**Agrivoltaics in the Himalayan and Gangetic Plain: Pioneering Sustainable Solutions for Biodiversity Conservation and Mitigating Alien Species Invasion**

**Abstract**

Agrivoltaics, the integration of solar energy generation with agriculture, offers a promising solution for the Himalayan and Gangetic Plain regions, where over 500 million people depend on agriculture for their livelihoods. Climate change, with average temperatures projected to rise by 1.5–2°C by 2050, leading to erratic rainfall and declining crop yields, biodiversity and increasing invasion of Allien Species. Agrivoltaic systems can enhance land productivity through dual land use while reducing soil moisture loss by 20–30% due to shading effects. Additionally, solar panels can provide an alternative income stream for farmers, potentially increasing annual farm earnings by 30–40%. Studies indicate that agrivoltaics setups can improve water-use efficiency crucial for water-stressed areas in the Gangetic basin. Furthermore, these systems create microhabitats that promote biodiversity by reducing land degradation and fostering pollinator populations. However, challenges such as land availability, initial investment costs, and policy frameworks must be addressed. This study examines the feasibility and benefits of agrivoltaics in the Himalayan and Gangetic Plain regions, emphasizing its role in sustainable agriculture, environmental harmony, and biodiversity conservation policy and mitigation of alien species invasion.

**Introduction**

Agrivoltaics represents a transformative approach that integrates solar energy production with agricultural activities. This dual-use system involves installing solar panels over crops or livestock, optimizing land for both energy generation and food production. The panels, elevated or mounted, shade crops and livestock while generating clean energy. This mutually beneficial system not only improves land utilization but also enhances crop yields by reducing water evaporation and creating favourable microclimates. Agrivoltaics systems can reduce energy costs for farmers and increase biodiversity by attracting pollinators. Additionally, they contribute to the reduction of carbon emissions by supporting renewable energy (Sirnik et al, 2023).

The technology has multiple configurations ground-mounted, elevated, or roof-mounted panels and is adaptable to various farming practices. However, optimizing these systems for specific crops, climates, and geographical needs remains a challenge. This could help to meet global food security and renewable energy demands, particularly in regions vulnerable to climate change.

This innovative approach not only optimizes land use by combining food production with renewable energy generation but also creates diverse microhabitats under and around solar arrays. Flora, fauna, agriculture, soil, and other biodiversity are declining day by day because of human intervention and climate change (Mishra et al., 2021). Climate change is accelerating the invasion of alien animal species, disrupting ecosystems and threatening native biodiversity. Climate change, with average temperatures projected to rise by 1.5–2°C by 2050 Khaiwal et al 2024, leading to erratic rainfall and declining crop yields, biodiversity and increasing invasion of allien species. Rising temperatures, altered precipitation patterns, and habitat degradation create favorable conditions for non-native species to thrive, often outcompeting indigenous wildlife. Warmer climates allow invasive species like Giant African Snail (*Achatina fulica*), damages 500 plant species, including banana, papaya, coffee and pulses leading to ecological, agricultural and economic harm. In India, 28 invasive alien insect species have been identified by Sandilyan et al., 2018. These insects spread through global trade, ornamental plant imports, climate change, and accidental human activities. Imported goods, nursery plants, and contaminated cargo introduce pests, while rising temperatures allow their survival in new regions. These factors threaten agriculture and biodiversity, emphasizing the necessity of stringent biosecurity measures. Several of these invasive insect species in India pose significant threats to agriculture, forestry, and public health. The serpentine leaf miner (*Liriomyza trifolii*) damages a variety of vegetable and ornamental crops by mining leaves, reducing photosynthesis, and causing premature leaf drop. The oriental fruit fly (*Bactrocera dorsalis*) is a major pest of fruit crops like mango and guava, as its larvae develop inside ripening fruits, leading to decay and economic losses (Mutamiswa et al; 2021).

 The southern house mosquito (*Culex quinquefasciatus*) and the yellow fever mosquito (*Aedes aegypti*) are notorious disease vectors, transmitting filariasis, dengue, chikungunya, and Zika virus, making them serious public health concerns. In agriculture, the coffee berry borer (*Hypothenemus hampei*) severely affects coffee production by boring into coffee berries, while the ambrosia beetle (*Xyleborus volvulus*) weakens trees by burrowing into wood and transmitting fungal pathogens (Haraprasad et al 2001). The diamond-back moth (*Plutella xylostella*) is a major pest of cruciferous vegetables, causing severe defoliation and crop losses, whereas the potato tuber moth (*Phthorimaea operculella*) tunnels into potato tubers both in the field and in storage, reducing quality and yield (Saleh et al 2023). Another serious threat to agriculture is the tomato pinworm (*Tuta absoluta*), which devastates tomato crops by mining into leaves, stems, and fruits, leading to significant yield losses (Chavan et al 2021). These invasive pests collectively threaten India’s economy, food security, and ecosystems, necessitating stringent monitoring and management strategies. Effective management strategies, including early detection, habitat restoration, and stricter biosecurity measures, are essential to control the spread of invasive species and mitigate their impact on ecosystems (Burgiel and Muir; 2010).

Therefore, Agrivoltaics, the integration of solar panels with agricultural activities, presents a unique opportunity to enhance biodiversity, particularly by supporting insect habitats. The partial shading provided by solar panels can foster a range of plant species that might not thrive in full sunlight, thereby offering varied resources for pollinators and other beneficial insects. Additionally, the reduced use of chemical inputs in agrivoltaic systems can further benefit insect populations by minimizing harmful impacts on their environments. By carefully designing agrivoltaic systems to include flowering plants and nesting sites, these installations can become valuable refuges for insects, thereby contributing to overall ecosystem health and resilience (Walston,et al, 2022).

One of the most compelling advantages of agrivoltaic systems is their potential to enhance biodiversity. Solar panels and their supporting infrastructure can create new microhabitats that support a variety of plant and insect species. The shaded areas beneath solar arrays can be ideal for growing shade-tolerant plants that might not otherwise thrive in full sunlight. These plants can attract and support pollinators like bees and butterflies, which are crucial for the health of many ecosystems.

Additionally, agrivoltaic systems can be designed to include features that further benefit biodiversity, such as flowering plants and nesting sites for insects. By providing diverse habitats and resources, these systems can contribute to the conservation of local wildlife and the promotion of ecological balance.

 The integration of solar energy production with agricultural activities, offers a unique solution for addressing India’s growing energy needs while optimizing land use. In regions like Jammu & Kashmir, Himachal Pradesh, and West Bengal, where agriculture is a key part of the economy and climate change poses significant challenges, agrivoltaics presents an opportunity to enhance both energy security and agricultural productivity. Agrivoltaic systems can be assisted with polyhouse and fruit and vegetable can also be grown. Hence, this system can be used in open field or in controlled structure.

In the Himalayan northern regions of Jammu & Kashmir and Himachal Pradesh, the high altitudes and clear skies provide exceptional solar potential, making these areas ideal for agrivoltaics systems. The valleys and mountainous terrains offer vast agricultural land that can be effectively utilized for projects combining crops like saffron, grains, fruits, and apple orchards with solar energy production. Agrivoltaics here can also help mitigate the regions’ energy dependency, addressing frequent energy supply issues. Integrating saffron farming with solar panels, due to its compatibility with partial shading, could serve as a model for other high-altitude regions in India. Similarly, in Himachal Pradesh, solar panels can help reduce water evaporation, a crucial benefit in areas facing water scarcity. By reducing reliance on external energy sources, agrivoltaics can support the region’s tourism industry, providing renewable energy for hotels, resorts, and related infrastructure. Pilot projects involving apple orchards, where the shade from solar panels benefits crop growth, could be particularly valuable.

Both Jammu & Kashmir and Himachal Pradesh experience significant variations in humidity and solar intensity. Jammu & Kashmir, with its relatively lower humidity and high solar intensity, offers longer durations of sunlight, making it ideal for solar energy production (Rather et al 2018). Himachal Pradesh, while having high to medium humidity levels, still benefits from substantial solar radiation, especially in the summer months, which can be harnessed effectively through agrivoltaics systems.

In West Bengal Gangetic plain, the focus shifts to integrating agrivoltaics with rice cultivation and fisheries. With water scarcity being a concern, the technology can help manage evaporation in rice fields while generating clean energy. In coastal areas, agrivoltaics systems could protect ecosystems and contribute to the local economy by powering shrimp farms and fish processing facilities (Matulić et al 2023)

West Bengal’s coastal lands, underutilized for agriculture, present an excellent opportunity for expanding agrivoltaics systems, combining aquaculture with solar energy. The region’s high humidity and moderate solar intensity, particularly during the monsoon season, can be managed through adaptive agrivoltaics designs that optimize both energy production and agricultural output.

The potential of agrivoltaics in these regions is significant but comes with challenges. Land acquisition in densely populated areas, the need for policy support, and the cost of advanced technologies are barriers to large-scale implementation. However, government initiatives, technological advancements in solar panels, and the focus on high-value crops like saffron and apples highlight the opportunities for success. Engaging local farmers and communities will be crucial for ensuring the adoption and scalability of these systems.

By overcoming these challenges and leveraging emerging trends, agrivoltaics can play a crucial role in sustainable development, enhancing energy security, and promoting agricultural resilience in these key regions of India with following advantage (Wagner, et al 2023).

**Key Benefits of Agrivoltaics**

1. **Enhanced Land Utilization:** Agrivoltaics optimizes land use by simultaneously utilizing the same area for agriculture and solar energy generation, addressing the growing competition for land resources
2. **Improved Crop Yields:** Solar panels can provide shade, reducing water evaporation and improving crop yields, particularly in arid and semi-arid regions. Additionally, the microclimate created by solar panels can enhance the resilience of crops to extreme weather conditions.
3. **Reduced Energy Costs:** Farmers can generate their own electricity, reducing reliance on the grid and saving money on energy bills. This can also provide a potential source of revenue by selling surplus electricity back to the grid (Mahto et al 2021).
4. **Increased Biodiversity:** The cooler and more humid conditions under solar panels can foster the growth of beneficial insects and pollinators, supporting biodiversity and improving crop health (Ludzuweit et al; 2025)
5. **Reduced Carbon Footprint:** By generating clean energy and reducing reliance on fossil fuels, agrivoltaics contributes to climate change mitigation efforts by lowering greenhouse gas emissions (Mahto et al; 2021)
6. **Balancing Energy Production with Environmental Conservation:** The environmental benefits of agrivoltaics extend beyond biodiversity. By reducing the need for separate land for solar farms and agricultural fields, agrivoltaics helps minimize land degradation and habitat destruction. This dual-use approach also reduces the carbon footprint of energy production and food production, as it leverages renewable energy and reduces the reliance on fossil fuels.
7. **Improve soil health:**  Agrivoltaics can also enhance soil health by incorporating cover crops or reducing soil erosion through careful land management practices. The reduced need for chemical inputs, such as pesticides and fertilizers, due to the improved shading and reduced irrigation needs, can also lead to better water quality and less pollution. The shading provided by solar panels can affect soil temperature and moisture levels, which in turn influences soil health and microbial activity. Improved soil health can enhance plant growth and support a diverse range of soil organisms. However, excessive shading or poorly managed agrivoltaic systems might lead to reduced soil fertility.

**Classification of Agrivoltaics**

Agrivoltaics can be classified into several types based on design and application. Fixed tilt agrivoltaics have stationary solar panels, while adjustable or dynamic systems allow panel movement to optimize sunlight. Tracking agrivoltaics follow the sun's path for maximum energy generation. Elevated agrivoltaics place panels 3–5 meters above ground, suitable for tall crops and livestock grazing, whereas vertical agrivoltaics position panels upright, benefiting vine crops. Floating agrivoltaics integrate solar panels on water bodies for aquaculture, while greenhouse agrivoltaics use semi-transparent panels for controlled-environment farming. Row-based agrivoltaics arrange panels in spaced rows for better light distribution, and mixed-use agrivoltaics combine grazing, crops, and solar energy. Agroforestry agrivoltaics integrate solar with tree-based farming, enhancing biodiversity and sustainability (Sarr et al., 2023).

**Agrivoltaics impacts on biodiversity and invasion of alien animal species**

When integrating agrivoltaics solar photovoltaic (PV) systems combined with agricultural practices into land management, several specific factors can influence biodiversity.

1. **Habitat Modification**

The installation of solar panels alters the physical landscape by adding structures and shading. This modification can affect the types of plants and animals that can thrive in the area. The creation of new microhabitats under solar panels can support different plant species, potentially enhancing local biodiversity if manage properly. However, it could also disrupt existing habitats if not planned carefully (Suuronen et al 2017; Lambert et al 2017)

1. **Microclimate Changes**

Solar panels can create shaded areas with different temperature and humidity conditions compared to full sunlight areas. This microclimate change can affect plant growth and the types of species that can inhabit these areas. The cooler and more humid conditions under solar panels may benefit shade-tolerant plants and insects, thus supporting a wider range of species. Conversely, it may disadvantage plants and animals adapted to full sun conditions. (Suuronen et al 2017)

1. **Water Management**

Agrivoltaic systems may influence water availability and management through changes in evaporation rates and runoff patterns. Improved water conservation due to reduced evaporation can benefit plants and insects. However, altered runoff patterns could potentially lead to changes in soil moisture levels, which might impact local flora and fauna. (Liu et al 2023)

1. **Plant Diversity and Growth**

The introduction of solar panels can allow for the cultivation of different types of plants that are better suited to the shaded conditions or more tolerant of reduced light. Increased plant diversity under and around solar panels can enhance habitat complexity and provide resources for a variety of insects and other wildlife. However, inappropriate plant choices could lead to competition with existing species (Soto-Gómez, 2024)

1. **Pollination and Pest Control**

The presence of flowering plants and other vegetation within agrivoltaic systems can attract pollinators and natural pest controllers. Supporting pollinators like bees and butterflies can benefit both the agricultural crops and the surrounding ecosystems. Integrated pest management can reduce the need for chemical pesticides, thus further supporting biodiversity (Katumo et al 2022)

1. **Species Displacement and Adaptation**

The installation of solar panels may displace species that are not adapted to the new conditions created by the panels. While some species may adapt to the new conditions, others might be displaced or face increased competition for resources. The success of these species in adapting can vary widely (Stringer et al 2020)

Agrivoltaics can help minimize the invasion of alien animal species by creating controlled agricultural environments that disrupt the conditions favorable for invasive species. The strategic placement of solar panels alters the microclimate, reducing open, sun-exposed spaces where invasive species might thrive. Shading from panels lowers soil temperature and evaporation, making it less suitable for heat-loving invasive pests. Additionally, diverse cropping systems under agrivoltaic structures promote native plant and insect biodiversity, which strengthens natural pest control and reduces the dominance of invasive species. The reduced chemical use in agrivoltaic farming due to natural shade benefits and increased soil moisture—supports the growth of native plant species while limiting the spread of invasive weeds that often flourish in degraded lands. Moreover, integrating pollinator-friendly crops and native vegetation attracts beneficial insects and birds, which help control alien pests naturally. In water-based agrivoltaic systems, floating solar panels reduce excessive water surface exposure, helping to control invasive aquatic species like water hyacinth (Eichhornia crassipes) and predatory alien fish. Therefore, relative to open field, agrivoltaics help to control invasion of species.

By enhancing biodiversity, modifying habitats, and supporting sustainable farming practices, agrivoltaics contributes to ecological resilience, making ecosystems more resistant to invasive animal species while promoting a balance between renewable energy, agriculture, and environmental conservation.

**Factors Influencing Crop Yields and Biodiversity**

Garrod et al 2024 observed the impact of agrivoltaics on crop yields can vary depending on several factors which are as follows:

1. **Crop Type and cropping system:** Different crops have varying tolerances to shade and can respond differently to the microclimate created by solar panels. he choice of crops and agricultural methods in agrivoltaics significantly influences biodiversity and the potential invasion of alien species. Diverse cropping systems, such as polyculture and intercropping, promote a variety of plant species, attracting a wider range of pollinators (e.g., bees, butterflies) and beneficial insects (e.g., ladybugs, lacewings) that help control pest populations naturally. This reduces the chances of invasive species outcompeting native organisms. Conversely, monoculture farming creates ecological imbalances, making ecosystems more vulnerable to invasive pests and weeds that spread quickly in uniform environments. Organic farming practices, which limit chemical pesticide use, help maintain soil microbial diversity and support natural predators that keep invasive insects in check. Additionally, planting native crops and flowering plants fosters habitat restoration, discouraging the establishment of non-native species that thrive in disturbed ecosystems. In contrast, excessive fertilizer and irrigation use can create conditions favorable for aggressive alien species by promoting excessive plant growth and altering soil composition. Furthermore, crop shading under solar panels influences temperature and moisture levels, creating microclimates that may either suppress or encourage invasive species. For instance, high soil moisture in shaded areas can reduce the spread of drought-tolerant invasive weeds but may support invasive fungi and pests. Thus, careful crop selection, agroecological farming, and biodiversity-friendly land management in agrivoltaic systems can enhance native biodiversity while minimizing the risk of alien species invasion.
2. **Solar Panel Configuration:** The design and placement of solar panels can affect the amount of sunlight reaching crops and the overall microclimate. The configuration of solar panels in agrivoltaic systems directly affects sunlight distribution, temperature, humidity, and crop growth. Fixed tilt panels provide consistent shading, benefiting shade-tolerant crops like lettuce, while tracking panels optimize light exposure by adjusting angles throughout the day. Vertical panels allow sunlight to reach both sides of crop rows, making them ideal for intercropping. Shading reduces heat stress during the day and retains warmth at night, protecting cold-sensitive crops. It also lowers evaporation rates, increases soil moisture retention, and raises humidity, creating a favorable microclimate for plant growth. Additionally, solar panels act as windbreaks, reducing wind speeds and preventing soil erosion. Proper panel placement ensures that shade-tolerant crops thrive while sun-loving crops receive adequate light through wider spacing or dynamic panel adjustments. Thus, an optimal solar panel design balances energy generation and agricultural productivity, fostering a sustainable farm ecosystem.
3. **Regional Climate:** The local climate, including temperature, rainfall, and humidity, can influence crop growth and response to agrivoltaics systems. The factors being considered are air temperature, humidity, wind speed, wind direction, soil temperature, soil moisture, crop temperature, vapour pressure deficit (VPD), and photosynthetically active radiation (PAR)
4. **Soil Conditions:** The soil quality and nutrient content can impact crop performance in agrivoltaics systems. he partial shading from solar panels reduces evaporation, helping maintain soil moisture and reducing the need for frequent irrigation. This can enhance microbial activity and support earthworms and beneficial soil organisms, improving soil fertility. However, uneven light distribution may lead to variations in soil temperature, affecting root development and nutrient uptake. Additionally, organic matter decomposition rates may slow under shaded areas, requiring strategic soil management practices like composting, mulching, and crop rotation to maintain soil health. Proper soil monitoring, along with the use of cover crops and organic fertilizers, can help balance nutrient levels, ensuring optimal growth conditions for crops in agrivoltaic setups (Dvořáčková, et al 2024)

Agrivoltaics systems can positively impact crop yields such as potatoes. spinach tomato, wheat basil broccoli, lettuce. Research has indicated that basil plants can exhibit increased growth and yield and improve quality under solar panels, potentially due to the filtered sunlight and improved microclimate. Agrivoltaics systems have been shown to enhance the growth and yield of celery plants, corn/maize, particularly in regions with high temperatures and water stress and intense sunlight and high temperatures respectively. Research has demonstrated that chili peppers, such as chiltepin peppers, can experience increased yield and improved flavour when grown under solar panels Fig 1. These systems can be used to enhance the growth and quality of pasture grass, providing benefits for livestock grazing (Asa'a et al, 2024 and Widmer et al 2024).

**Potential Challenges and Limitations**

Fig 1: Crop grown under agrivoltaics system

Gomez-Casanovas et al 2023 and Mohammad et al 2024 suggested that Agrivoltaics offers numerous benefits, it is essential to consider the potential challenges and limitations:

1. **Land Loss:** While agrivoltaics can enhance land use efficiency, there may still be some loss of agricultural land due to the installation of solar panels and supporting infrastructure.
2. **Crop Yield Reduction:** Certain crops, particularly those that require high levels of sunlight, may experience reduced yields under solar panels.
3. **Initial Investment:** Agrivoltaics systems can require significant upfront costs for installation and infrastructure.
4. **Technical Complexity:** Maintaining and operating agrivoltaics systems may require specialized knowledge and skills, potentially increasing labour costs.
5. **Regulatory Hurdles:** Navigating regulations and obtaining necessary permits can be time-consuming and challenging.
6. **Compatibility with Existing Farming Practices:** Agrivoltaics may not be suitable for all farming practices or crop types, requiring careful planning and adaptation.

**Challenges and Future Directions**

Despite its potential, agrivoltaics is not without challenges. Technical and economic hurdles, such as the initial cost of installation and the need for specialized equipment, must be addressed to make this technology more widely accessible. Additionally, careful planning and management are required to ensure that agrivoltaic systems are designed to maximize benefits for both energy production and biodiversity.

Future research and development will be crucial in optimizing agrivoltaic systems for different climates and crops, as well as in exploring innovative designs that further enhance their environmental benefits. Collaboration between researchers, farmers, and energy producers will be key to overcoming these challenges and advancing the adoption of agrivoltaics**.** Economic incentives and policies related to agrivoltaics can influence how these systems are implemented and managed. Supportive policies and funding for biodiversity-friendly practices within agrivoltaic systems can lead to greater biodiversity benefits. Conversely, lack of incentives or poorly designed policies might result in less consideration for ecological impacts.Therefore, there is need to improve economic and policy factors. There is also lot of scope for educational and research opportunities such as **a**grivoltaic systems provide opportunities for research and education on sustainable practices and biodiversity conservation**.** Research initiatives can lead to improved designs and practices that enhance biodiversity. Education can increase awareness and encourage the adoption of best practices for integrating agriculture and renewable energy (Pulipaka, & Peparthy,2021). The maintenance of solar panels, including cleaning and infrastructure management, can affect surrounding vegetation and soil. Careful management practices that minimize disturbance to the surrounding environment can help maintain or enhance biodiversity. In contrast, invasive maintenance practices could negatively impact local ecosystems.

**Conclusion**

Agrivoltaics in the Himalayan and Gangetic Plain presents a groundbreaking opportunity to harmonize agriculture, renewable energy, and environmental conservation. By carefully selecting crops that thrive under partial shade, such as grapes, leafy greens, and legumes, agrivoltaics systems enhance land-use efficiency, reduce environmental impact, and contribute to food security. This innovative synergy holds immense potential to address the pressing challenges of climate change, energy demands, and sustainable farming, offering a brighter, more sustainable future for regions around the world. Agrivoltaics represents a pioneering approach to achieving environmental harmony and supporting biodiversity. By integrating solar energy production with agricultural practices, this technology offers a sustainable solution that enhances land use efficiency, promotes ecological balance, and reduces environmental impacts. As the world seeks innovative solutions to pressing environmental issues, agrivoltaics stands out as a promising pathway towards a more sustainable and biodiverse future. Advanced insect net houses can also be used as both an insect net house and Agrivoltaic system. There is also a need to improve policy for better future, generation, biodiversity and alien animal species

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