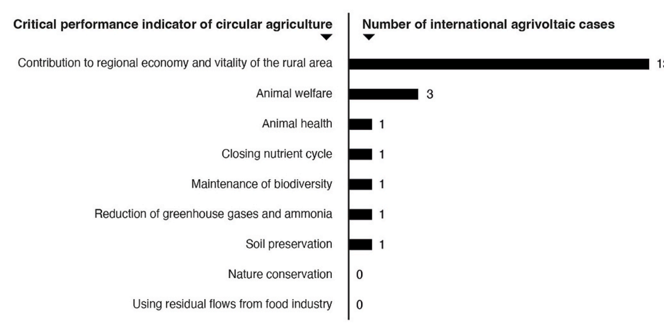

Fig. 6. Number of international agrivoltaic cases with identified critical performance indicators of circular agriculture.

contribution to the regional economy by showing the economic benefits of dual land use, producing both food and electricity on the same area [51]. Agrivoltaic impact on crop yield was reported as being beneficial in most international agrivoltaic cases compared to the cropland without PV arrays. A study on agrivoltaics in Oregon, in the United States of America (US), reported a higher yield of lettuce on land with agrivoltaics than land without [52]. The results are in line with a study from Arizona (US), which reported total fruit production rates twice as high underneath PV arrays compared to open fields [53]. The yield increase was also noticed in the livestock sector. The study by Andrew et al. [54] demonstrated higher growth increase in weaned Polypay lambs underneath agrivoltaic systems compared to livestock living in open pastures. However, several international agrivoltaic cases also reported lower crop yield underneath PV arrays compared to open fields. For example, pasture yield in one agrivoltaic case in Oregon produced 38% lower herbage underneath PV arrays [54]. Another study showed decreased yield of rice crop in Japan, caused by a decrease in the number of panicles [55]. The authors argued that grain yield was positively correlated with the amount of solar radiation.

Another way in which agrivoltaics contributes to CPICA *contribution to regional economy and vitality of the rural area* is by increasing food security [56]. Food security is dependent on crop yield stability. Agrivoltaics have the potential to increase and stabilise yield by reducing evapotranspiration and soil temperature [57]. Additionally, the literature demonstrated that agrivoltaics decrease the risk of food shortage and market shocks, particularly for non-irrigated crops [57]. Crop stability influences the economy as a whole and is consequentially beneficial for regional and local economies. One study in India demonstrated a higher 'land equivalent ratio' efficiency of land with agrivoltaics compared to land without [51]. These findings are in line with the study by Andrew et al. [54], which demonstrated an increased land equivalent ratio of up to 1.81 for pasture production and 2.04 for spring lamb production.

Agrivoltaics positively affect *animal welfare* and *animal health* by lowering levels of livestock heat stress. It was reported that livestock spent their time predominantly in the shade underneath PV panes [58]. A study by Andrew et al. [54] showed that lambs completed up to 96% of ruminating and idling activities underneath PV arrays. The same study demonstrated lower heat stress among livestock grazing underneath PV arrays, stating that PV arrays provided "*pleasant temperatures for livestock*" [56]. Andrew et al. [54] suggested that agrivoltaics affect livestock by limiting the body tempearture of the animals .

Agrivoltaics has a demonstrable positive impact on soil properties in the international cases, contributing to *closing nutrient cycle* and *soil preservation*. In western India, a case study reported the reduced evaporation underneath the PV arrays reduced soil salinity, possibly due to reduced evapotranspiration [56]. As a result, the soil beneath the PV arrays became favourable for growing tomatoes. The same study demonstrated that bacteria growth underneath PV arrays directly helped to enhance soil fertility by increasing carbon and nitrogen concentrations.

Maintenance of biodiversity in agrivoltaics depends on the diversity of crops and animals, which are prime land users beneath PV arrays. The changes in biodiversity underneath PV arrays were discussed in the agrivoltaic case in Malaysia. The authors found higher biodiversity levels underneath agrivoltaic systems through the increased numbers of lace bugs [59]. The lace bugs were attracted to the higher humidity environment underneath PV arrays. These results are in line with Toledo & Scognamiglio [21], who argued that higher levels of biodiversity can be reached underneath agrivoltaic systems.

A study in Arizona (US) discussed the importance of growing crops beneath PV arrays to enhance carbon dioxide uptake from the atmosphere [53] contributing to *reduction of greenhouse gases and ammonia*. The same study showed that cumulative carbon dioxide uptake in chiltepin was 33% greater underneath PV arrays compared to open fields. Nevertheless, the uptake of carbon dioxide in jalapeño was 11% lower underneath agrivoltaic arrays. *Nature conservation* and *using residual flows from food industry* were not reported in any of the studied literature for international cases.

3.2. Landscape experience of international agrivoltaic cases

Of the 16 identified international cases, landscape experience was discussed in only one agrivoltaic case in Switzerland [58]. Agrivoltaics had a negative visual impact on the natural landscape due to the elevated structure of agrivoltaic systems, which was very visible from a distance. The selection of the crop type can also effect the landscape experience. Arable farming is used in most international agrivoltaic cases (56%), followed by outdoor vegetable production (44%), other livestock farming (13%) and fruit growing (13%) (Fig. 7). Herbs, tomatoes and lettuce were found in the highest number of agrivoltaic cases; six, four and three, respectively. Maize soybean and pepper crops were identified only in two cases each. Other crops were only found in single instances (Fig. 7).

The crop selection in agrivoltaics is influenced also by environmental factors and the amount of solar irradiance received by the crop. Due to reduced solar irradiation underneath PV arrays in agrivoltaic sites, shade-tolerant crops often offer higher potential compared to shade-intolerant crops due to their ability to endure low light [4]. Furthermore, crop performance is affected by shading, which is plant-specific and linked to different plant adaptations [60]. The crop selection of the studied international agrivoltaic cases shows that several crops are shade-intolerant, such as corn in Italy [61], rice in Japan [55] and tomato in western India [62].

3.3. Circularity in agrivoltaic cases in the Netherlands

Fewer circular aspects were found in Dutch agrivoltaic cases compared to international agrivoltaic cases. Three out of nine CPICA were identified in Dutch agrivoltaic cases (Fig. 8). *Contribution to regional economy and vitality of the rural area* was identified in more than half agrivoltaic Dutch cases. *Maintenance of biodiversity* and *soil*

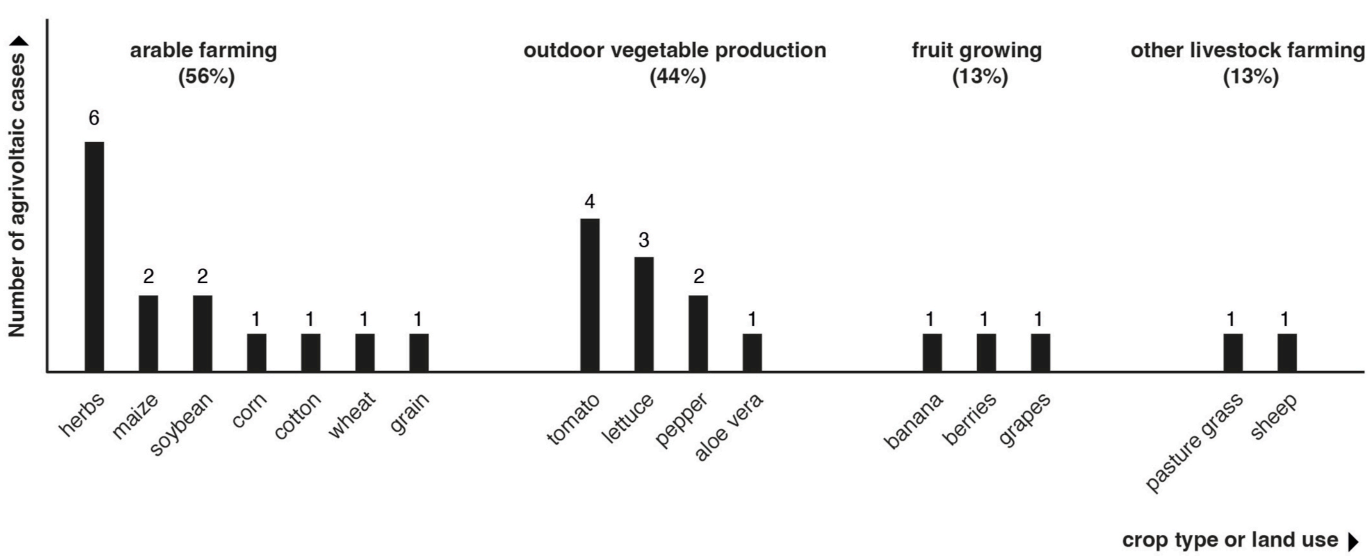

Fig. 7. Number of agrivoltaic cases with specific crop type or land uses identified in international literature. Crop type or land uses are clustered in four agricultural sectors (arable farming, outdoor vegetable production, fruit growing and other livestock farming). The percentage between brackets indicates the share of studied international agrivoltaic cases with a crop type or land use in that agricultural sector. A single case can contain multiple crop types or land uses. Agricultural sectors tree nursery, greenhouse horticulture, bulb farming, dairy farming, poultry farming and pig farming were not identified in any of the studied international agrivoltaic cases.

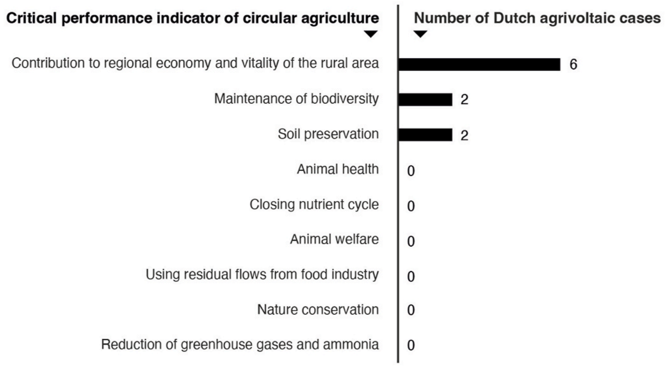

Fig. 8. Number of Dutch agrivoltaic cases with identified critical performance indicators of circular agriculture.

preservation were identified in two Dutch agrivoltaic cases. The other six CPICA were not identified in any of the Dutch agrivoltaic cases. We found one negative and one 'unchanged' aspect of circularity of agrivoltaics systems. Stadskanaal reported lower biodiversity levels underneath PV arrays, and Babberich reported the same amount of crop diseases compared to the agricultural land covered by foil.

In the cases of Babberich and Wadenoijen, it was reported that agrivoltaics benefited the economy through crop and energy production. The energy production benefits for the local economy were discussed in the Stadskanaal agrivoltaic case, where higher crop yield on the edges of fields underneath PV arrays was reported. Another practice that supports the regional economy is the financial participation of inhabitants in the vicinity of agrivoltaic projects. For example, the inhabitants near the Etten-Leur agrivoltaic case were given priority to financially invest in the agrivoltaic project. Another contribution to regional economy was the creation of additional jobs, as reported in the literature on the Haren case.

Regional economies also depend on the quality and quantity of crop yields. The quality of the yield can be improved as agrivoltaic systems can support a longer growth period for crops [53]. A longer growth period of crops underneath PV arrays was reported in the Babberich case. The quantity and reliability of crop yields can also be increased by agrivoltaics, as was identified in Wadenoijen and align with the study on agrivoltaic case in Italy. The study confirmed that agrivoltaics have the potential to stabilise crop yield by reducing evapotranspiration and the soil temperature underneath the PV arrays [57].

A positive impact was reported in *maintenance of biodiversity* under the PV arrays. In Broekhuizen, it was reported that biodiversity was stimulated in poor quality soil through the use of diverse flower varieties. In the Haren case, it was argued that the agrivoltaics system positively influenced levels of biodiversity. These results are in line with the study by Walston et al. [63], whom demonstrated that agrivoltaic systems are beneficial for enhancing biodiversity levels. In Stadskanaal, however, lower biodiversity levels were reported compared to agricultural land without agrivoltaic systems. Fewer insects and plant species were found underneath the PV arrays. Plants also experienced water stress in the shade of the PV arrays. *Soil preservation* was reported in two Dutch agrivoltaic cases: Broekhuizen and Haren. In Broekhuizen, it was argued that soil will not be exhausted at the end of the PV lifespan. In the case of Haren, it was suggested that PV arrays positively affected soil. *Animal health, closing nutrient cycles, animal welfare, using residual flows from the food industry, nature conservation* and *reduction of greenhouse gases and ammonia* were not reported in any of the studied literature for Dutch cases.

3.4. Landscape experience of agrivoltaic cases in the Netherlands

Agrivoltaic systems affected the landscape experience of landscape users in Dutch agrivoltaic cases; this was reported on in the literature of two cases: Haren and Wadenoijen. In the Haren case, it was mentioned that agrivoltaic systems represented added value to the landscape in terms of aesthetic addition to the existing facilities, such as a shop, tearoom and petting zoo. The agrivoltaic case in Wadenoijen was identified as having a positive impact on the landscape experience, and it was noted that it looked more attractive compared to the plastic foils used in the previous situation. In the following section, the results of the analysis of four spatial properties are presented: accessibility, visibility, patch configuration and agricultural land use underneath PV arrays.

3.4.1. Accessibility of Dutch agrivoltaic cases

Eight out of ten Dutch AVPP agrivoltaic cases were accessible upon request (Table 2). Only Sint-Oedenrode and Etten-Leur were inaccessible to the public. The literature on Lochem reported the existence of elements used to welcome and invite landscape users, such as information boards and rest points with picnic tables for cyclists and pedestrians. The elements were located near the agrivoltaic system to ensure the visitors could see the AVPP. In the literature on the Haren agrivoltaic case, it is argued that the agrivoltaic system presents an added value to the landscape for the neighbourhood and environment by aesthetic addition to the existing facilities.

The lack of accessibility for landscape users implies that the owners of Dutch AVPPs are not in favour of the general public being able to access the sites. The most likely reason for this is the risk of the disturbance of work-related processes and potential damage to agrivoltaic systems and crops. These results are similar to the results of the study of accessibility of SPPs where most of the cases were inaccessible to landscape users [38]. AVPP access offers the opportunity to enhance the public's knowledge of sustainable energy, the energy transition and agriculture. Furthermore, this concept may contribute to increasing public acceptance of future AVPPs. The open access principle is also used in 'energy gardens' where renewable energy installations are placed in a public places with open access [64].

3.4.2. Visibility of Dutch agrivoltaic cases

Spatial analysis demonstrated low visibility in the majority of Dutch agrivoltaic cases (Fig. 9). The AVPP in Someren and Stadskanaal were completely hidden from landscape users, where the level of invisibility was found to be 100%. Partly visible sections were detected in Lochem, Haren and Babberich, with less than 35% of the entire perimeter of the AVPP being visible. Three agrivoltaic cases showed visibility percentages higher than 50%: Etten-Leur, Haren and Wadenoijen. The average levels of visibility, partial visibility and invisibility of Dutch cases were 27%, 9% and 64%, respectively. The results suggest that very few of the studied AVPPs can be observed by landscape users. However, landscape users are encouraged to appreciate the view of the AVPPs in two agrivoltaic cases: Haren and Lochem. The literature on the Haren case mentioned how the visibility of the AVPP was enhanced through the avoidance of fences, which separated agrivoltaics system from landscape. Instead of a fence, a ditch filled with water was used to prevent the visitors from entering the AVPP. In the Lochem case, welcoming

Table 2
Accessibility of Dutch agrivoltaic cases.

Agrivoltaic case	Accessibility
Etten-Leur	Inaccessible
Broekhuizen	Accessible upon request
Sint-Oedenrode	Inaccessible
Boekel	Accessible upon request
Haren	Accessible upon request
Someren	Accessible upon request
Stadskanaal	Accessible upon request
Lochem	Accessible upon request
Babberich	Accessible upon request
Wadenoijen	Accessible upon request

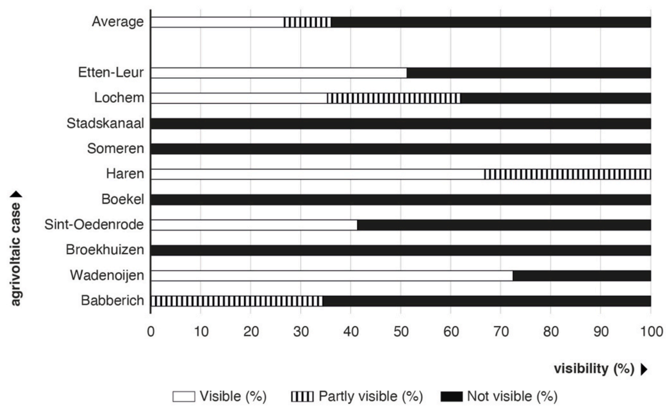

Fig. 9. Degree of visibility of solar infrastructure of Dutch agrivoltaic cases.

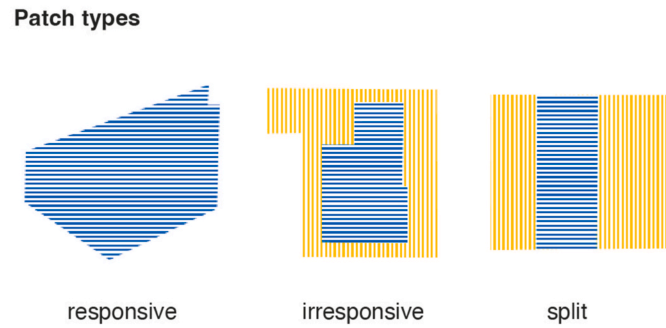

Fig. 10. Three types of patch configurations. The characteristics of the patch are: alignment to plot and coverage of the plot by the PV patch. The area with blue lines represents land covered by PV arrays, and the area with orange lines represents a plot. Example of each patch configuration: Responsive patch is the Babberich case, The irresponsive patch is Wadenoijen case and split patch is the Broekhuizen case.

elements were installed, including an information board and picnic tables, intended to invite visitors to view the AVPP. However, the literature on two agrivoltaic cases reported that the owners were planning on introducing screening elements around the AVPP to reduce their visibility. In the Haren case, there was the intention to plant shrubs to screen the view from the pathways, and in Wadenoijen, there were plans to install hedgerows adjacent to the agrivoltaic system to reduce visibility from the neighbouring houses.

Due to the scarcity of publications on visibility in agrivoltaics, the results were compared with the visibility analysis of conventional SPPs in Germany, Italy, United Kingdom and the Netherlands, conducted by Oudes & Stremke [38]. Average visibility showed similar results on 'not visible' level of parameter. The average 'not visible' value of our study showed 64%, which is comparable to the values (63%) found in the study by Oudes & Stremke [38]. Although the average values are comparable, the values of the individual cases differ substantially from those in the study by Oudes & Stremke [38].

Our results imply that AVPPs are somewhat hidden from the landscape users. The literature also suggests that several agrivoltaic cases introduced barriers to reduce visibility. Nevertheless, in some agrivoltaic cases, there was no need to add elements to reduce visibility due to pre-existing elements in the host landscape (e.g. hedgerows). Hiding AVPPs from landscape users may affect public acceptance. This confirms the participative study of SPPs in Slovenia, which argus that public acceptance could be enhanced by placing SPPs in less visible areas [65]. Another study by Fernandez-Jimenez et al. [44] suggests lowering the visual impact of SPPs by building them in less visible locations, thereby enhancing public acceptance.

3.4.3. Patch configuration of Dutch agrivoltaic cases

Three patch configurations were identified in Dutch agrivoltaic cases: responsive, irresponsive and split type (Fig. 10).

Most Dutch agrivoltaic systems showed a shape that matched the shape of the plot. However, substantial parts of some plots were not covered by PV arrays; up to 50%. This patch configuration type is referred to as 'split'. Irresponsive and responsive patch configuration types are only applied in one and two cases, respectively (Table 3).

The TRL may have influenced the patch configuration of the AVPP. TRLs equal or higher than eight (TRL 8: agrivoltaic systems complete and qualified) may affect the surface of AVPP in the way that the area covered by PV arrays is larger compared to the prototype. However, the shape of agricultural plots remain the same. In instances of higher TRL values, the AVPP patch configuration may be different due to the larger scale of the area covered by PV arrays. Several Dutch agrivoltaic cases with relatively low TRLs demonstrated relatively small areas occupied by the agrivoltaic system. Patch configuration is likely to change when the project scale of the AVPP is increased.

The results are compared to the results of SPP studies due to the lack of literature on the topic. In the study by Oudes & Stremke [38], eight of 11 studied SPP cases fall into the responsive, irresponsive and split type patch configurations. Among them, three, two and three SPP cases correspond to responsive, irresponsive and split type of patch configuration, respectively. The results show different distributions of patch configuration among the SPPs, compared to the results of this research, where the split patch configuration of AVPPs is predominant. The shape of PV patches of SPPs fall into the category where the PV patches are independent of the existing shape of the plot. The most likely reason for this is that AVPPs are more focused on the crop delineation than plot shape.

Table 3
Patch types of Dutch agrivoltaic cases.

Agrivoltaic case	Patch type
Etten-Leur	Split
Broekhuizen	Split
Sint-Oedenrode	Split
Boekel	Split
Haren	Split
Someren	Split
Stadskanaal	Split
Lochem	Responsive
Babberich	Responsive
Wadenoijen	Irresponsive

In the study by Lobaccaro et al. [66], conducted in the US, China and Europe, it is suggested that AVPPs are characterised by smaller PV patches compared to SPPs. Moreover, Scognamiglio [67] suggests that the shape of the PV patch depends on the features of the available land area, which is influenced by the topography and boundaries of the landscape. Scognamiglio argues that the patch of PV arrays should be designed in a way that suits the pattern of the landscape, and they should be merged with the landscape through the following properties: size and shape of the patch, type of pattern, grain and colour. The cases studied in this research are mostly in line with the guidelines proposed by Scognamiglio [67], since the predominant patch configurations correspond to the categories where shape of the PV patch matches the shape of the plot. Nevertheless, a substantial part of the plots of Dutch agrivoltaic cases were unoccupied by PV patches. One possible reason for this could be the relatively low TRLs of Dutch agrivoltaic cases (Table 1).

3.4.4. Agricultural land use underneath PV arrays of Dutch agrivoltaic cases

Land beneath agrivoltaic systems in the Netherlands was mostly used for fruit production. This is followed by other livestock farming, arable farming, bulb growing and greenhouse horticulture – 30%, 10%, 10%

and 10% respectively (Fig. 11). Tree nursery, outdoor vegetable production, dairy farming, poultry farming and pig farming were not found in Dutch agrivoltaic cases. In two agrivoltaic cases, the land underneath the PV arrays had three different uses: Stadskanaal and Haren. Land use was monofunctional in three agrivoltaic cases: Etten-Leur, Boekel and Broekhuizen. The other five cases contained two different land uses. Sheep farming and raspberry production were the predominant uses for the land, found in three agrivoltaic cases. These were followed by red berries, blueberries, strawberries and flowers, which were reported in two cases. Mushrooms, plum trees, nut trees, barley and chicory were reported in Lochem, Wadenoijen, Haren, Stadskanaal and Stadskanaal, respectively.

Solar irradiance affects the crop selection [4] and crop yield. The global solar horizontal irradiation is adequate for agrivoltaics in latitudes of less than 45° [68]. The geographical latitude of the Dutch agrivoltaic cases are between 51° and 53°, so shade-tolerant crops should be primary used in the Netherlands. Moreover, the study by Dinesh & Pearce [69] suggests the selection of shade-tolerant crops for maximising crop yield. This is confirmed by the crop selection of mushrooms (Shitake) in the Lochem case. Mushroom growth in agrivoltaic cases was also reported in one agrivoltaic case in China [70], which receives similar solar irradiation as Lochem. The difference in global horizontal irradiation between both location is 550 kWh/m^2 per year.

In the agrivoltaic case study by Trommsdorff et al. [12] in Germany, different crops were reported: potato, celeriac, clover grass and winter wheat. The Köppen-Geiger climate class Cfb is the same as in Dutch agrivoltaic case [71]. The difference of global horizontal irradiation between the location of the study by Trommsdorff et al. [12] and the Netherlands is roughly 180 kWh/m^2. Crop selection may still be influenced by different policies, soil type and other environmental conditions. The crop selection was most likely influenced by economic reasons, such as the lack of need for common agricultural machinery and the relatively low structure of agrivoltaic systems compared to agrivoltaic systems for arable farming. Furthermore, agrivoltaic systems offer protection from extreme weather conditions; this was reported in both the Babberich and Wadenoijen cases. Tree growth underneath PV arrays is rare according to studied literature, however, it does occur. Olive tree growth was reported in an agrivoltaic case in southern Spain [3], increasing the land equivalent ratio up to 47.2%. Sheep grazing was reported in three Dutch agrivoltaic cases, the highest number of agrivoltaic cases and equal to raspberry production. The reason for this high number of agrivoltaic cases with sheep grazing beneath may be due to practical reasons. Agrivoltaic systems do not affect stock density, can provide shelter for livestock and have the added benefit of controlling vegetation growth [4,72]. There are relatively few studies on livestock in agrivoltaics [73], nevertheless sheep farming was reported in Australia [74] and Oregon (US) [54].

The choice of land use in agrivoltaic cases is also impacted by legislation. Governmental policies affect the crop selection in AVPP [4]. On the one hand, local land policy presents a significant barrier for agrivoltaics development in the US [75]. On the other hand, the Dutch government promotes building multifunctional SPPs [76]. Nevertheless, there are still many uncertainties regarding crop selection in AVPP, which remains a key issue for the scientific community [21].

3.5. Limitations

For this study, five data and methodological limitations can be identified. First, agrivoltaics is a dynamic field with a growing number of cases [8]. However, the existing literature on agrivoltaics and agrivoltaic cases is still limited due to the novelty of agrivoltaics. The lack of literature was particularly noticeable through the absence of peer-reviewed literature on Dutch agrivoltaic cases. This is why we had to rely on grey literature and field work. Second, 'circularity' has numerous definitions. In this research, we limited circularity to meaning circular agriculture and nine CPICA. Agrivoltaics may touch upon more circularity aspects than were studied in this research. However, they are not reported in the studied literature yet. Third, part of our research is limited to a single country, The Netherlands, which results in relatively low number of built agrivoltaic cases. Agrivoltaic cases outside the Netherlands could not be examined by means of field work due to travel limitations put in place during the COVID-19 pandemic, which was ongoing at the time of study. Fourth, the number of studied international agrivoltaic cases was limited by the pool of peer-reviewed literature in databases Scopus and Web of Science. Using additional databases would mean a higher number of studied international cases that would influence the results. Finally, the land use underneath PV panels is a dynamic

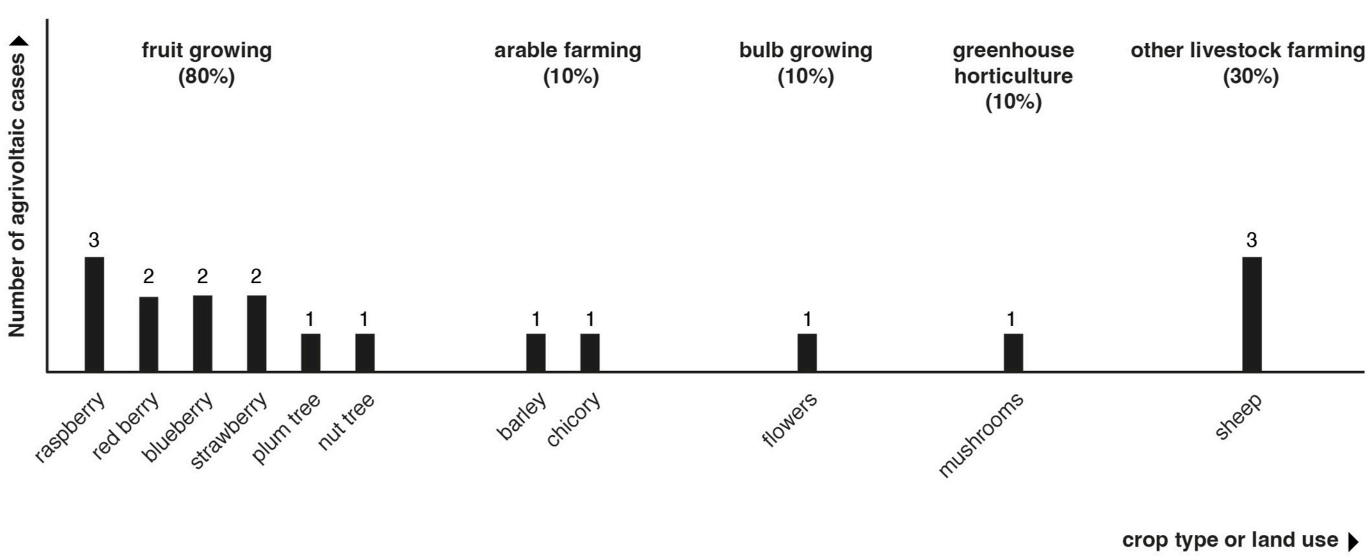

Fig. 11. Number of agrivoltaic cases with specific crop type or land uses identified in the literature of Dutch cases. Crop type or land uses are clustered in five agricultural sectors (fruit growing, arable farming, bulb growing, greenhouse horticulture and other livestock farming). The percentage between brackets indicates the share of studied Dutch agrivoltaic cases with a crop type or land use in that agricultural sector. A single case can contain multiple crop types or land uses. Agricultural sectors tree nursery, outdoor vegetable production, dairy farming, poultry farming and pig farming were not identified in any of the studied Dutch agrivoltaic cases.

parameter, changing yearly in some agrivoltaic cases. Retrieving more detailed land use data from all studied cases would provide more insight in this dynamic land use.

Potential errors in the analysis may have affected the TRL and the visibility levels of agrivoltaic cases. TRL classification is not exact and was created for photovoltaic technology in general [33]. An agrivoltaics-specific TRL classification could improve results. However, such a specific classification does not yet seem to exist, most probably due to the novelty of the technology. Futhermore, grey literature contains more potential source errors, compared to peer-reviewed literature. Consequentially, the results based on grey literature might be less accurate compared to the results based on peer-reviewed literature. Nevertheless, the growth of peer-review literature in agrivoltaics [8] will provide more peer-review literature for future research.

4. Conclusion

This research provides a detailed overview of circularity and landscape experience in agrivoltaics. The study was guided by two research questions: (1) Which aspects of circularity and landscape experience are addressed in the international literature on agrivoltaics? (2) What are the key technical properties and aspects of circularity of built agrivoltaic systems in the Netherlands, and how are landscape users' experiences addressed?

Internationally, agrivoltaic cases showed the most identified aspect of circularity was *contribution to regional economy and vitality of the rural area*, which was identified in 82% of the international agrivoltaic cases. However, none of the studied cases addressed *nature conservation* or *usage of residual flows from food industry*. Contrary to the aspects about circularity, landscape experience was largely absent in the international literature on agrivoltaics. Landscape experience was only identified in one agrivoltaic case in Switzerland. Considering the current attention to landscape experience of conventional SPPs in both research and practice, increased attention to this topic for agrivoltaics is expected and relevant for future research.

On the level of the Netherlands, results revealed that the most identified aspect of circularity in Dutch cases is the same as in international cases, namely *contribution to regional economy and vitality of the rural area.* It was identified in 60% of the Dutch agrivoltaic cases. The CPICA *animal health, closing nutrient cycle, animal welfare, using residual flows from food industry, nature conservation* and *reduction of greenhouse gases and ammonia* were not mentioned in any of the Dutch agrivoltaic cases. Due to the high number of circularity aspects that were not mentioned (six out of nine CPICA), one may infer that Dutch stakeholders currently pay less attention to circularity compared to their international colleagues. Similarly, 'landscape experience' was only addressed in the literature of one Dutch agrivoltaic case. Furthermore, Dutch agrivoltaic cases showed relatively low accessibility and visibility. These findings suggest that most Dutch AVPPs are designed to be hidden from landscape users. Low visibility was identified in 30% of cases, meaning the entire perimeter was identified as 'not-visible'. However, in one case, the literature reported the existence of inviting elements for landscape users, such as information boards, rest points for cyclists and picnic tables. Dutch agrivoltaic cases tend to be inaccessible or only accessible upon request, which may be a drawback for landscape users wishing to visit AVPPs.

Together, the results on both levels clearly show that international agrivoltaic cases have higher levels of variability in terms of circularity compared to Dutch cases. One possible reason for this may be that a higher number of international agrivoltaic cases were studied, there was more detailed literature and there were longer observation times. Many synergies between food and energy production were identified in both international and Dutch agrivoltaic cases. Several agrivoltaic cases reported that PV arrays protected the crops from extreme weather conditions and consequently improved the security of the crop yield. Apart from synergies, trade-offs between food production and energy production were found in several international agrivoltaic cases, such as lower crop production. A loss of biodiversity was reported in one Dutch agrivoltaic case and another Dutch case reported that the amount of plant diseases did not change after PV installation. The results suggest that circularity in international and Dutch cases is mainly based upon an economic perspective.

Due to climate change and the rising incidences of extreme weather events, the security of crop yields is becoming an important factor in ensuring economic income for farmers. International agrivoltaic cases showed several synergies between food and energy production that were not found in Dutch agrivoltaic cases, such as animal health, animal welfare and reduction of greenhouse gases. To ensure a smooth transition to circular agriculture, aspects of circularity should be more integrated into agrivoltaic systems. Farmers, agrivoltaic developers and policy makers can learn from synergies in successful agrivoltaics examples and can implement these insights in future developments and policies.

Landscape experience is an important part of agrivoltaics due to the impact of AVPP on landscape experience and, consequently, public acceptance. In one international agrivoltaic case, it was argued that AVPPs had a negative effect on the landscape due to their elevated structure. Even though our spatial analysis of Dutch agrivoltaic cases indicated low accessibility and visibility, some suggested that agrivoltaics improved landscape experience and has a preferable aesthetics compared to plastic foil or greenhouses. The visual appearance of the previous agricultural system is therefore essential in assessing landscape experience. The spatial analysis revealed that most APV systems cover less than 50% of their plots, and that patch shape matches the shape of the plot. The Dutch agrivoltaic cases showed a high variability of crop selection for a relatively small area of the Netherlands, with the majority of cases being used by the fruit growing sector. Nevertheless, the patch configuration was influenced by TRL, and further improvement of technology and business cases of AVPP may increase the share of the plot used as AVPP.

This study provides recommendations for future research into circular agrivoltaic power plants with attention to landscape experience. Using this research as a basis, future research should explore alternative designs of AVPPs that consider landscape experience, for example the accessibility and visibility of AVPPs. Furthermore, future research should study how the currently missing circularity indicators could be implemented, such as *nature conservation* and *using residual flows from food industry*. Legislation is an important driver for advancing these aspects of agrivoltaics. There are already several countries that are introducing legal guidelines, standards and legislation for agrivoltaics (e.g. Italy, Germany). Policy makers, in collaboration with farmers, developers and landscape users, should devise legislation that supports innovation of circularity and landscape experience of AVPPs.

The identified synergies and trade-offs of studied agrivoltaic cases show advantages and disadvantages of agrivoltaics in the context of circularity and landscape experience. Decision-making processes can benefit from these results to improve policies for designing AVPP in aspects of circularity and contribute to accelerate energy transition with higher public support. Moreover, the missing circularity aspects in the studied agrivoltaic cases can be included in the design of future AVPPs. The results also show the advantages of agrivoltaics compared to conventional monofunctional SPPs, providing evidence to promote agrivoltaics in a circular manner with attention to landscape experience rather than monofunctional SPPs.

Agrivoltaics is a relatively novel concept that is already showing promising results in terms of energy, food production and, more recently, mitigating conflicts between the two. It provides synergies in the context of nature conservation, accelerating the energy transition and providing crop protection whilst ensuring yield stability. There are also challenges facing agrivoltaics, much like other types of SPP, including low public acceptance due to changes in landscape experience. Nevertheless, agrivoltaics may have the potential to become a leading solution for future proof farming, contributing to the energy transition and mitigating climate change. In turn, it also contributes to circular agriculture, meeting environmental targets and reaching the Sustainable Development Goals set by the United Nations such as ensuring zero hunger and creating affordable, clean energy.

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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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.rser.2023.113250.

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