

Health-Farm Agrivoltaics: Strategic Development Goals and Food Sustainability

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Abstract

Agrivoltaics is an emerging approach that integrates photovoltaic (PV) energy generation with agricultural production on the same land, offering opportunities to address challenges related to renewable energy, food production, water use, and climate resilience. This review examines the strategic development of health-farm agrivoltaics as a multifunctional agricultural system that supports the Sustainable Development Goals (SDGs). It emphasizes interactions among PV system configuration, crop performance, microclimatic conditions, soil health, water-use efficiency, and land-use productivity. Key design and performance indicators, including land equivalent ratio, PV ground coverage ratio, shading factor, panel height and density, photosynthetically active radiation, crop yield stability, and economic feasibility, are considered when evaluating agrivoltaic systems. The review also discusses how well-managed shading can modify crop growing conditions and influence plant physiological responses, including antioxidant and secondary-metabolite production. Agrivoltaics may also improve resource-use efficiency while generating renewable electricity and maintaining agricultural productivity. Integrating these functions within a health-oriented farming framework could strengthen links among sustainable agriculture, clean energy, environmental conservation, and human well-being. Overall, the review highlights agrivoltaics as a promising pathway for integrated land management and sustainable agricultural development, while identifying the need for site-specific system design, crop selection, economic assessment, and long-term field evaluation.

Keywords: Regenerative Agrivoltaics; Flavonoids; Medicinal Plants; Molecular Docking; DNA Binding; Climatic Environment; UN SDGs

Highlights

1. This overview is directed towards nutrition and global human health using agrivoltaics, a dual-role system using the same land cover for crops and solar power.
2. Information was obtained from PubMed, PubChem, Google, Google Scholar, and ChatGPT 5 in Microsoft Copilot- an AI tool- with caution and validation of output.

3. Key agrivoltaic design features were investigated, including Land Equivalent Ratio, Photovoltaic (Ground) Coverage Ratio, Shading Factor, Panel Height, etc.
4. Focus was placed on classes of flavonoids, shade-tolerant food sources and potential health benefits, particularly those arising from an imbalance of oxidative stress.
5. Overarching emphasis was placed on UN SDGs and future research.

Introduction

Agrivoltaics (AV) is the practice of using the same land for both agricultural production and solar energy generation. This dual-use system combines crops or livestock with solar panels, creating synergies like increased land-use efficiency, supplemental income for farmers, and benefits for certain crops from shade and protection. Figure 1 outlines this article.

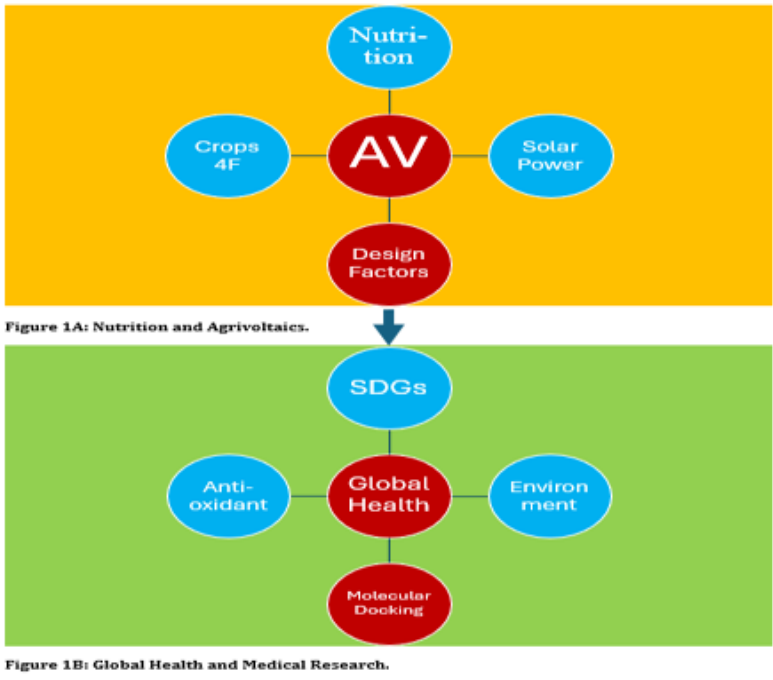


Figure 1

GM crops can reduce land use by increasing crop yields on existing land, which can prevent deforestation. However, concerns remain about potential negative effects on land, such as the development of herbicide-resistant weeds that require more chemicals, and the impact of these chemicals on biodiversity and non-target organisms like monarch butterflies. Additionally, some areas attribute biodiversity loss to GM crops. Apart from this, some sweetened GM foods, like American corn, increase body weight and predispose to diabetes [1].

Economic development is associated with increased consumption of saturated fat and refined starchy foods high in salt and sugar, manufactured by the food industry, along with physical inactivity, which contribute to obesity and related noncommunicable diseases (NCDs). However, functional foods characterized by traditional whole grains; wheat, grains, beans with fruits, vegetables, legumes, nuts, olive oil, mustard oil/canola oil have been found to be protective against NCDs [2]. Obesity is one of the biggest risk factors for NCDs:

cardiovascular diseases, hypertension, coronary artery disease, strokes, heart failure, and other types of chronic diseases, such as type 2 diabetes mellitus, cancer, chronic respiratory diseases, bone and joint diseases, and neurodegenerative diseases. There is potential to develop international consensus on preventing undernutrition by increasing food availability through Functional Foods and Functional Farming (4 F), so human vulnerability to obesity and NCDs does not rise. Previous attempts to improve food security through energy-rich products such as manufactured foods, as well as farming (more energy, fewer nutrients), have increased the burden of obesity. It has been demonstrated that an Indo-Mediterranean dietary pattern characterized by functional foods: whole grains, vegetables, fruits, nuts, and fish in conjunction with olive oil plus mustard or canola oil can help prevent various diseases. Further efforts must provide nutrient-rich feedstock for animals and birds and soil for growing foods to develop new functional foods, such as Sim’s egg, to increase food availability.

Global crop yield and quality will be reduced by the end of this century due to the impact of patterns of climate change (temperature, water, GHG, nutrients), such reductions [3], in countries e.g. in South Asia, sub-Saharan Africa, North America, and Oceania, may lead to food insecurity, and populations will be unable to meet their national calorie demand, *ceteris paribus*. Despite mitigating circumstances such as the use of agrochemicals, alternative marine and terrestrial insect sources of protein, remote sensing, AI, remediation of land/soil/ water, reduction of GHG, agrivoltaics, etc., humanity must prepare for worst-case future scenarios; hence, this paper is directed towards the latter, i.e. agrivoltaics [1,3,4]. Agrivoltaics is a complex dual-use system combining solar energy generation from photovoltaics with agricultural production [5], which, coupled with an emphasis on soil conservation, will promote the environmental. economic and social dimensions of sustainable food production which are called ‘regenerative agrivoltaics’ [6]. This identifies research areas such as carbon sequestration, soil health and fertility, soil moisture, soil microbial activity, soil nutrients, and crop performance water-use efficiency and economics. Agrivoltaics [7] on large-scale solar farms compete for crop production and energy requirements for the same area of land and, i.a., not the same light intensity, which limits crop production and suggests the need for shade-tolerant substitutes which have potential health benefits, e.g. combating rising oxidative stress [8] (health-farm agrivoltaics) and influences experiment design. Fifteen examples of crop and yield increases with agrivoltaics for studies across the world are given in table 1 (also table 1 of [9]). The crops in italics have some reported association with cardiovascular disease (CVD) risk factors and require detailed investigation through reported meta-analysis or multiple regression.

Crop	Yield
<i>Celeriac</i>	31.9%, 48% [10]
<i>Winter wheat</i>	3% [11]
<i>Pasture grass</i>	90% [12]
<i>Potato</i>	11% [13]
<i>Celery</i>	12% [13]
<i>Chiltepin pepper</i>	150% [14]
<i>Cherry tomato</i>	90% [14]
<i>Vine grapes</i>	25%, 60% [15]
<i>Corn</i>	4.9% [9]
<i>Swiss chard</i>	70% [15,16]
<i>Broccoli</i>	40% [15,16]
<i>Kale</i>	25% [15,16]
<i>Common bean</i>	350% [15,16]
<i>Strawberries</i>	18% [17]
<i>Lettuce</i>	2%, 3.6% [18,19]

Table 1: Crop and yield increase with agrivoltaics for studies throughout the world. Open access Creative Commons CC BY license. Jamil, U. and Pearce, J.M., 2025, [1]. Modified only to accommodate the new referencing numbering sequence and italics.

An important aspect of agrivoltaics (q.v. [20] for international terminology) is the design of the photovoltaic system figure 1, first to optimize solar energy collectors, and then to optimize their location above co-existing cropland space (first proposed by [21]) for maximum light, suitably integrated over photosynthetic time.

Design of critical factors associated with agrivoltaics

Several key design indicators have been identified and analyzed to understand their effects on system performance. These include [22,23]: Land Equivalent Ratio [24], Photovoltaic (Ground) Coverage Ratio [25], Shading Factor [22], Panel Height, Panel Arrangement Density [26], Photosynthetically Active Radiation, Tilt Angle, Crop Yield Stability Index, Water Use Efficiency [27], and Economic Feasibility.

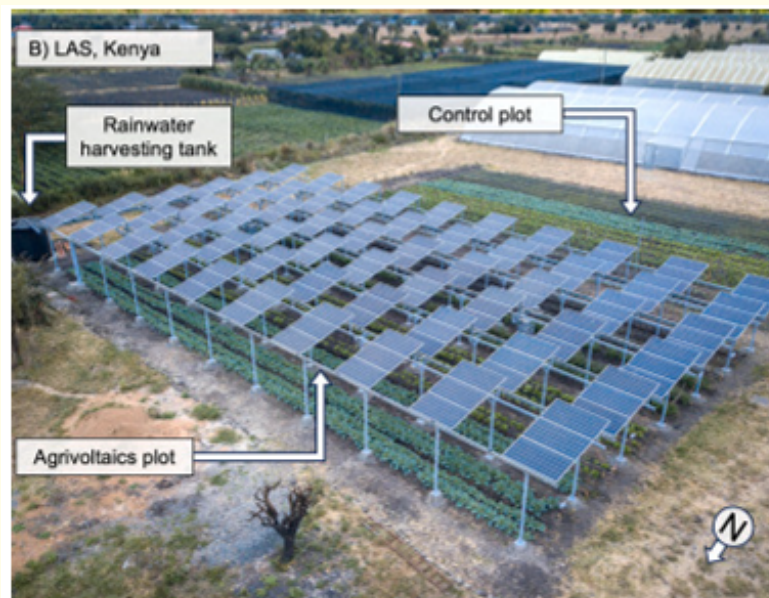


Figure 2: Small-scale agrivoltaics in Africa, B, Kenya. The 62.1 kWp (kiloWatt peak) grid-tie system at Latia Agribusiness Solutions (LAS), Kenya, comprising 12 growing beds running the length of the plot. Guttering at the lower edges of the panels channels water runoff into the rainwater harvesting tanks, which can supplement the centralized irrigation systems. Photo credits: Chloride Exide Ltd. Open access Creative Commons CC BY license. Randle-Boggis, et al. [28]. Modified only to accommodate half of figure 1 in reference 28.

Land Equivalent Ratio is described as the area required under sole cropping (IY) to produce the same yield as intercropping (SY).

where m = the number of different crops intercropped, is the yield for the i^{th} crop under intercropping, and is the yield for the i^{th} crop under a sole-crop regime on the same area. Photovoltaic (Ground) Coverage Ratio is the ratio of the total area occupied by solar modules to the total land area available for installation. $GCR = (\text{number of PV modules}) \times (\text{area of each module}) / \text{total area of PV array}$. The shadow effect cast by the photovoltaic module in an open field or greenhouse, sui generis, reduces the energy available for photosynthesis, which may correlate with plant growth, antioxidant synthesis, sugar content, etc. The shadow effect is multifarious and dependent on module design, application (e.g. crop(s) allocation to land), daylight, skylight, season, time of day, longitude, latitude, weather, zones of production, geographical relief, etc. Shadow effect can be crudely expressed as the quotient of the total area under shade and the total agricultural area [29], e.g. 0.4, and models are available to help the farmer/horticulturist standardize the effect of such conditions [22,23] which are

beyond the remit of this article. No distinction is made herein between shadow and shade. Panel height to some extent is determined by the crop height and, in open farming, may be 4-7m, e.g. tall panel height-maize, short height-lettuce; in any case, the nearer the ground, notwithstanding other reasons, e.g. harvesting access or sheep foraging in winter, when impracticable, etc., the greater the shadow effect and to the detriment of sun-loving crops and favouring shade-tolerant ones. Panel arrangement density methods [30], e.g. half-density and full density, the former allowing more light to the crops and the latter lighter for energy production, *ceteris paribus*, are another factor. Photosynthetically Active Radiation (PAR) is the 400-700 nanometre (nm) waveband over which plants can utilize this energy (W/m) of irradiance, W/m², per unit area, for photosynthesis. PAR efficiency is the quotient, expressed as a percentage, of the PAR received by crops and the total available [31]. Another critical factor is the panel tilt relative to the ground, which depends on the required power/crop yield; too steep, and it produces more shade, which may result in lower crop yield and relatively more energy; too shallow, and vice versa. Ideally, the crop yield stability index (standard deviation/mean) should be low under shading/variable lighting conditions (rather than high), as it may indicate that the agrivoltaics system has an optimal crop growth rate, or vice versa, i.e., unstable. This statistic is now even more important in the era of adverse climate change, e.g. cereal grain-legume intercropping [27]. Water use efficiency is linked to shade created by the agrivoltaics panels. More shade lowers temperature, reduces evaporation, and lowers crop water demand; less shade increases temperature, increases evaporation, and increases crop water demand. Guidelines for its determination are given [20,27]; the greater the output per unit of water, the higher the water use efficiency, which is important in relatively dry regions. Economic feasibility [20] results from good system design and affordable construction and operating costs, leading to a return on investment if the system is sufficiently large, calculated as the quotient of net profit over initial investment.

Agrivoltaics: UN strategic/sustainable development goals (SDGs)

SDL n	Description	SDL n	Description
1	No poverty	2	Zero hunger
3	Good health and well-being	4	Quality education
5	Gender equality	6	Clean water and sanitation
7	Affordable and clean energy	8	Decent work and economic growth
9	Industry, innovation and infrastructure	10	Reduced inequalities
11	Sustainable cities and communities	12	Responsible consumption and production
13	Climate action	14	Life below water
15	Life on land	16	Peace, justice and strong institutions
17	Partnerships for the Goals	Strategic Development Goals [32]	 United Nations

Table 2: Agrivoltaics systems that fall under the main target UN SDGs are in italics.

The largest planned agrivoltaics system, if it comes into operation, is the Oak Run Solar Project with a capacity of 800MW of solar power and 300MW of battery storage (SDG 7), 4000 acres for agrivoltaics, crops and livestock [33] based in Madison County, Ohio, in partnership with Shell (SDG 17). Table 2 shows the agrivoltaics-relevant UN SDGs in italics. Another US facility is Jack’s Solar Garden, an agrivoltaics research centre in Colorado with a capacity of 1.2 MW (SDG 7) and a focus on education and community (SDG 4). It is through education and financial and social investment that agrivoltaics can deliver affordable clean energy, alleviate dire hunger and

poverty, and mitigate the vagaries of adverse climate change (SDG 1-4, 7, 13, 17) encountered, for example, by 360 million of the 600 million living in Sub-Saharan Africa [31]. Affordable energy will also allow the cultivation of plants yielding secondary metabolites [34] of potential intervention/chemoprevention [10] value for human diseases (SDG 3) (indirect or direct routes: cancer, type 2 diabetes, cardiovascular disease, retinopathy, neurodegeneration, metabolic syndrome [35], etc.) arising from excessive oxidative stress over and above that needed for natural defence [26]. A systematic approach is needed to identify candidate natural products that will have a global impact on well-being. We live as 'a grain of sand upon the infinite shore of an infinite sea [11], so it seems when trying to evaluate natural products; e.g. over 10,000 flavonoids alone have been identified thus far, and countless other compounds are not even documented herein. Throwing off the shackles of Sisyphus to make headway, we select and describe a few flavonoids in the context of SDGs and agrivoltaics as follows, but first the authors seek to understand what is meant by 'oxidative stress'; how it becomes manifest in diseases; and how the threat to health can be ameliorated by natural product intervention through agrivoltaics.

Prelude to health-farm agrivoltaics: plant antioxidants

In a bygone age, we may have sought the goddess of universal health and remedy to cure disease. Today, we have more facilities akin to Jack's Solar Garden, with reservation status, where science can take the stage for molecular medicine [36]. Culprits of oxidative stress, such as reactive oxygen species (ROS) and other mechanisms associated with serum biomarkers from damaged DNA/RNA (e.g. 8-hydroxy-2'-deoxyguanosine (8-OHdG), 8-oxo-7,8-dihydro-2'-deoxyguanosine, 8-hydroxyguanine), can be investigated, especially by Pharma and academic institutions (SDG 17). ROS may be produced by mitochondrial activity (e.g. as superoxide anion (O_2^-), hydrogen peroxide (H_2O_2), or a hydroxyl radical ($\bullet OH$)) or found in microsomes, peroxisomes, and cytoplasmic membranes [37]. The 2,2-diphenylpicrylhydrazyl test [38] may be used to assess free radical neutralization [39]. Its ROS effect/e.g. free radical formation) is neutralized by generally rather weak nucleophilic (mainly because of hydroxyl groups) antioxidants donating lone pairs of electrons from hydroxyl groups to electrophilic centres to produce more stable electronic structures.

If biochemistry were that simple, and oxidative stress were the only mechanism involved in DNA flavonoid protection [39], as deduced from, for example, the protective effect of DNA binding of quercetin and naringenin (and naringin) on otherwise damaged nucleic acid induced by hydrogen peroxide and cupric ions. Spectroscopy and molecular docking investigations also showed that quercetin intercalated between the DNA double helix and that naringenin binding formed a groove-like structure [12]. Molecular docking studies visually display different binding modes and interaction forces, and so far, different DNA-binding regions have not been discussed herein.

Most enlightening and thrilling was the report by Moulishankar, *et al.* [40], which studied 26 natural flavonoids using molecular docking with 11 protein targets, assessing docking score, glide energy, interacting residues, interaction types, and bond lengths between residues and ligands. This suggests that regular flavonoid consumption may reduce the risk of inflammation, cancer, and infectious disease. Agrivoltaics systems support crop growth (Table 3), such as vegetables, fruits, grains, legumes, beans, herbs, roots, leaves, seeds, etc., and flavonoid production under standardized/known conditions and on a scale suited to local consumption.

Health-farm agrivoltaics: plant antioxidants and disease intervention

The authors are well aware of, and almost blinded by, the vast literature on flavonoid therapeutic potential for neurodegenerative [41,42] and cardiovascular diseases [43], cancer [42], diabetes [44], and metabolic syndrome [45], etc. Table 4 shows snippets of six flavonoid types as aglycones and food crops with possible disease implications.

Gene upregulation expression due to dietary flavonoid intake, specifically genes (*APEX*, *ERCC1*, *ERCC2*, *ERCC4*, *MGMT*, *OGG1*, *XPA*, *XPC*, *XRCC1*, *XRCC3*, *AHR*, *CYP1A1*) was investigated and a significant increase ($P < 0.001$) was

Anthocyanins	Cyanidin, Delphinidin, Malvidin	Blueberries, blackberries, red grapes, cherries	Antioxidant, anti-diabetic, anti-obesity, cardiovascular and cognitive health.
Isoflavones	Genistein, Daidzein	Soybeans, legumes	Hormonal balance, bone health, reduced risk of hormone-related cancers.

Table 4: Potential agrivoltaics health-farm benefits of flavonoid crops grown in open fields or greenhouses
[modified from references 42, 46, 47].

found [48] in male smokers but statistically relating this to DNA repair and metabolic genes requires caution. Flavonoids, morin, apigenin, naringin, quercetin, kaempferol, and delphinidin bind DNA and RNA [49] via both intercalation and groove binding, as reported for quercetin and naringenin for DNA [2]. Complexing in this way makes flavonoids candidates for DNA protection and disease intervention and drug development, though physicochemical data [49] are beyond the remit of this article.

Sustainable agrivoltaics

Altered, overworked, or neglected soil harms crop success in agrivoltaics [50], and regeneration is vital [9] for sustainability and the wider environment [51]. Reduced tillage considers soil structure, nutrients, residues, and pollution, while addressing five key environmental dimensions: soil vitality, water integrity, biodiversity, ecosystem functionality, and atmospheric carbon capture [9], some of which are mentioned as research areas in the ‘Introduction’. Combining agrivoltaics with environmental strategies such as cover crops, animal integration, organic annual cropping, and soil nutrient restoration builds a sustainable agrivoltaics system and contributes to human health through the UN SDGs.

Discussion and Conclusion

The overarching advantages of agrivoltaics is a reduction in the use of fossil fuels and associated respiratory-related illnesses (bronchitis, asthma, etc.), alleviation of heat stress in plants and animals, suitable conditions for growing shade tolerant high value cosmetic; and medicinal crops: such as lavender, calendula, chamomile, aloe vera; echinacea, lemongrass, peppermint, turmeric, basil, rosemary, thyme, sage, mint, oregano, etc.; to which the authors, recognising the contribution of Disciglio., *et al.* [52], have added the role of the almost ubiquitous plant flavonoids, for the chemoprevention of human disease caused by oxidative stress. The scale of agrivoltaics systems is commensurate with need, but many projects could have a ‘medicinal garden’ to facilitate research on phytochemistry such as flavonoids.

Disadvantages of agrivoltaics come at the onset of the project, e.g. planning permission, design costs, high initial investment in equipment (solar panels, infrastructure), expertise (in agronomy, engineering, academia and pharma), business acumen (optimizing crop and power production profitability), crop drawbacks (shade and microclimate), and training requirements for various professions.

In conclusion, this article supports several UN SDGs to benefit humanity.

Conflict of Interest

None were declared.

Author Contributions

RBS- substantive written input; HSB- reviewer; PJ-reviewer and collation of references; DWW-mainly wrote the paper; IGT- reviewer.

Data Availability

No data relevant to this article are held by any of the authors.

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