

Review

Regenerative Agrivoltaics: Integrating Photovoltaics and Regenerative Agriculture for Sustainable Food and Energy Systems

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Abstract: Regenerative agriculture has emerged as an innovative approach to food production, offering the potential to achieve reduced or even positive environmental and social outcomes compared to the soil degradation and greenhouse gas emissions of conventional agriculture. Simultaneously, a sophisticated dual-use system combining solar energy generation from photovoltaics with agricultural production, called agrivoltaics, is rapidly expanding. Combining these approaches into *regenerative agrivoltaics* offers a promising solution to the challenges regarding food in a rapidly warming world. This review theoretically examines the compatibility and mutual benefits of combining agrivoltaics and regenerative agriculture while also identifying the challenges, opportunities, and pathways for implementing this system. A foundation for advancing regenerative agrivoltaics is made by identifying areas for research, which include the following: (1) carbon sequestration, (2) soil health and fertility, (3) soil moisture, (4) soil microbial activity, (5) soil nutrients, (6) crop performance, (7) water-use efficiency, and (8) economics. By addressing the intersection of agriculture, renewable energy, and sustainability, regenerative agrivoltaics emphasizes the transformative potential of integrated systems in reshaping land use and resource management. This evaluation underscores the importance of policy and industry collaboration in facilitating the adoption of regenerative agrivoltaics, advocating for tailored support mechanisms to enable widespread implementation of low-cost, zero-carbon, resilient food systems.

Keywords: agrivoltaics; climate-resilient agriculture; regenerative agriculture; photovoltaics; sustainability; renewable energy; land use



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1. Introduction

As the world population continues to grow, so does the agricultural system that feeds humanity. To meet this need, farmers rely on fertilizers, pesticides, and land expansion, leading to a more than 60% rise in methane emissions from agriculture over the past four decades [1,2]. Although modern techniques have boosted productivity, they have also contributed to soil degradation, nutrient depletion, and pollution [3]. Practices including monoculture and excessive chemical application have led to declining soil health, water contamination, and biodiversity loss, threatening ecological stability [4]. Agriculture remains a primary driver of greenhouse gas (GHG) emissions, being responsible for over 11% of global anthropogenic emissions from direct sources [5]. If GHG emissions remain

unchanged until 2100, crop yields will be reduced approximately by 45%, with wheat yields alleviating by 50%, and rice yields by 30% [6]. These alarming projections highlight the urgent need to explore sustainable food production systems that can mitigate environmental impacts while ensuring long-term agricultural resilience.

1.1. Regenerative Agriculture: A Sustainable Approach to Food Production

Regenerative agriculture (RA) has emerged as an alternative, sustainable, and restorative approach to food production, offering the potential to achieve reduced or even positive environmental and social outcomes [7]. Schreefel et al. defined RA as “an approach to farming that uses soil conservation as the entry point to regenerate and contribute to multiple provisioning, regulating and supporting ecosystem services, with the objective that this will enhance not only the environmental but also the social and economic dimensions of sustainable food production” [8]. It is increasingly recognized as a method to promote sustainability in food systems, with the added potential of contributing to climate change mitigation [9]. RA addresses five key environmental dimensions: enhancing soil vitality, preserving water integrity, supporting biodiversity, maintaining ecosystem functionality, and capturing atmospheric carbon [10].

Project Drawdown [11], a nonprofit organization, with the aim to help the world stop climate change, emphasizes that RA improves soil health by replenishing carbon content, leading to greater productivity, an outcome that contrasts sharply with conventional farming practices [12]. Key agronomic challenges linked to RA include rebuilding soil health, capturing carbon to combat climate change, and reversing biodiversity loss [13]. With its numerous co-benefits, including the production of nutritious food, RA is seen as a vital component in addressing the challenges posed by escalating climate instability [14].

Recent scholarship has introduced the Farmscape Function framework, designed to evaluate temporal changes in agricultural assets while also assessing their interactions with system costs, environmental reliability, and land quality metrics [15]. The applicability of regenerative practices in the developing world has also been examined, highlighting both opportunities and implementation challenges [16]. Lal emphasized that regenerative agriculture can meet the nutritional demands of a growing and increasingly affluent global population while simultaneously mitigating human-induced GHG emissions [17]. Globally, regenerative practices are currently implemented on approximately 180 million hectares, with no-till farming representing the most prevalent method in the United States, covering around 22.6% of cultivated land [18]. As for economic outlook, the global market for regenerative agriculture was valued at USD 975.2 million in 2022, with projections indicating a compound annual growth rate (CAGR) of 15.9%, potentially exceeding USD 4.29 billion by 2032 [19].

1.2. Agrivoltaics: Integrating Energy and Agriculture

Clean energy technologies are taking a central role to achieving global sustainability goals [20]. Among these, solar photovoltaics (PVs) has gained prominence as a cost-effective and rapidly expanding energy solution [21,22]. The extensive land requirements for traditional PV installations to meet the growing energy demands of an expanding global population often result in land-use conflicts [23]. This is a particular problem if PV systems displace food production on agricultural land, thereby running the risk of repeating the ethanol debacle and increasing food prices and global hunger [24].

Agrivoltaics, a dual-use system combining solar energy generation with agricultural production, offers a promising solution to this challenge [25]. The agrivoltaics approach provides numerous benefits, including lower GHG emissions (replacing grid electricity with photovoltaics can cut related air emissions by nearly 90%) [26]; increased economic

advantages with farmers' incomes augmenting by up to 5.14 times [27], as well as a 26% reduction in investment costs due to PV modules substituting for conventional hail protection infrastructures [28]; enhanced water-use efficiency [29,30], with one study reporting a 20–30% reduction in water usage under agrivoltaic systems [31], while another demonstrated a savings of 289 L of water for 24 lettuce plants cultivated in such conditions [32]; better land-use efficiency, with the land equivalent ratio (LER) increasing up to 70% [33]; and, perhaps most importantly, increased crop yields of a wide variety of human food crops. Table 1 summarizes the studies that have shown increased crop yield with agrivoltaics.

Table 1. Crop and yield increase with agrivoltaics for studies throughout the world.

Crop Type	Crop Yield Increase with Agrivoltaics
Celeriac	31.9%, 48% [34]
Winter wheat	3% [35]
Pasture grass	90% [36,37]
Potato	11% [35]
Celery	12% [35]
Chiltepin pepper	150% [38]
Cherry tomato	90% [38]
Vine grapes	25%, 60% [39,40]
Corn	4.9% [41]
Swiss chard	70% [40,42,43]
Broccoli	40% [40,42,43]
Kale	25% [40,42,43]
Common bean	350% [40,42,43]
Strawberries	18% [44–46]
Lettuce	2%, 3.6% [47,48]

Beyond agricultural productivity, agrivoltaics delivers multiple co-benefits, including the protection of crops from environmental stressors such as wind [49], mitigation of soil erosion [50], and reversal of desertification [51]. Furthermore, the system improves solar module efficiency because of plant transpiration cooling the modules [52,53], resulting in a 1% increase in electricity generation annually [38], alleviates agricultural displacement for energy requirements [54–56], localizes food production [57–59], improves health due to reduced pollution [60], acts as a hedge against inflation [61], and provides energy for computing [62] and opportunities for integrating renewable fuel production, such as hydrogen [63–65] and anhydrous ammonia [66], as well as the production of on-farm nitrogen fertilizers [67]. In addition, improved nutrients (protein content) were also observed for spinach and basil under agrivoltaic configuration [68], which can further help to feed everyone [69]. A study conducted in the Mediterranean region demonstrated that agrivoltaic systems have the potential to generate over 560,000 jobs while simultaneously reducing annual CO₂ emissions by approximately 4 million metric tonnes [70]. Case studies conducted in San Francisco, Houston, Albany, London, Montreal, and Edmonton demonstrate that agrotunnels (vertical growing systems) are technically feasible and can be effectively integrated with agrivoltaic infrastructure to achieve net-zero energy performance [71].

The differences between regenerative agrivoltaics and conventional agriculture are summarized in Figure 1.

While agrivoltaics broadly refers to the dual use of land for agricultural production and solar energy generation, the concept of regenerative agrivoltaics specifically emphasizes integrating agrivoltaic systems with the principles of regenerative agriculture. This innovative technology prioritizes ecosystem restoration, soil health improvement, biodiversity enhancement, and long-term sustainability rather than simply optimizing energy-agriculture coexistence. In regenerative agrivoltaics, system designs are tailored

not only to avoid trade-offs but to actively contribute to the regeneration of degraded agricultural landscapes.

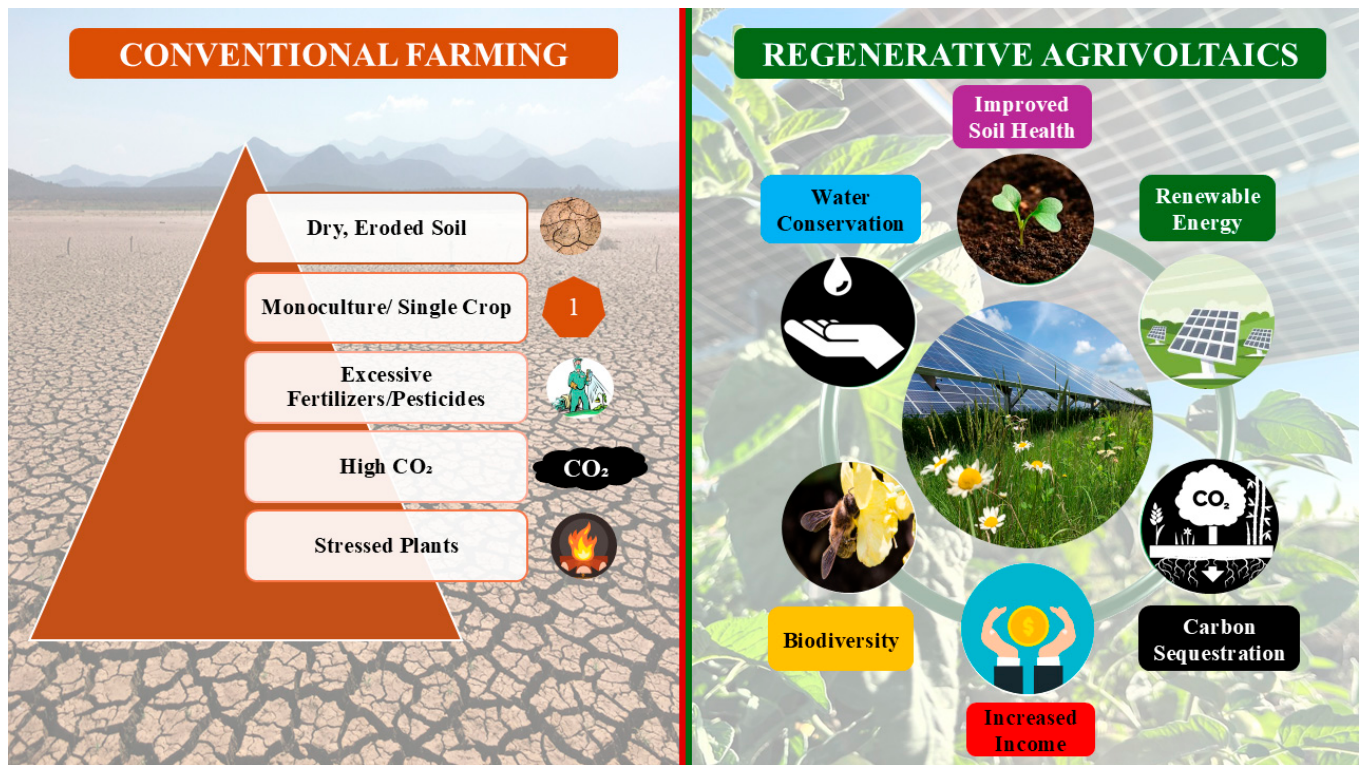


Figure 1. A comparison of conventional farming and regenerative agrivoltaics.

1.3. Economics and Market Growth of Agrivoltaics

From an economic perspective, agrivoltaics generates dual revenue streams through agricultural outputs and energy sales, enhancing farmers' financial stability [72]. For instance, spinach grown under agrivoltaic systems demonstrated financial gains of up to 35% alongside improved nutritional value [68]. Similarly, grazing sheep beneath PV arrays not only creates a better environment for sheep but is highly profitable for solar shepherds that earn additional income from controlling vegetation on a solar farm [73]. These opportunities have been driving rapid growth in agrivoltaics, whose market is valued at over USD 3.64 billion in 2022 and is projected to grow at a compound annual growth rate (CAGR) of 38% between 2024 and 2030 [74]. As a strategy addressing both food security and energy sustainability, agrivoltaics holds significant potential to tackle critical global challenges [75,76], highlighting the need for continued research and development in this area.

1.4. Combining Regenerative Farming and Agrivoltaics

Despite the growing interest in agrivoltaics and regenerative agriculture as independent approaches to sustainable land management, no prior research has explored the integration of these two systems. The potential synergy between agrivoltaics and regenerative agriculture remains largely unexplored, leaving a significant gap in understanding how these approaches could complement one another. This mini-review aims to theoretically examine the compatibility and mutual benefits of agrivoltaics and regenerative agriculture while also identifying the challenges, opportunities, and pathways for implementing this innovative dual-use system. By bridging these fields, this article seeks to lay the groundwork for future research and practical applications in sustainable food and energy systems.

2. Fostering Resilience: Agrivoltaics Meets Regenerative Agriculture in Regenerative Agrivoltaics

The integration of agrivoltaics and regenerative agriculture offers a unique opportunity to enhance the environmental and economic benefits of each system. By leveraging the complementary strengths of these approaches, society can address pressing challenges in sustainable agriculture and energy production. Agrivoltaics not only provides a means of clean energy generation but also creates microclimatic conditions [77] that can bolster regenerative practices [78], such as cover cropping, composting, and organic annual cropping. Similarly, regenerative agriculture principles [79] can enhance the sustainability of agrivoltaic systems by improving soil health, reducing chemical inputs, and increasing biodiversity. This convergence represents a holistic approach to land management that prioritizes resilience, productivity, and ecological health, creating a pathway to achieve multiple sustainability goals simultaneously, specifically the following U.N. Sustainable Development Goals (SDGs) [80]: 2. zero hunger, 3. good health and well-being, 7. affordable and clean energy, 14. climate action, and 15. life on land.

The following sections explore key areas of synergy between these two approaches, focusing on their potential to integrate cover cropping, composting, increasing crop diversity, and organic annual cropping within agrivoltaic systems. These innovations provide insights into how dual-use systems can be optimized to maximize co-benefits and establish a sustainable future for food and energy production.

3. Innovative Agrivoltaic Strategies for Regenerative Agriculture

3.1. Cover Cropping

Cover cropping, as highlighted in regenerative agriculture frameworks, has the potential to capture atmospheric CO₂ and sequester it in the form of soil organic matter [81]. This practice enhances soil biology, contributes essential nutrients to the soil [82], and mitigates soil erosion [83], thereby promoting healthier and more sustainable agroecosystems [84].

Agrivoltaics can bolster the efficacy of cover cropping, particularly under extreme weather conditions where the PV modules can act as shields for hail, for example. The shade provided by solar modules enhances the resilience of cover crops, preventing heat stress during high temperatures [70]. Shading apple trees using an agrivoltaic system has been shown to lower ambient air temperatures by up to 3.8 °C [85], with another study reporting more modest temperature reductions of approximately 1.1 °C [77]. This might improve the ability of cover crops to build soil organic matter and sequester carbon. The combination of agrivoltaic systems and cover cropping can contribute to an improved soil structure and a reduction in erosion, furthering the goals of regenerative agriculture.

3.2. Increasing Crop Diversity

Agrivoltaic systems can facilitate intercropping and polyculture practices by providing a modular layout that supports diverse planting configurations. This design enhances biodiversity [86,87] and builds resilience against climate variability [88,89]. Moreover, the microclimatic effects of agrivoltaics, such as moderated temperatures [34,38,90,91] and improved water efficiency [34,92,93], create favorable conditions for a variety of crops to thrive simultaneously. Water-use efficiency improvements have been observed in various crops under agrivoltaic systems, with increases of 157% in jalapeño and 65% in tomato cultivation [38]. Additionally, a separate study on apple orchards reported reductions in irrigation requirements ranging from 6% to 31% [85]. The integration of crop diversity into agrivoltaic systems aligns with regenerative goals of enhancing ecosystem services and increasing farm productivity.

3.3. Organic Annual Cropping

The integration of organic annual cropping into agrivoltaic systems offers a dual benefit of sustainable land use and environmental health. Organic farming practices, which rely on natural soil amendments and reduced chemical inputs [94,95], seem inherently compatible with agrivoltaics. The absence of synthetic pesticides and fertilizers minimizes the risk of PV module contamination or corrosion, reducing maintenance needs and associated costs. Additionally, the shade from modules can support crops prone to heat stress [96,97], aligning with the principles of low-impact, sustainable agriculture.

Environmentally focused production methods that limit chemical inputs often result in lower economic returns—particularly in high-yield or specialized systems—leading financially vulnerable farmers to depend on pesticide-intensive approaches to maintain profitability [98]. Agrivoltaic systems enhance agricultural risk management by serving as an alternative to crop insurance, with studies reporting increases in worst-case net revenues by 48–53% [99]. Scenario analyses suggest that integrating solar photovoltaics with agriculture can boost yearly net income by approximately 3 to 50 times compared to agriculture-only systems [99]. Another study has shown that the life-cycle revenue of agrivoltaic systems is 5–40% higher than only PV systems [100]. Consequently, agrivoltaics may incentivize farmers to adopt regenerative agricultural practices, facilitating a transition towards a more resilient and sustainable regenerative agrivoltaic food production system.

3.4. Composting and Soil Nutrients

Enhancing soil organic matter is fundamental to restoring degraded soils [101]. Regenerative agriculture emphasizes the importance of incorporating composted biological materials, including crop residues, food scraps, and animal waste, to enrich soil health and fertility [102,103]. Agrivoltaic systems have been reported to significantly enhance soil nutrient content and biological activity. Increases in soil nitrate-nitrogen (NO_3^- -N) ranged from 3.89 to 8.15 times, while potassium concentrations rose by 3.48% to 29.97% [104]. Microbial indicators also demonstrated notable improvements, with microbial biomass carbon (MBC), nitrogen (MBN), and phosphorus (MBP) elevated by factors of 6.29, 4.02, and 14.42, respectively [104]. Furthermore, the cultivation of peanuts and ryegrass beneath photovoltaic installations led to substantial gains in the soil quality index (SQI), ranging from 44.70% to 184.02%, and multifunctionality index (MFI), between 18.06% and 117.49% [104]. These outcomes suggest that combining agrivoltaics with composting practices can offer an effective pathway for integrating agrivoltaic systems within regenerative agriculture frameworks.

3.5. Animal Integration

Solar grazing presents an ideal opportunity for on-site soil improvement creating a closed-loop system for nutrient recycling. Animal waste from solar grazing can contribute significantly to enhance soil nutrients. The shade from solar modules can facilitate animal grazing [105], making the soil enrichment process more efficient in extreme climates, as more animals would graze and benefit from shade [105]. Compost application within these systems not only improves soil fertility [106] but also reduces the need for external chemical fertilizers [107], contributing to energy-efficient and waste-reducing food production. This approach provides an avenue that enhances both soil health and environmental sustainability while also lowering operational costs for farmers.

Agrivoltaics offers opportunities for livestock integration, combining vegetation management with enhanced soil fertility. Animals used on solar farms include sheep [73,92,108], rabbits [109,110], and now cows [105,111]. Grazing animals can maintain under-module vegetation, reducing the need for mechanical mowing [109], while their manure enriches

soil organic content [112,113]. Furthermore, the shade provided by solar modules improves animal welfare by protecting livestock from heat stress [25,105,114], which can enhance productivity and health [108]. Cattle provided with shade exhibited reduced core temperatures (afternoon: 39.0 °C and evening: 39.2 °C) compared to those without shade (afternoon: 39.3 °C and evening: 39.4 °C) [109]. Additionally, in the afternoon, shaded animals recorded slower respiration rates (66.4 breaths per minute) relative to their unshaded counterparts (78.3 breaths per minute) [109]. The integration of pasture-based agrivoltaic systems have resulted in 69.3% less emissions and 82.9% less energy requirements, indicating a highly sustainable food–energy system [110]. This synergy exemplifies a holistic approach to regenerative agriculture, optimizing land use for food, energy, and livestock production.

3.6. *Managed Grazing*

Rotational grazing under solar modules presents a viable strategy for pasture regeneration and carbon storage [115]. By controlling grazing patterns, farmers can ensure even vegetation coverage, reducing overgrazing risks [109]. The shade from modules creates a microclimate that promote diverse forage growth [36,116], supporting livestock nutrition and ecosystem health. Prior research has demonstrated up to a 90% increase in pasture yield under agrivoltaic systems [36]. Building on this enhanced productivity, a Canadian case study estimates that agrivoltaics in Saskatchewan could support an additional 3.9 to 4.6 million sheep, resulting in an annual revenue increase of approximately CAD 731 to 860 million [37]. Managed grazing within agrivoltaic systems offers a scalable solution contributing to dual-use land management.

3.7. *Reduced/No-Till Farming Practices*

Undisturbed soils foster an increase in both the abundance and diversity of soil microbial communities, contributing to enhanced soil structure and overall microbiome health [117]. Farmers who implement reduced or no-till practices can experience numerous advantages that not only improve soil health but also provide long-term economic benefits [118]. These practices enhance water infiltration and retention, improve nutrient retention and availability for crops, reduce soil crusting, and lead to a gradual accumulation of soil organic matter, collectively promoting more sustainable and resilient agricultural systems [118,119].

Pairing no-till farming with agrivoltaic systems presents significant potential to enhance soil health and water retention. The partial shade provided by solar modules reduces soil surface temperatures [77,120,121], minimizing water evaporation and fostering a microclimate conducive to moisture retention [85,93]. This synergy supports no-till practices by reducing the likelihood of soil compaction, especially as the shade mitigates the direct impact of heavy rain. Recent forecasts indicate that approximately 80–85% of the world's land area is expected to experience a notable rise—averaging around 30%—in rainfall erosivity between 2050 and 2070 [122]. In this context, photovoltaic installations may help mitigate erosion by lessening the impact of raindrop splash on soil surfaces [123]. Furthermore, the reduced soil disturbance inherent in no-till systems aligns with the fixed nature of agrivoltaic infrastructure, promoting long-term soil stability and resilience. From the PV side, reduced tilling would also reduce the risk of module soiling, which can cause a decrease in energy conversion efficiency [124].

3.8. *Silvopasture/Agroforestry*

Integrating silvopasture or agroforestry with agrivoltaics presents a promising avenue for long-term sustainability. Integrating agrivoltaics with apple trees have shown reduced water needs [85]. Designs that incorporate trees, solar modules, and grazing animals

create a multi-layered system capable of delivering carbon sequestration [125,126], soil fertility [126], and diversified farm incomes [27,68,89,127,128]. The shade from trees and modules moderates temperature extremes, improving animal welfare [25,105,114] and forage quality [116]. Additionally, the long-term carbon storage provided by trees [129] complements the renewable energy benefits of agrivoltaics, positioning these systems as a cornerstone of sustainable land-use practices.

4. Unlocking the Potential of Regenerative Agrivoltaics: Synergies, Challenges, and Theoretical Contributions

4.1. Synergies and Opportunities

Agrivoltaics serves as a powerful catalyst for advancing regenerative agricultural practices by addressing land-use competition while enhancing economic viability. By integrating solar energy systems with farming, agrivoltaics enables dual land use, reducing the need to dedicate vast areas solely for energy production. This synergy creates opportunities to scale regenerative practices, fostering climate resilience through improved soil health, water retention, and carbon sequestration.

Beyond land-use efficiency, the co-location of agrivoltaics and RA unlocks tangible environmental and economic benefits. For instance, agrivoltaic systems have been shown to increase soil nitrate concentrations by up to 8 times, potassium by nearly 30%, and microbial biomass indicators (carbon, nitrogen, and phosphorus) by several-fold [104], core metrics associated with regenerative soil restoration. Moreover, integrating peanuts and ryegrass within AV arrays has been associated with a 44.7–184% increase in the soil quality index and up to a 117% rise in the multifunctionality index [104], confirming the ecological enhancements resulting from combined implementation.

Water-use efficiency is another key area of overlap. AV installations have led to significant reductions in irrigation requirements, with 1410 m³/ha reduced water consumption according to a study conducted in Chile [130]. Another study reported an increase in soil moisture content ranging from 8.22% to 56.06% [104]. These gains directly support the low-input water strategies central to RA, especially under climate-stressed conditions.

Economic resilience also emerges as a major benefit. AV systems have been linked to net revenue increases ranging from 22 to 115 times over conventional farming of rice alone [131]. A separate investigation found that integrating rabbit farming with solar installations presents a feasible agrivoltaic model, boosting total land-based income by 2.5% to 24% beyond the expected returns from electricity generation alone [109]. Furthermore, a study in Hungary for apple agrivoltaics showed a profitability index of 3.79 and internal rate of return (IRR) of 25% [132], effectively serving as a financial buffer akin to crop insurance. These advantages can encourage wider adoption of regenerative practices, which often require initial financial risk taking.

The co-benefits extend to animal husbandry and ecosystem regulation. Agrivoltaic shading has reduced air temperatures by up to 2 °C [133], contributing to cooler microclimates that improve crop health and animal welfare. Studies show shaded livestock maintain lower core temperatures and respiration rates compared to unshaded controls, which are indicators of stress mitigation.

Socially, AV systems can promote rural development through job creation. A study from the Mediterranean projects that agrivoltaic deployment could generate over 560,000 jobs while simultaneously reducing annual CO₂ emissions by 4 million metric tonnes [70]. In grazing systems, increased pasture production under AV arrays has supported estimates of an additional 3.9 to 4.6 million sheep grazed annually in Canada, contributing up to CAD 860 million in added revenue [37].

In sum, the synergy between agrivoltaics and regenerative agriculture is not merely conceptual but is supported by empirical results demonstrating enhanced soil function, improved water efficiency, diversified income, microclimate regulation, and job creation. Together, these approaches can underpin a resilient and climate-smart food-energy system. Further field-based research under diverse climates and land types is recommended to validate these integrated benefits and optimize system design for broader adoption.

4.2. Challenges, Barriers, and Future Directions

Building on the literature synthesized in Section 3, it is evident that while agrivoltaics and regenerative agriculture each offer distinct environmental and economic benefits, their integration remains underexplored and fragmented in existing research. Several gaps persist—such as a lack of empirical studies on soil carbon dynamics, insufficient understanding of PV-induced microclimatic effects on regeneration processes, and limited system-specific optimization for diverse agroecological zones. These gaps reflect unresolved scientific questions that warrant targeted investigation. Consequently, the following research priorities are proposed as a reflection of real, critical limitations and opportunities identified in the scientific literature.

Despite its promise, agrivoltaics faces significant challenges in aligning system design and operations with regenerative agricultural goals. The complexities of optimizing dual-use systems to balance energy production, crop growth, and ecological benefits require innovative engineering and site-specific solutions. For instance, specialized racking solutions may be required for integrating solar PV modules with agriculture, on which limited work/research has so far been performed [134–136]. In addition, customized and low-cost electronic systems, such as photosynthetically active radiation (PAR) sensors [137], as well as PV mounting mechanisms [138], designed specifically for agrivoltaic applications, could enhance system integration and further improve cost effectiveness.

The absence of well-defined government policies integrating sustainable agriculture and renewable energy development presents another barrier to the widespread adoption of regenerative agrivoltaics. Establishing clear policy frameworks could provide crucial guidance and incentives, encouraging stakeholders to adopt practices that enhance both food production and clean energy generation. These policies, however, should be informed by empirical research exploring the intersection of agrivoltaics and regenerative agriculture.

Future experimental studies could focus on addressing the knowledge gaps to generate empirical evidence that demonstrates the long-term viability and benefits of agrivoltaics. For instance, analyzing the benefits of incorporating animal and crop waste as soil amendments are important parameters to examine during such experiments. These research efforts are essential for generating the empirical evidence needed to shape effective policies and scale regenerative agrivoltaics as a viable solution for sustainable food and energy production.

To unlock the full potential of regenerative agrivoltaics, future experimental studies must generate robust, context-specific empirical evidence that demonstrates the long-term viability and co-benefits of such systems. Several critical research directions become evident:

- Assessing soil health, fertility, microbial activity, and nutrient cycling under various PV module configurations, types of shading, spectral transmission/spectral engineering and transparency levels to determine optimal conditions for regenerative practices;
- Evaluating carbon sequestration potential through practices like cover cropping, organic amendments, and reduced tillage within agrivoltaic systems;
- Analyzing the effects of shading from solar modules on microbial activity, nutrient cycling, and organic matter dynamics;

- Investigating soil moisture retention and water-use efficiency, as well as agrivoltaic systems integrated with irrigation and fertigation, especially in arid or drought-prone regions;
- Measuring crop performance under different spectral qualities, light intensities, and shading durations and dynamics produced by diverse photovoltaic materials;
- Expanding the crop performance with agrivoltaics to more complicated/alternative cropping systems than standard monocrops, such as mixed, intercrop, and strip cropping systems, for both human food as well as forage;
- Exploring the impacts on biodiversity, including pollinators and above-ground wildlife, within integrated agrivoltaic landscapes;
- Examining the integration of livestock and composted organic waste, evaluating effects on soil structure and nutrient availability;
- Quantifying economic feasibility, including revenue from both energy and agricultural outputs, and cost–benefit comparisons.

Additional areas that require targeted attention include the following:

- Conducting integrated environmental life-cycle assessments (LCA) to evaluate environmental trade-offs and synergies between energy generation and regenerative land use;
- Developing multifunctionality performance metrics that assess system outcomes across ecological, economic, and social domains;
- Testing policy instruments and incentive models, such as agri-energy subsidies or carbon credits, tailored to regenerative agrivoltaic systems;
- Engaging farmers through participatory research models to understand adoption behaviors, cultural barriers, and site-specific adaptations.

Long-term field trials across multiple agroecological zones are essential to validate findings from controlled environments and short-term studies. These should be supported by sensor-based monitoring technologies to measure real-time soil, crops, and environmental parameters. Innovative designs—such as adaptive racking systems, combinations of tracking/anti-tracking, or semi-transparent PV modules—could help optimize light sharing and enhance multifunctionality. Finally, coordinated policy-oriented research is needed to evaluate land-use regulations, incentive structures, and cross-sectoral governance strategies. This will ensure that regenerative agrivoltaics is not only technically viable but also supported by enabling environments for large-scale deployment. By systematically addressing these knowledge gaps, innovation areas, and policy needs, future research will be instrumental in scaling regenerative agrivoltaics as a cornerstone of climate-resilient, resource-efficient agriculture.

5. Conclusions

This review lays a critical foundation for advancing regenerative agrivoltaics by identifying key areas ripe for innovation and development, which include the following: (1) carbon sequestration, (2) soil health and fertility, (3) soil moisture, (4) soil microbial activity, (5) soil nutrient, (6) crop performance, (7) water-use efficiency, and (8) regenerative agrivoltaics economics. By addressing the intersection of agriculture, renewable energy, and sustainability, regenerative agrivoltaics emphasizes the transformative potential of integrated systems in reshaping land use and resource management. Furthermore, the evaluation underscores the importance of policy and industry collaboration in facilitating the adoption of regenerative agrivoltaics, advocating for tailored support mechanisms to enable widespread implementation. By bridging knowledge gaps (soil health impacts, optimal module configuration, water-use and microclimate effects, biodiversity implications, livestock and composting integration effects, economic feasibility, policy gaps, long term

empirical field studies, and farmer engagement research) and highlighting opportunities (biodiversity benefits, enhancement of soil regeneration, improving water efficiency, and increasing farm revenue streams) for synergy, this research provides a framework to guide future studies and inform practical applications in dual-use agricultural systems.

Looking ahead, future development in regenerative agrivoltaics should focus on long-term field-based trials across diverse climatic and geographic conditions to validate lab-scale findings. Technological advancements such as dynamic PV modules or racking, smart soil monitoring systems, and precision agriculture tools can further optimize system performance. Whenever possible, these systems can be developed using open-source methodologies to maximize innovation rates and reduce costs to make the technologies as universally accessible as possible. Policy innovation, including land-use incentives and low-interest financing models, will be essential to enable adoption at scale. Interdisciplinary collaboration across agronomy, energy systems, and environmental science will be key to designing integrated, resilient food-energy systems that contribute to climate adaptation and sustainability goals globally.

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References

1. Fróna, D.; Szenderák, J.; Harangi-Rákos, M. The Challenge of Feeding the World. *Sustainability* **2019**, *11*, 5816. [CrossRef]
2. Hofstra, N.; Vermeulen, L.C. Impacts of Population Growth, Urbanisation and Sanitation Changes on Global Human *Cryptosporidium* Emissions to Surface Water. *Int. J. Hyg. Environ. Health* **2016**, *219*, 599–605. [CrossRef] [PubMed]
3. Hamuda, H.E.A.F.B.; Patko, I. Relationship between Environmental Impacts and Modern Agriculture. *Obuda Univ. E-Bull.* **2010**, *1*, 87–98.
4. Padhiary, M.; Kumar, R. Assessing the Environmental Impacts of Agriculture, Industrial Operations, and Mining on Agro-Ecosystems. In *Smart Internet of Things for Environment and Healthcare*; Azrou, M., Mabrouki, J., Alabdulatif, A., Guezzaz, A., Amounas, F., Eds.; Springer Nature: Cham, Switzerland, 2024; pp. 107–126, ISBN 978-3-031-70102-3.
5. Maraseni, T.N.; Qu, J. An International Comparison of Agricultural Nitrous Oxide Emissions. *J. Clean. Prod.* **2016**, *135*, 1256–1266. [CrossRef]
6. Arora, N.K. Impact of Climate Change on Agriculture Production and Its Sustainable Solutions. *Environ. Sustain.* **2019**, *2*, 95–96. [CrossRef]
7. Rhodes, C.J. The Imperative for Regenerative Agriculture. *Sci. Prog.* **2017**, *100*, 80–129. [CrossRef]
8. Schreefel, L.; Schulte, R.P.O.; de Boer, I.J.M.; Schrijver, A.P.; van Zanten, H.H.E. Regenerative Agriculture—The Soil Is the Base. *Glob. Food Secur.* **2020**, *26*, 100404. [CrossRef]
9. Newton, P.; Civita, N.; Frankel-Goldwater, L.; Bartel, K.; Johns, C. What Is Regenerative Agriculture? A Review of Scholar and Practitioner Definitions Based on Processes and Outcomes. *Front. Sustain. Food Syst.* **2020**, *4*, 577723. [CrossRef]
10. Elevitch, C.R.; Mazaroli, D.N.; Ragone, D. Agroforestry Standards for Regenerative Agriculture. *Sustainability* **2018**, *10*, 3337. [CrossRef]
11. Project Drawdown. About Project Drawdown. Available online: <https://drawdown.org/about> (accessed on 29 January 2025).
12. Eichler, S.; Mehra, M.; Toensmeier, E.; Frischmann, C. Regenerative Annual Cropping. *Project Drawdown*. Available online: <https://drawdown.org/solutions/regenerative-annual-cropping> (accessed on 27 January 2025).
13. Giller, K.E.; Hijbeek, R.; Andersson, J.A.; Sumberg, J. Regenerative Agriculture: An Agronomic Perspective. *Outlook Agric.* **2021**, *50*, 13–25. [CrossRef]
14. White, C. Why Regenerative Agriculture? *Am. J. Econ. Sociol.* **2020**, *79*, 799–812. [CrossRef]

15. O'Donoghue, T.; Minasny, B.; McBratney, A. Regenerative Agriculture and Its Potential to Improve Farmscape Function. *Sustainability* **2022**, *14*, 5815. [\[CrossRef\]](#)
16. Francis, C.A.; Harwood, R.R.; Parr, J.F. The Potential for Regenerative Agriculture in the Developing World. *Am. J. Altern. Agric.* **1986**, *1*, 65–74. [\[CrossRef\]](#)
17. Lal, R. Regenerative Agriculture for Food and Climate. *J. Soil Water Conserv.* **2020**, *75*, 123A–124A. [\[CrossRef\]](#)
18. Al-Kaisi, M.M.; Lal, R. Aligning Science and Policy of Regenerative Agriculture. *Soil Sci. Soc. Am. J.* **2020**, *84*, 1808–1820. [\[CrossRef\]](#)
19. Grand View Research. *Regenerative Agriculture Market Size & Share Report, 2030*; Grand View Research: San Francisco, CA, USA, 2023.
20. Østergaard, P.A.; Duic, N.; Noorollahi, Y.; Kalogirou, S. Advances in Renewable Energy for Sustainable Development. *Renew. Energy* **2023**, *219*, 119377. [\[CrossRef\]](#)
21. Choudhary, P.; Srivastava, R.K. Sustainability Perspectives- a Review for Solar Photovoltaic Trends and Growth Opportunities. *J. Clean. Prod.* **2019**, *227*, 589–612. [\[CrossRef\]](#)
22. National Renewable Energy Laboratory. Documenting a Decade of Cost Declines for PV Systems. Available online: <https://www.nrel.gov/news/program/2021/documenting-a-decade-of-cost-declines-for-pv-systems.html> (accessed on 6 September 2024).
23. Späth, L. Large-Scale Photovoltaics? Yes Please, but Not like This! Insights on Different Perspectives Underlying the Trade-off between Land Use and Renewable Electricity Development. *Energy Policy* **2018**, *122*, 429–437. [\[CrossRef\]](#)
24. Pimentel, D.; Marklein, A.; Toth, M.A.; Karpoff, M.; Paul, G.S.; McCormack, R.; Kyriazis, J.; Krueger, T. Biofuel Impacts on World Food Supply: Use of Fossil Fuel, Land and Water Resources. *Energies* **2008**, *1*, 41–78. [\[CrossRef\]](#)
25. Jamil, U.; Bonnington, A.; Pearce, J.M. The Agrivoltaic Potential of Canada. *Sustainability* **2023**, *15*, 3228. [\[CrossRef\]](#)
26. Fthenakis, V.M.; Kim, H.C.; Alsema, E. Emissions from Photovoltaic Life Cycles. *Environ. Sci. Technol.* **2008**, *42*, 2168–2174. [\[CrossRef\]](#) [\[PubMed\]](#)
27. Zheng, J.; Meng, S.; Zhang, X.; Zhao, H.; Ning, X.; Chen, F.; Omer, A.A.A.; Ingenhoff, J.; Liu, W. Increasing the Comprehensive Economic Benefits of Farmland with Even-Lighting Agrivoltaic Systems. *PLoS ONE* **2021**, *16*, e0254482. [\[CrossRef\]](#) [\[PubMed\]](#)
28. Trommsdorff, M.; Hopf, M.; Hörnle, O.; Berwind, M.; Schindele, S.; Wydra, K. Can Synergies in Agriculture through an Integration of Solar Energy Reduce the Cost of Agrivoltaics? An Economic Analysis in Apple Farming. *Appl. Energy* **2023**, *350*, 121619. [\[CrossRef\]](#)
29. Al-Saidi, M.; Lahham, N. Solar Energy Farming as a Development Innovation for Vulnerable Water Basins. *Dev. Pract.* **2019**, *29*, 619–634. [\[CrossRef\]](#)
30. Miao, R.; Khanna, M. Harnessing Advances in Agricultural Technologies to Optimize Resource Utilization in the Food-Energy-Water Nexus. *Annu. Rev. Resour. Econ.* **2020**, *12*, 65–85. [\[CrossRef\]](#)
31. Elamri, Y.; Cheviron, B.; Lopez, J.-M.; Dejean, C.; Belaud, G. Water Budget and Crop Modelling for Agrivoltaic Systems: Application to Irrigated Lettuces. *Agric. Water Manag.* **2018**, *208*, 440–453. [\[CrossRef\]](#)
32. Giudice, B.D.; Stillinger, C.; Chapman, E.; Martin, M.; Riihimäki, B. Residential Agrivoltaics: Energy Efficiency and Water Conservation in the Urban Landscape. In Proceedings of the 2021 IEEE Green Technologies Conference (GreenTech), Denver, CO, USA, 7–9 April 2021; pp. 237–244.
33. Trommsdorff, M.; Kang, J.; Reise, C.; Schindele, S.; Bopp, G.; Ehmann, A.; Weselek, A.; Högy, P.; Obergfell, T. Combining Food and Energy Production: Design of an Agrivoltaic System Applied in Arable and Vegetable Farming in Germany. *Renew. Sustain. Energy Rev.* **2021**, *140*, 110694. [\[CrossRef\]](#)
34. Weselek, A.; Bauerle, A.; Zikeli, S.; Lewandowski, I.; Högy, P. Effects on Crop Development, Yields and Chemical Composition of Celeriac (*Apium graveolens* L. Var. *rapaceum*) Cultivated Underneath an Agrivoltaic System. *Agronomy* **2021**, *11*, 733. [\[CrossRef\]](#)
35. Weselek, A.; Ehmann, A.; Zikeli, S.; Lewandowski, I.; Schindele, S.; Högy, P. Agrophotovoltaic Systems: Applications, Challenges, and Opportunities. A Review. *Agron. Sustain. Dev.* **2019**, *39*, 35. [\[CrossRef\]](#)
36. Adeh, E.H.; Selker, J.S.; Higgins, C.W. Remarkable Agrivoltaic Influence on Soil Moisture, Micrometeorology and Water-Use Efficiency. *PLoS ONE* **2018**, *13*, e0203256. [\[CrossRef\]](#)
37. Jamil, U.; Pearce, J.M. Maximizing Biomass with Agrivoltaics: Potential and Policy in Saskatchewan Canada. *Biomass* **2023**, *3*, 188–216. [\[CrossRef\]](#)
38. Barron-Gafford, G.A.; Pavao-Zuckerman, M.A.; Minor, R.L.; Sutter, L.F.; Barnett-Moreno, I.; Blackett, D.T.; Thompson, M.; Dimond, K.; Gerlak, A.K.; Nabhan, G.P.; et al. Agrivoltaics Provide Mutual Benefits across the Food–Energy–Water Nexus in Drylands. *Nat. Sustain.* **2019**, *2*, 848–855. [\[CrossRef\]](#)
39. Deboutte, G. Agrivoltaics Can Increase Grape Yield by Up to 60%. *pv Magazine International*. 2024. Available online: <https://www.pv-magazine.com/2024/11/29/agrivoltaics-can-increase-grape-yield-by-up-to-60/> (accessed on 16 April 2025).
40. Trommsdorff, M.; Dhal, I.S.; Özdemir, Ö.E.; Ketzer, D.; Weinberger, N.; Rösch, C. Chapter 5—Agrivoltaics: Solar Power Generation and Food Production. In *Solar Energy Advancements in Agriculture and Food Production Systems*; Gorjian, S., Campana, P.E., Eds.; Academic Press: Cambridge, MA, USA, 2022; pp. 159–210, ISBN 978-0-323-89866-9.

41. Sekiyama, T.; Nagashima, A. Solar Sharing for Both Food and Clean Energy Production: Performance of Agrivoltaic Systems for Corn, A Typical Shade-Intolerant Crop. *Environments* **2019**, *6*, 65. [CrossRef]
42. Herbert, S.J. Yield Comparisons UMass Farm NREL Co-Location Project 2016–17. 2018. Available online: <https://www.umass.edu/agriculture-food-environment/clean-energy/research-initiatives/solar-agriculture/researching-agricultural-economic-impacts-of-agrivoltaics-dual-use-solar> (accessed on 16 April 2025).
43. Herbert, S.J.; Oleskewicz, K. *UMass Dual-Use Solar Agricultural Report and Final Report Summary*; University of Massachusetts: Amherst, MA, USA, 2019.
44. Jamil, U.; Givans, J.; Pearce, J.M. Impacts of Type of Partial Transparency on Strawberry Agrivoltaics: Uniform Illumination Thin Film Cadmium-Telluride and Non-Uniform Crystalline Silicon Solar Photovoltaic Modules. *Renew. Energy* **2025**, *247*, 122913. [CrossRef]
45. Jamil, U.; Pearce, J.M. Experimental Impacts of Transparency on Strawberry Agrivoltaics Using Thin Film Photovoltaic Modules under Low Light Conditions. *Solar Energy* **2025**, *290*, 113375. [CrossRef]
46. Jamil, U.; Pearce, J.M. Strawberry Agrivoltaics in Canada: Comparing Uniform Thin Film and Non-Uniform Crystalline Silicon Semi-Transparent Solar Photovoltaic Modules in Controlled Environment Agriculture (To Be Published). 2025, *in press*.
47. Jamil, U.; Rahman, M.; Pearce, J.M. Complexities in Agrivoltaic Policy Mandates Illustrated with Semitransparent Photovoltaic Yields. *SSRN* **2024**. [CrossRef]
48. Jamil, U.; Rahman, M.M.; Hayibo, K.S.; Alrayes, L.; Fordjour, E.; Thomas, R.; Pearce, J.M. Impacts of Transparency in Agrivoltaics Lettuce Cultivation Using Uniform or Non-Uniform Semitransparent Solar Photovoltaic Modules. *SSRN* **2024**. [CrossRef]
49. Willockx, B.; Kladas, A.; Lavaert, C.; Uytterhaegen, B.; Cappelle, J. How agrivoltaics can be used as a crop protection system. In Proceedings of the EUROSIS, Rennes, France, 5–8 April 2022.
50. Xiao, Y.; Zhang, H.; Pan, S.; Wang, Q.; He, J.; Jia, X. An Agrivoltaic Park Enhancing Ecological, Economic and Social Benefits on Degraded Land in Jiangshan, China. *AIP Conf. Proc.* **2022**, *2635*, 020002. [CrossRef]
51. Williams, J. *How China Uses Renewable Energy to Restore the Desert*; The Earthbound Report: Singapore, 2022.
52. Dupraz, C.; Marrou, H.; Talbot, G.; Dufour, L.; Nogier, A.; Ferard, Y. Combining Solar Photovoltaic Panels and Food Crops for Optimising Land Use: Towards New Agrivoltaic Schemes. *Renew. Energy* **2011**, *36*, 2725–2732. [CrossRef]
53. Schindele, S.; Trommsdorff, M.; Schlaak, A.; Obergfell, T.; Bopp, G.; Reise, C.; Braun, C.; Weselek, A.; Bauerle, A.; Högy, P.; et al. Implementation of Agrophotovoltaics: Techno-Economic Analysis of the Price-Performance Ratio and Its Policy Implications. *Appl. Energy* **2020**, *265*, 114737. [CrossRef]
54. Mavani, D.D.; Chauhan, P.M.; Joshi, V. Beauty of Agrivoltaic System Regarding Double Utilization of Same Piece of Land for Generation of Electricity & Food Production. *Int. J. Sci. Eng. Res.* **2019**, *10*, 118–148.
55. Mow, B. Solar Sheep and Voltaic Veggies: Uniting Solar Power and Agriculture. Available online: <https://web.archive.org/web/20241205025105/https://www.nrel.gov/state-local-tribal/blog/posts/solar-sheep-and-voltaic-veggies-uniting-solar-power-and-agriculture.html/> (accessed on 1 April 2023).
56. Adeh, E.H.; Good, S.P.; Calaf, M.; Higgins, C.W. Solar PV Power Potential Is Greatest Over Croplands. *Sci. Rep.* **2019**, *9*, 11442. [CrossRef] [PubMed]
57. Brain, R. The Local Food Movement: Definitions, Benefits, and Resources. *USU Ext. Publ.* **2012**, *1*, 1–4.
58. Martinez, S.; Hand, M.; Pra, M.; Pollack, S.; Ralston, K.; Smith, T.; Vogel, S.; Clark, S.; Lohr, L.; Low, S.; et al. Local Food Systems: Concepts, Impacts, and Issues. In *Local Food Systems: Background and Issues*; Diane Publishing: Collingdale, PA, USA, 2010; pp. 1–75.
59. Feenstra, G.W. Local Food Systems and Sustainable Communities. *Am. J. Altern. Agric.* **1997**, *12*, 28–36. [CrossRef]
60. Prehoda, E.W.; Pearce, J.M. Potential Lives Saved by Replacing Coal with Solar Photovoltaic Electricity Production in the U.S. *Renew. Sustain. Energy Rev.* **2017**, *80*, 710–715. [CrossRef]
61. Sommerfeldt, N.; Pearce, J.M. Can Grid-Tied Solar Photovoltaics Lead to Residential Heating Electrification? A Techno-Economic Case Study in the Midwestern U.S. *Appl. Energy* **2023**, *336*, 120838. [CrossRef]
62. McDonald, M.T.; Hayibo, K.S.; Hafting, F.; Pearce, J.M. Economics of Open-Source Solar Photovoltaic Powered Cryptocurrency Mining. *Ledger* **2022**, *8*, 1–26.
63. Tributsch, H. Photovoltaic Hydrogen Generation. *Int. J. Hydrogen Energy* **2008**, *33*, 5911–5930. [CrossRef]
64. Fereidooni, M.; Mostafaeipour, A.; Kalantar, V.; Goudarzi, H. A Comprehensive Evaluation of Hydrogen Production from Photovoltaic Power Station. *Renew. Sustain. Energy Rev.* **2018**, *82*, 415–423. [CrossRef]
65. Pal, P.; Mukherjee, V. Off-Grid Solar Photovoltaic/Hydrogen Fuel Cell System for Renewable Energy Generation: An Investigation Based on Techno-Economic Feasibility Assessment for the Application of End-User Load Demand in North-East India. *Renew. Sustain. Energy Rev.* **2021**, *149*, 111421. [CrossRef]
66. Fasihi, M.; Weiss, R.; Savolainen, J.; Breyer, C. Global Potential of Green Ammonia Based on Hybrid PV-Wind Power Plants. *Appl. Energy* **2021**, *294*, 116170. [CrossRef]

67. Du, Z.; Denkenberger, D.; Pearce, J.M. Solar Photovoltaic Powered On-Site Ammonia Production for Nitrogen Fertilization. *Solar Energy* **2015**, *122*, 562–568. [CrossRef]
68. Thompson, E.P.; Bombelli, E.L.; Shubham, S.; Watson, H.; Everard, A.; D'Ardes, V.; Schievano, A.; Bocchi, S.; Zand, N.; Howe, C.J.; et al. Tinted Semi-Transparent Solar Panels Allow Concurrent Production of Crops and Electricity on the Same Cropland. *Adv. Energy Mater.* **2020**, *10*, 2001189. [CrossRef]
69. Meyer, T.K.; Pearce, J.M. How Easy Is It to Feed Everyone? Economic Alternatives to Eliminate Human Nutrition Deficits. *Food Ethics* **2022**, *8*, 3. [CrossRef]
70. Fernández-Solas, Á.; Fernández-Ocaña, A.M.; Almonacid, F.; Fernández, E.F. Potential of Agrivoltaics Systems into Olive Groves in the Mediterranean Region. *Appl. Energy* **2023**, *352*, 121988. [CrossRef]
71. Asgari, N.; Jamil, U.; Pearce, J.M. Net Zero Agrivoltaic Arrays for Agrotunnel Vertical Growing Systems: Energy Analysis and System Sizing. *Sustainability* **2024**, *16*, 6120. [CrossRef]
72. Jamil, U.; Pearce, J.M. Energy Policy for Agrivoltaics in Alberta Canada. *Energies* **2023**, *16*, 53. [CrossRef]
73. Gasch, A.; Lara, R.; Pearce, J.M. Financial Analysis of Agrivoltaic Sheep: Breeding and Auction Lamb Business Models. *Appl. Energy* **2025**, *381*, 125057. [CrossRef]
74. MarkNtel Advisors. Global Agrivoltaics Market Research Report: Forecast (2024–2030). Available online: <https://www.marknteladvisors.com/research-library/agrivoltaic-market.html> (accessed on 6 September 2024).
75. Singh, S. Energy Crisis and Climate Change. In *Energy*; John Wiley & Sons, Ltd.: Hoboken, NJ, USA, 2021; pp. 1–17, ISBN 978-1-119-74150-3.
76. Peterson, E. The Coming Global Food Crisis. In *Cornhusker Economics*; University of Nebraska-Lincoln: Lincoln, NE, USA, 2022.
77. Weselek, A.; Bauerle, A.; Hartung, J.; Zikeli, S.; Lewandowski, I.; Högy, P. Agrivoltaic System Impacts on Microclimate and Yield of Different Crops within an Organic Crop Rotation in a Temperate Climate. *Agron. Sustain. Dev.* **2021**, *41*, 59. [CrossRef]
78. Khangura, R.; Ferris, D.; Wagg, C.; Bowyer, J. Regenerative Agriculture—A Literature Review on the Practices and Mechanisms Used to Improve Soil Health. *Sustainability* **2023**, *15*, 2338. [CrossRef]
79. Schulte, L.A.; Dale, B.E.; Bozzetto, S.; Liebman, M.; Souza, G.M.; Haddad, N.; Richard, T.L.; Basso, B.; Brown, R.C.; Hilbert, J.A.; et al. Meeting Global Challenges with Regenerative Agriculture Producing Food and Energy. *Nat. Sustain.* **2022**, *5*, 384–388. [CrossRef]
80. UN THE 17 GOALS. Sustainable Development. Available online: <https://sdgs.un.org/goals> (accessed on 24 May 2023).
81. Poelplau, C.; Don, A. Carbon Sequestration in Agricultural Soils via Cultivation of Cover Crops—A Meta-Analysis. *Agric. Ecosyst. Environ.* **2015**, *200*, 33–41. [CrossRef]
82. Fageria, N.K.; Baligar, V.C.; Bailey, B.A. Role of Cover Crops in Improving Soil and Row Crop Productivity. *Commun. Soil Sci. Plant Anal.* **2005**, *36*, 2733–2757. [CrossRef]
83. Frye, W.W.; Blevins, R.L.; Smith, M.S.; Corak, S.J.; Varco, J.J. Role of Annual Legume Cover Crops in Efficient Use of Water and Nitrogen. In *Cropping Strategies for Efficient Use of Water and Nitrogen*; ASA Special Publications: Madison, WI, USA, 1988; Volume 51.
84. Lal, R. Soil Carbon Sequestration to Mitigate Climate Change. *Geoderma* **2004**, *123*, 1–22. [CrossRef]
85. Juillion, P.; Lopez, G.; Fumey, D.; Lesniak, V.; Génard, M.; Vercambre, G. Shading Apple Trees with an Agrivoltaic System: Impact on Water Relations, Leaf Morphophysiological Characteristics and Yield Determinants. *Sci. Hortic.* **2022**, *306*, 111434. [CrossRef]
86. Agostini, A.; Colauzzi, M.; Amaducci, S. Innovative Agrivoltaic Systems to Produce Sustainable Energy: An Economic and Environmental Assessment. *Appl. Energy* **2021**, *281*, 116102. [CrossRef]
87. Chen, X.; Jia, L.; Jia, T.; Hao, Z. An Carbon Neutrality Industrial Chain of “Desert-Photovoltaic Power Generation-Ecological Agriculture”: Practice from the Ulan Buh Desert, Dengkou, Inner Mongolia. *Zgdyw* **2022**, *5*, 549–552. [CrossRef]
88. Ramos-Fuentes, I.A.; Elamri, Y.; Cheviron, B.; Dejean, C.; Belaud, G.; Fumey, D. Effects of Shade and Deficit Irrigation on Maize Growth and Development in Fixed and Dynamic AgriVoltaic Systems. *Agric. Water Manag.* **2023**, *280*, 108187. [CrossRef]
89. Semeraro, T.; Scarano, A.; Curci, L.M.; Leggieri, A.; Lenucci, M.; Basset, A.; Santino, A.; Piro, G.; De Caroli, M. Shading Effects in Agrivoltaic Systems Can Make the Difference in Boosting Food Security in Climate Change. *Appl. Energy* **2024**, *358*, 122565. [CrossRef]
90. Uchanski, M.; Hickey, T.; Bousset, J.; Barth, K.L. Characterization of Agrivoltaic Crop Environment Conditions Using Opaque and Thin-Film Semi-Transparent Modules. *Energies* **2023**, *16*, 3012. [CrossRef]
91. Zhang, Z.; Zhang, F.; Zhang, W.; Li, M.; Liu, W.; Ali Abaker Omer, A.; Zheng, J.; Zhang, X.; Liu, W. Spectral-Splitting Concentrator Agrivoltaics for Higher Hybrid Solar Energy Conversion Efficiency. *Energy Convers. Manag.* **2023**, *276*, 116567. [CrossRef]
92. Handler, R.; Pearce, J.M. Greener Sheep: Life Cycle Analysis of Integrated Sheep Agrivoltaic Systems. *Clean. Energy Syst.* **2022**, *3*, 100036. [CrossRef]
93. Verheijen, F.G.A.; Bastos, A.C. Discussion: Avoid Severe (Future) Soil Erosion from Agrivoltaics. *Sci. Total Environ.* **2023**, *873*, 162249. [CrossRef]
94. Gomiero, T.; Pimentel, D.; Paoletti, M.G. Environmental Impact of Different Agricultural Management Practices: Conventional vs. Organic Agriculture. *Crit. Rev. Plant Sci.* **2011**, *30*, 95–124. [CrossRef]

95. Watson, C.A.; Atkinson, D.; Gosling, P.; Jackson, L.R.; Rayns, F.W. Managing Soil Fertility in Organic Farming Systems. *Soil Use Manag.* **2002**, *18*, 239–247. [\[CrossRef\]](#)
96. Lamaoui, M.; Jemo, M.; Datla, R.; Bekkaoui, F. Heat and Drought Stresses in Crops and Approaches for Their Mitigation. *Front. Chem.* **2018**, *6*, 26. [\[CrossRef\]](#)
97. Cherlinka, V. Heat Stress in Plants: Symptoms, Prevention, and Recovery. Available online: <https://eos.com/blog/heat-stress-in-plants/> (accessed on 27 January 2025).
98. Brunelle, T.; Chakir, R.; Carpentier, A.; Dorin, B.; Goll, D.; Guilpart, N.; Maggi, F.; Makowski, D.; Nesme, T.; Roosen, J.; et al. Reducing Chemical Inputs in Agriculture Requires a System Change. *Commun. Earth Environ.* **2024**, *5*, 369. [\[CrossRef\]](#)
99. Cuppari, R.I.; Higgins, C.W.; Characklis, G.W. Agrivoltaics and Weather Risk: A Diversification Strategy for Landowners. *Appl. Energy* **2021**, *291*, 116809. [\[CrossRef\]](#)
100. Ravilla, A.; Shirkey, G.; Chen, J.; Jarchow, M.; Sary, O.; Celik, I. Techno-Economic and Life Cycle Assessment of Agrivoltaic System (AVS) Designs. *Sci. Total Environ.* **2024**, *912*, 169274. [\[CrossRef\]](#)
101. Lal, R. Challenges and Opportunities in Soil Organic Matter Research. *Eur. J. Soil Sci.* **2009**, *60*, 158–169. [\[CrossRef\]](#)
102. De Corato, U. Agricultural Waste Recycling in Horticultural Intensive Farming Systems by On-Farm Composting and Compost-Based Tea Application Improves Soil Quality and Plant Health: A Review under the Perspective of a Circular Economy. *Sci. Total Environ.* **2020**, *738*, 139840. [\[CrossRef\]](#)
103. Scotti, R.; Pane, C.; Spaccini, R.; Palese, A.M.; Piccolo, A.; Celano, G.; Zaccardelli, M. On-Farm Compost: A Useful Tool to Improve Soil Quality under Intensive Farming Systems. *Appl. Soil Ecol.* **2016**, *107*, 13–23. [\[CrossRef\]](#)
104. Luo, J.; Luo, Z.; Li, W.; Shi, W.; Sui, X. The Early Effects of an Agrivoltaic System within a Different Crop Cultivation on Soil Quality in Dry–Hot Valley Eco-Fragile Areas. *Agronomy* **2024**, *14*, 584. [\[CrossRef\]](#)
105. Sharpe, K.T.; Heins, B.J.; Buchanan, E.S.; Reese, M.H. Evaluation of Solar Photovoltaic Systems to Shade Cows in a Pasture-Based Dairy Herd. *J. Dairy Sci.* **2021**, *104*, 2794–2806. [\[CrossRef\]](#)
106. Diacono, M.; Montemurro, F. Long-Term Effects of Organic Amendments on Soil Fertility. In *Sustainable Agriculture Volume 2*; Lichtfouse, E., Hamelin, M., Navarrete, M., Debaeke, P., Eds.; Springer: Dordrecht, The Netherlands, 2011; pp. 761–786, ISBN 978-94-007-0394-0.
107. Bedada, W.; Karlton, E.; Lemenih, M.; Tolera, M. Long-Term Addition of Compost and NP Fertilizer Increases Crop Yield and Improves Soil Quality in Experiments on Smallholder Farms. *Agric. Ecosyst. Environ.* **2014**, *195*, 193–201. [\[CrossRef\]](#)
108. Andrew, A.C.; Higgins, C.W.; Smallman, M.A.; Graham, M.; Ates, S. Herbage Yield, Lamb Growth and Foraging Behavior in Agrivoltaic Production System. *Front. Sustain. Food Syst.* **2021**, *5*, 659175. [\[CrossRef\]](#)
109. Lytle, W.; Meyer, T.K.; Tanikella, N.G.; Burnham, L.; Engel, J.; Schelly, C.; Pearce, J.M. Conceptual Design and Rationale for a New Agrivoltaics Concept: Pasture-Raised Rabbits and Solar Farming. *J. Clean. Prod.* **2021**, *282*, 124476. [\[CrossRef\]](#)
110. Pascaris, A.S.; Handler, R.; Schelly, C.; Pearce, J.M. Life Cycle Assessment of Pasture-Based Agrivoltaic Systems: Emissions and Energy Use of Integrated Rabbit Production. *Clean. Responsible Consum.* **2021**, *3*, 100030. [\[CrossRef\]](#)
111. Heins, B.J.; Sharpe, K.T.; Buchanan, E.S.; Reese, M.H. Agrivoltaics to Shade Cows in a Pasture-Based Dairy System. *AIP Conf. Proc.* **2022**, *2635*, 060001. [\[CrossRef\]](#)
112. Mao, J.; Olk, D.C.; Fang, X.; He, Z.; Schmidt-Rohr, K. Influence of Animal Manure Application on the Chemical Structures of Soil Organic Matter as Investigated by Advanced Solid-State NMR and FT-IR Spectroscopy. *Geoderma* **2008**, *146*, 353–362. [\[CrossRef\]](#)
113. Wilkinson, S.R. Plant Nutrient and Economic Value of Animal Manures. *J. Anim. Sci.* **1979**, *48*, 121–133. [\[CrossRef\]](#)
114. Udriou, N.-A. The Use of Agrivoltaic Systems, an Alternative for Romanian Farmers. *Sci. Pap. Ser. D Anim. Sci.* **2023**, *66*, 410–420.
115. Díaz de Otálora, X.; Epelde, L.; Arranz, J.; Garbisu, C.; Ruiz, R.; Mandaluniz, N. Regenerative Rotational Grazing Management of Dairy Sheep Increases Springtime Grass Production and Topsoil Carbon Storage. *Ecol. Indic.* **2021**, *125*, 107484. [\[CrossRef\]](#)
116. Sturchio, M.A.; Kannenberg, S.A.; Knapp, A.K. Agrivoltaic Arrays Can Maintain Semi-Arid Grassland Productivity and Extend the Seasonality of Forage Quality. *Appl. Energy* **2024**, *356*, 122418. [\[CrossRef\]](#)
117. Seitz, T.J.; Schütte, U.M.E.; Drown, D.M. Soil Disturbance Affects Plant Productivity via Soil Microbial Community Shifts. *Front. Microbiol.* **2021**, *12*, 619711. [\[CrossRef\]](#) [\[PubMed\]](#)
118. Nunes, M.R.; van Es, H.M.; Schindelbeck, R.; Ristow, A.J.; Ryan, M. No-till and Cropping System Diversification Improve Soil Health and Crop Yield. *Geoderma* **2018**, *328*, 30–43. [\[CrossRef\]](#)
119. Sharma, P.; Singh, G.; Singh, R.P. Conservation Tillage and Optimal Water Supply Enhance Microbial Enzyme (Glucosidase, Urease and Phosphatase) Activities in Fields under Wheat Cultivation during Various Nitrogen Management Practices. *Arch. Agron. Soil Sci.* **2013**, *59*, 911–928. [\[CrossRef\]](#)
120. Amaducci, S.; Yin, X.; Colauzzi, M. Agrivoltaic Systems to Optimise Land Use for Electric Energy Production. *Appl. Energy* **2018**, *220*, 545–561. [\[CrossRef\]](#)
121. Yue, S.; Guo, M.; Zou, P.; Wu, W.; Zhou, X. Effects of Photovoltaic Panels on Soil Temperature and Moisture in Desert Areas. *Environ. Sci. Pollut. Res.* **2021**, *28*, 17506–17518. [\[CrossRef\]](#)

122. Panagos, P.; Borrelli, P.; Matthews, F.; Liakos, L.; Bezak, N.; Diodato, N.; Ballabio, C. Global Rainfall Erosivity Projections for 2050 and 2070. *J. Hydrol.* **2022**, *610*, 127865. [\[CrossRef\]](#)
123. Wang, F.; Gao, J. How a Photovoltaic Panel Impacts Rainfall-Runoff and Soil Erosion Processes on Slopes at the Plot Scale. *J. Hydrol.* **2023**, *620*, 129522. [\[CrossRef\]](#)
124. Maghami, M.R.; Hizam, H.; Gomes, C.; Radzi, M.A.; Rezadad, M.I.; Hajighorbani, S. Power Loss Due to Soiling on Solar Panel: A Review. *Renew. Sustain. Energy Rev.* **2016**, *59*, 1307–1316. [\[CrossRef\]](#)
125. Krasner, N.Z.; Fox, J.; Armstrong, A.; Ave, K.; Carvalho, F.; Li, Y.; Walston, L.J.; Ricketts, M.P.; Jordaan, S.M.; Abou Najm, M.; et al. Impacts of Photovoltaic Solar Energy on Soil Carbon: A Global Systematic Review and Framework. *Renew. Sustain. Energy Rev.* **2025**, *208*, 115032. [\[CrossRef\]](#)
126. Towner, E.; Karas, T.; Janski, J.; Macknick, J.; Ravi, S. *Managed Sheep Grazing Can Improve Soil Quality and Carbon Sequestration at Solar Photovoltaic Sites*; dSPACE Inc.: Wixom, MI, USA, 2022. [\[CrossRef\]](#)
127. Grubbs, E.K.; Gruss, S.M.; Schull, V.Z.; Gosney, M.J.; Mickelbart, M.V.; Brouder, S.; Gitau, M.W.; Bermel, P.; Tuinstra, M.R.; Agrawal, R. Optimized Agrivoltaic Tracking for Nearly-Full Commodity Crop and Energy Production. *Renew. Sustain. Energy Rev.* **2024**, *191*, 114018. [\[CrossRef\]](#)
128. Willockx, B.; Reher, T.; Lavaert, C.; Herteleer, B.; Van de Poel, B.; Cappelle, J. Design and Evaluation of an Agrivoltaic System for a Pear Orchard. *Appl. Energy* **2024**, *353*, 122166. [\[CrossRef\]](#)
129. Nowak, D.J.; Greenfield, E.J.; Hoehn, R.E.; Lapoint, E. Carbon Storage and Sequestration by Trees in Urban and Community Areas of the United States. *Environ. Pollut.* **2013**, *178*, 229–236. [\[CrossRef\]](#) [\[PubMed\]](#)
130. Bruhwylter, R.; Sánchez, H.; Meza, C.; Lebeau, F.; Brunet, P.; Dabadie, G.; Dittmann, S.; Gottschalg, R.; Negroni, J.J. Vertical Agrivoltaics and Its Potential for Electricity Production and Agricultural Water Demand: A Case Study in the Area of Chanco, Chile. *Sustain. Energy Technol. Assess.* **2023**, *60*, 103425. [\[CrossRef\]](#)
131. Sojib Ahmed, M.; Rezwan Khan, M.; Haque, A.; Ryyan Khan, M. Agrivoltaics Analysis in a Techno-Economic Framework: Understanding Why Agrivoltaics on Rice Will Always Be Profitable. *Appl. Energy* **2022**, *323*, 119560. [\[CrossRef\]](#)
132. Chalgybayeva, A.; Balogh, P.; Szöllősi, L.; Gabnai, Z.; Apáti, F.; Sipos, M.; Bai, A. The Economic Potential of Agrivoltaic Systems in Apple Cultivation—A Hungarian Case Study. *Sustainability* **2024**, *16*, 2325. [\[CrossRef\]](#)
133. Juillion, P.; Lopez, G.; Fumey, D.; Lesniak, V.; Génard, M.; Vercambre, G. Combining Field Experiments under an Agrivoltaic System and a Kinetic Fruit Model to Understand the Impact of Shading on Apple Carbohydrate Metabolism and Quality. *Agrofor. Syst.* **2024**, *98*, 2829–2846. [\[CrossRef\]](#)
134. Jamil, U.; Vandewetering, N.; Sadat, S.A.; Pearce, J.M. Wood- and Cable-Based Variable Tilt Stilt-Mounted Solar Photovoltaic Racking System. *Designs* **2024**, *8*, 6. [\[CrossRef\]](#)
135. Jamil, U.; Vandewetering, N.; Pearce, J.M. Solar Photovoltaic Wood Racking Mechanical Design for Trellis-Based Agrivoltaics. *PLoS ONE* **2023**, *18*, e0294682. [\[CrossRef\]](#) [\[PubMed\]](#)
136. Vandewetering, N.; Jamil, U.; Pearce, J.M. Ballast-Supported Foundation Designs for Low-Cost Open-Source Solar Photovoltaic Racking. *Designs* **2024**, *8*, 17. [\[CrossRef\]](#)
137. Rahman, M.M.; Jamil, U.; Pearce, J.M. Open-Source Photosynthetically Active Radiation Sensor for Enhanced Agricultural and Agrivoltaics Monitoring. *Preprints* **2025**. [\[CrossRef\]](#)
138. Jamil, U.; Sadat, S.A.; Pearce, J.M. Distributed Manufacturing for Distributed Generation: 3-D Printed Solar Photovoltaic Module Mounting Mechanisms for Wood Racking. *Renew. Energy* **2024**, *228*, 120651. [\[CrossRef\]](#)

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