REVIEW ARTICLE

Check for updates

Prospects of Agrivoltaics as a Sustainable Mitigation Solution to the Nomadic Cattle Rearing Crisis in Nigeria: A Review

Chinedu Christian Anyene[1], **Daniel Olisaeloka Udorah**[1], **Patience Stella Nsofor**[1] and **Nnaemeka Reginald Nwakuba**[2,*]

[1] Department of Agricultural and Bio-environmental Engineering, Federal Polytechnic, Oko, Nigeria
[2] Department of Agricultural and Biosystems Engineering, Federal University of Technology, Owerri, Nigeria

Abstract

The ongoing conflict between herdsmen and farmers across different regions in Nigeria over scarce natural resources continues to generate disputes that threaten the lives and property of citizens. The impact of this crisis is now escalating to a level that significantly endangers the country's socio-economic development and overall security. It is essential to explore technological solutions that can sustain both herdsmen and farmers in their respective activities while making the best use of limited land resources. This study investigates the potential of agrivoltaics as a strategy to address Nigeria's nomadic cattle rearing challenges. A review of existing literature was conducted on the severity and implications of the nomadic cattle rearing crisis, along with the possibilities of applying agrivoltaic technology to cattle grazing systems. The technology involves a series of rack systems and photovoltaic panels installed based on the geographic coordinates and local climate conditions. The panels provide shade over grazing land, serving dual purposes: protecting livestock from heat stress caused by direct sun exposure and generating electrical energy for use on the same land. With optimal environmental conditions, structural compatibility, efficient photovoltaic configurations, and collaborative research, agrivoltaics emerges as a promising innovative technology capable of effectively addressing the issues associated with nomadic cattle rearing in Nigeria. This approach aligns with global efforts to produce clean, eco-friendly energy and to maximize the utilization of limited agricultural land to meet the rising food demands of the growing population. Additionally, agrivoltaics is compatible with both Industry 4.0 and 5.0, as it allows the integration of smart sensing and automatic systems for real-time monitoring of cattle behaviour, facilitating more effective rearing practices. Recommendations for sustainable agrivoltaic practices in Nigeria are also outlined.

Keywords: agrivoltaics, crisis, cattle rearing, ranching system.

Submitted: 12 August 2025
Accepted: 26 September 2025
Published: 08 December 2025

Vol. 2, **No.** 4, 2025.
10.62762/ASFP.2025.763200

***Corresponding author:**
Nnaemeka Reginald Nwakuba
nnaemeka.nwakuba@futo.edu.ng

Citation
Anyene, C. C., Udorah, D. O., Nsofor, P. S., & Nwakuba, N. R. (2025). Prospects of Agrivoltaics as a Sustainable Mitigation Solution to the Nomadic Cattle Rearing Crisis in Nigeria: A Review. *Agricultural Science and Food Processing*, 2(4), 148–172.

1 Introduction

Maximizing the use of natural resources (water, land and renewable energy) is fast becoming an area of great research concern. The devastating effects of fossil energy resources exploration and application to agriculture and our environment are the justification for the vigorous crusade on the adoption and maximized utilization of clean, renewable energy resources like solar energy alternatives. Solar radiation, one of the green sources of energy, is now being harnessed with the help of technological innovations to support various agricultural activities. It is then obvious that the meeting point of far-reaching scientific research breakthroughs and the effective application of derived real-world solutions has continued to culminate in the development of front-line technologies that have attracted serious consideration in modern agricultural endeavors.

Animal husbandry is a major practice of economic sustenance for the various citizens of Nigeria, and it is carried out either in confinement systems or open grazing systems. In the confinement system, domestic animals (goats, birds, pigs, cattle, dogs, rabbits, snails, grasscutter, etc.) are raised and intensively cared for in pens, barns, cages, barricaded open space or ranges that restrict the animals' movement. Whereas in the open grazing system, animals wander around in open fields without restraining barricades to their free movements in search of food for themselves [1]. Cattle rearing constitutes a major economic variable with an increasing population trend of 15.3 million in the year 2017 to 20.7 million in 2022 [2, 3]. Ajayi et al. [1] reported that the national cattle herd experiences an estimated growth rate of 1.5% annually. The major commercial cattle rearing system in Nigeria is the open grazing system, which is typically of the nomadic rearing category.

The nomadic rearing system that is mainly operated by the "Fulani herdsmen" has been attributed to being responsible for 90% of the livestock reared in Nigeria, thereby contributing about 3.2% of her Gross Domestic Product and one-third of the nation's agricultural GDP [4–7]. In the earlier days, pastoralists and farmers mutually co-existed in Nigeria. While the livestock that is reared by herders provides farmers with meat protein and manure for their fallow agricultural fields, the herders also derive feed resources (forage, hay and grains) from the agriculturalist communities [8]. In recent times, the relationship has been threatened by the reduction of grazing land due to tremendous population growth and the relative increase in farming activities.

The rate of crisis being experienced amidst the agrarian communities and nomadic livestock herders has caused severe loss of lives and properties in the prevalent regions [6]. Also, the crisis between herders and farmers is causing serious insecurity, which has, in turn, caused great hindrance to the campaign on national food security. These impasses result in the indiscriminate encroachment of reared animals of herders on cultivated farm fields, hence causing a serious crisis. In the intense form, the crisis often degenerates into armed weaponry conflicts that amount to the death of people, kidnapping and banditry. In the embattled regions, both the owners of small and commercial farms are unable to return to their farms due to fear of being attacked by aggressive herdsmen. Okojie [9] opined that technological intervention is one of the practicable remedies to the protracted crisis bedeviling nomadic cattle rearing in Nigeria.

The application of solar photovoltaic (PV) technology towards satisfying energy demands at homes and agricultural establishments has maintained a significant increase. This trend was advocated by IEA through their prediction that by the year 2050, about 6000 TWh of photovoltaic power must have been generated and supplied to attend to the power needs of societies. Whether on a regional or global scale, large expanses of land are required for mounting PV surface due to the diffusive characteristics of solar energy. This requirement is often met through massive buildings incorporating PVs, residential homes with rooftop PV units and photovoltaic/solar farms. In effect, there is increased competition for land resources as the ever-increasing population causes high food and energy demands. In order to comfortably integrate PV-generated energy resources into crop and animal husbandry operational requirements, agrivoltaics was conceived. According to the Fraunhofer Institute for Solar Energy Systems [10], China recorded the most significant participation in agrivoltaics for the year 2021 with a capacity of 12 GWp. Japan seconded this feat with more than three operational agrivoltaic systems. In principle, agrivoltaics entails the simultaneous development of land resources for both solar energy generation and agricultural purposes. This quest became obligatory due to the rising struggles posed by food and energy production on the limited land resources.

The concept of agrivoltaics reflects a viable solution for the optimized use of PV technology and limited available land. As most of the research works dedicated to agrivoltaics are focused on the simultaneous generation of energy and crop husbandry in a piece of land, this paper therefore reviews the prospects of agrivoltaics as an effective solution to the nomadic cattle rearing crisis in Nigeria. The objectives are to explore the severity and multi-dimensional effects of nomadic cattle rearing crisis in Nigeria, examine the economic significance of agrivoltaics technology to the agricultural sector, evaluate the potentials of agrivoltaics to the reduction of land-use conflicts and rivalry for limited arable land, appraise the solution prospects of agrivoltaics technology as viable intervention strategy to the nomadic cattle rearing crisis, and explore the alignment of cattle-rearing-integrated agrivoltaics systems with Industry 4.0 and 5.0 technologies.

A structured literature search was carried out across multiple sources. Key databases such as Web of Science and Google Scholar were used to find peer-reviewed studies and grey literature. Additional searches in Science Direct, Springer Link, and Research Gate helped to capture region-specific studies related to Africa and Nigeria. The search relied on keyword combinations linking three themes: technology (e.g., agrivoltaics, dual-use solar), livestock applications (e.g., cattle, grazing, pastoralism), and geography (e.g., Nigeria, Africa). The review focused mainly on work published between 2015 and 2025, when agrivoltaics research gained momentum and farmer–herder challenges in Nigeria became more critical. Only English-language materials were considered, including journal articles, conference papers, book chapters, and reports from governments or international organizations. Studies were selected if they addressed agrivoltaics, livestock under solar systems, or policy and economic issues relevant to Nigeria's land and cattle-rearing context.

2 The Severity and Effects of Nomadic Cattle Rearing Crisis in Nigeria

Nomadic cattle rearing constitutes a major means of livelihood for people dwelling in the Sahel and parts of the Savannah regions of Nigeria. Herders or pastoralists refer to a group of people whose major occupation is herding [6]. They move cattle around in groups in a transitory manner for them to be fed in open, uncultivated grasslands. The profession contributes to food production, and the "migration" herdsmen are directed by the need of their reared livestock for pasture. Herds are the major wealth reserve and constitute a dependable socio-economic worth. As nomadic herdsmen and their livestock travel through or dwell temporarily in regions, conflicts often ensue and escalate to insecurity that poses a threat to national security, crop farmers' livelihood and environmental sustainability.

The history of the nomadic system-related crisis dates back to the inception of agriculture. Olayoku [11] reported that agricultural expansion through the exploitation of pasture and irrigation facilities has compounded the extent of the herder-farmer crisis in Nigeria. The peak conflict period often spans through the rainy season (May – September) because the nomads begin to head back northwards as vegetation starts to grow. Arable lands are invaded, and many farms are lost during the peak planting season in the southern regions as the herders travel back northwards. In recent times, the Government on its own part has failed to optimally intervene through reliable policy, mediatory and resolution roles in the crises. In most cases, farmers in the affected regions often resort to taking the law into their own hands in order to protect their arable lands and cultivated farms [12].

In the year 1965, the Legislative Assembly of the Northern region of Nigeria established the first national livestock development programme as well as the grazing law that led to the provision of livestock grazing lands in specified areas to deactivate the usual Fulani nomadic livestock rearing system. According to Olayoku [11], the synergy with the International Livestock Research Institute (ILRI) was very helpful in the siting of 4,125 grazing outfits that were secured with perimeter fence work and other facilities (access roads, fire breaks, boreholes, veterinary services and a dam). Subsequently, from the year 2009, livestock grazing routes were established through the major cattle-rearing states in the northern region of Nigeria. Due to poor sustainability practices, only about 270 of the formally established grazing lands are aligned to their objectives for the nation's economic development.

In the past decade, several cases of loss of lives and destruction of agricultural products have been recorded on account of the nomadic cattle rearing system [13]. It was reported that about 615 deaths cases due to cattle grazing-related crisis as of the year 2014 [11]. UNHCR [14], Punch Editorial Board [15] and Ajayi et al. [1] reported the death tolls arising from the nomadic cattle rearing crisis from the year 2010 to 2023 in the North-Central region of Nigeria (see

Figure 1). With the characteristics of higher intensity, pattern and frequency, the nomadic cattle rearing crisis has continued to escalate across all the regions in the country [16]. Enactment and implementation of laws banning open grazing by some State governments' policies further intensified the hostility existing between the herdsmen and the communities they pass through to tend to their livestock. The issue is, in most instances, very complicated to be handled politically because a reasonable proportion of the livestock being reared by herdsmen is owned by influential business entrepreneurs, powerful political actors and high-ranking civil servants.

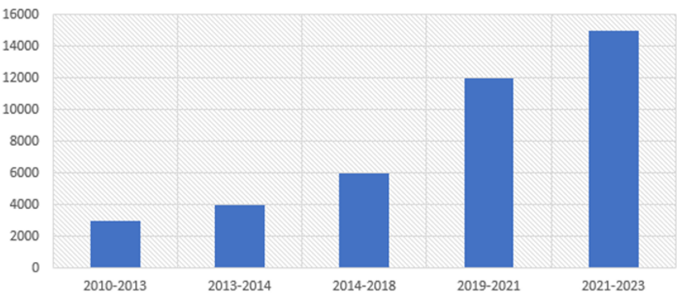

Figure 1. Number of deaths caused by the nomadic cattle rearing crisis in North-Central Nigeria from 2010-2023 [1, 14, 15].

The advancement of herdsmen-farmers' crisis over the year, with the negative results of kidnapping, banditry and terrorism, has rendered some of the States in Nigeria unsafe. Ilo et al. [17]reported that there are increased conflicts between herdsmen and farmers, with over 9000 death records and countless displacements of people. The issue has intensified so much that it is seriously threatening the security and socio-economic development of Nigeria [18]. Most herdsmen dwell in the northern region, while the farmers reside in the southern region. Nomadic cattle rearing crisis often begins from competition over limited farm lands and water resources, and transforms into a serious ethno-religious conflict. Other causative factors include increased human population, indiscriminate deforestation, cattle rustling, unreliable justice system, illegal arm carrying, and sluggish response to law enforcement officers to reported crises [19–21]. The consequences of the conflicts usually materialize in the destruction of farmlands, harassment/assault of women on farmland loss of lives, endless reprisals and destruction of properties [22, 23]. These consequences are felt by both parties (herdsmen and farmers), but the ripple effects go a long way in threatening the peace, unity, economic growth and food security across all the regions in Nigeria.

Ibrahim et al. [24] observed that Nigeria is persistently on the verge of anarchy due to the geometric increase in herdsmen-farmers' crisis across almost all the States. Akinyetun [25], Nkwunonwo et al. [26], Jinadu [5] and Ajayi [1] recounted that the major crises are experienced in such North-Central States as Benue, Nasarawa and Plateau. Also, the prevalence of herdsmen-farmers' conflicts is common in South-Eastern States like Imo and Enugu; South-Western States like Oyo and Ogun States; and North-Eastern States like Taraba and Adamawa States. The author further posits that about 3641 human lives were lost between January 2016 and October 2018 and many farmers abandoned their farmlands and fled for safety. ACAPS [27] reported that at the beginning of the year 2016, more than 1269 people were gruesomely killed in Benue State due to nomadic livestock rearing related crisis that occurred in about 14 of the 23 Local Government Areas in the State. Shortly after, there were reprisal attacks in more than 50 villages with consequent loss of lives and properties [21].

Government interventions towards the nomadic cattle rearing crisis are numerous, but issues like shortage of arable lands due to high population growth [28], transformation in land use techniques and ethno-religious rivalry pose a serious challenge to their sustainability. In 1965, when the national grazing reserves were established, the population of Nigeria was 55 million, and by the year 2019, its population rose to over 200 million, thereby making the sustenance of the intervention policies impossible. Figure 2 presents some major interventions by the government and their respective timelines.

In most cases, the farmers maintain the posture that the lands that are being exploited by herders are ancestral inheritances from their forefathers, and as such, any occupational intrusion for grazing activities will be met with serious confrontation and hostile actions. On the contrary, the herders who have been nurtured in the nomadic lifestyle reserve little or no regard for any people's rights to land but desire free movement through grazing routes for the proper feeding of their cattle [19]. The efforts to institute optimal co-existence between farmers and herders through such intervention strategies as the establishment of the Rural Grazing Area (RUGA) scheme by the Federal Government of Nigeria met serious criticism and rejection because of such issues as:

i. The intervention is being perceived as a

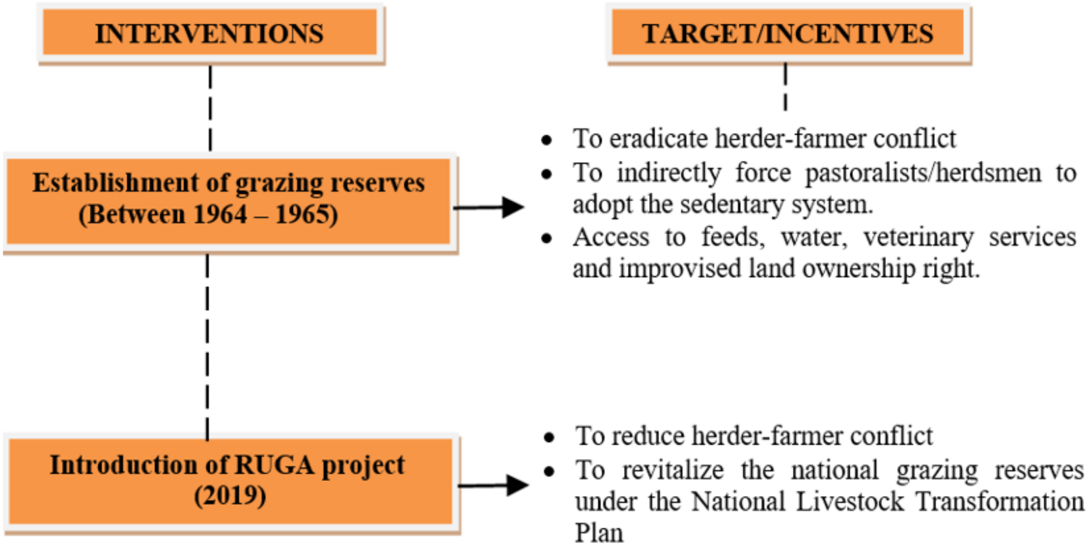

Figure 2. Nigerian government solution intervention on the nomadic livestock rearing crisis.

"land-grabbing attempt" by a particular ethnic group across the country.

ii. Fear of land use restrictions by the government over land owned by local farming communities.

iii. Persistent reduction of cultivable land due to the adverse effects of climate change and pollution.

iv. No clear information on those to be maintaining the grazing reserves.

v. The position is that herdsmen should acquire their land, set up a ranching system and manage the business as a private venture.

To these backdrops, the government is saddled with the responsibility of engaging the concerned stakeholders to contemplate the possibility of adopting alternative techniques of rearing cattle that will not only be acceptable to all and sundry but also foster the protection of lives and properties. If sustainable success can be achieved towards the maximum reduction of the nomadic livestock rearing crisis in Nigeria, there is a need for long-lasting novel approaches. Under modern agricultural dispensations, promotion of climate-smart agriculture, integration of renewable energy, combined energy generation and farming techniques, integration and land resources use optimization are presently being advocated.

2.1 Addressing the issue of land occupation in agriculture and herders' interests

To translate agrivoltaics in the Nigerian context for reduced land use conflicts and conserve the interest of herders, there is need for designs and structural configurations that will not only foster land productivity but excel in fundamental agriculture evaluations. Elevated and widely spaced agrivoltaic systems are ideal for the effective accommodation of reared livestock, farming equipment, pasture management equipment, as well as optimal light penetration. Agrivoltaics tends to provide such micro-infrastructure as solar-powered boreholes, charging booths and mobile dairy cold-chain at a land array edges for the pastoralists. In other words, it operates to convert the edges of land into service centres for travelling herders. For this to be possible, Nigeria has to establish integrated agrivoltaics-grazing pilot projects in existing cattle grazing conflict hotspots, carryout intensive research to measure animal health, pasture biomass, and operation and maintenance cost features for at least 24 months. Government as a matter of urgency should establish a functional agrivoltaics code of practice or legal frameworks, especially in the aspects of PV-modules design specifications, safety and monitoring metrics. Agrivoltaics finance, grants and funds models should be adequately instituted in consortia blueprints to promote sustainability across regions. The technology should be developed to scale with irrigation to support dry-season fodder production, thereby reducing migration pressure [29].

A practical solution to land occupation conflicts between farmers and herders is to adopt agrivoltaic land-sharing systems that encourage joint use instead of competition. This approach allows the same piece of land to produce solar power, support crop cultivation, and provide grazing areas for livestock [30]. Farmers benefit from growing shade-tolerant crops that thrive under solar panels while also securing steady income from energy partnerships. At the same time, herders gain reliable access to nutritious forage planted beneath and between panels, reducing the pressure for migration and opening opportunities for roles in site management or security. If supported by cooperative leasing models and integrated into national agricultural, energy, and peacebuilding policies, agrivoltaics can transform contested lands into shared economic zones, easing farmer–herder tensions and creating more resilient rural livelihoods.

3 Economic Significance of Agrivoltaics Technology in Agriculture

Energy from the sun is harvested, harnessed and applied to different agricultural and horticultural purposes (see Figure 3), and in the African continent, solar energy capacity has continued to increase as the days go by Sasu [3] reported that as of the year 2023, the capacity of solar energy in Nigeria stood at 112 meqawatts (MW). This showed a significant increase when compared with those of previous years. In recent times, researches are devoted across the globe toward land use maximization through process combination. The competition that is presently experienced in the use of land resources for energy generation and food production has been on since the 1970s [31]. As the demands for these two resources (energy and food) continue to maintain a rising trend due to the ever-growing world population, there is a dire need to adjust from the non-renewable energy options to the renewable sources, and also consider ways of maximizing the use of the limited land resources.

The efficient design and operation of photovoltaic technology in open fields requires a large expanse of land. In order to minimize such pressure posed by ground-based solar technology on available arable lands, synergistic approaches for the energy generation and agricultural production in the same piece of land have been the concern of many researchers. Photovoltaic systems, which are incorporated into agriculture to produce renewable energy, also influence crop production, animal rearing, ecosystem interaction processes and the sustenance of terrestrial habitat. This novel integration is also effective in promoting the Sustainable Development Goals (SDGs) that are uniquely directed towards greenhouse gas emission minimization, climate change adaptive practices, ecosystem and biodiversity conservation, deforestation and desertification eradication, degraded land reclamation, and land and water use optimization.

The deployment of agrivoltaics in unique configurations is a certain approach to derive mutual benefits and sustained value addition between solar and agricultural undertakings. It is to this need that agrivoltaics, one of the novel technological solutions, was first conceptualized by two German scholars (Goetzberger and Zastrow) in the 1980s and by 2004, the first agrivoltaic system was installed in Germany. Owing to the fact that the technology involves the innovative deployment of such green technology as photovoltaic, it has continued to attract attention globally. From the year 2011, research on the technology has maintained a growing trend. Fraunhofer Institute for Solar Energy Systems [10] outlined the timeline for the development of agrivoltaics and reported in the year 2021 that the global agrivoltaics capacity rose above 14 GWp (see Figure 4) [31].

The development progress pertaining to agrivoltacs has continued to be favorable in different countries across the globe. In Germany, the Fraunhofer Institute for Solar Energy Systems has sustained the APV-RESOLA research project with long-running trials of agrivoltaics. Data obtained indicated over 160% land-use efficiency in hot years [32]. In the year 2023, the technology took a different dimension in France when her government established APER law that is directed to accelerated production of renewable energy and features zoning for renewable energy, sustainable implementation of agrivoltaics, provision of solarized canopies and parking lots, and consolidation of legal framework on corporate power purchase agreements (CPPAs) [33, 34]. In 2024, the "Law 101/2024" was established in Italy to provide incentives for agrivoltaics schemes across regions of the country [35]. The United States of America established the National Renewable Energy Laboratory (NREL) and dedicated it to researches renewable energy system development and efficient applications. NREL has hundreds of sites with the integration of agrivoltaics to grazing amounting to more than 200 sites. In Japan, SMEs (small and medium enterprises) and universities have been in the forefront of commercial-scale production of vegetable with agrivoltaic systems. The Ministry of Agriculture, Forestry and Fisheries permits was necessary to ensure the solar panel systems are developed in a way not to block a greater proportion of the sunlight for improved crop growth. In order to alleviate the effect

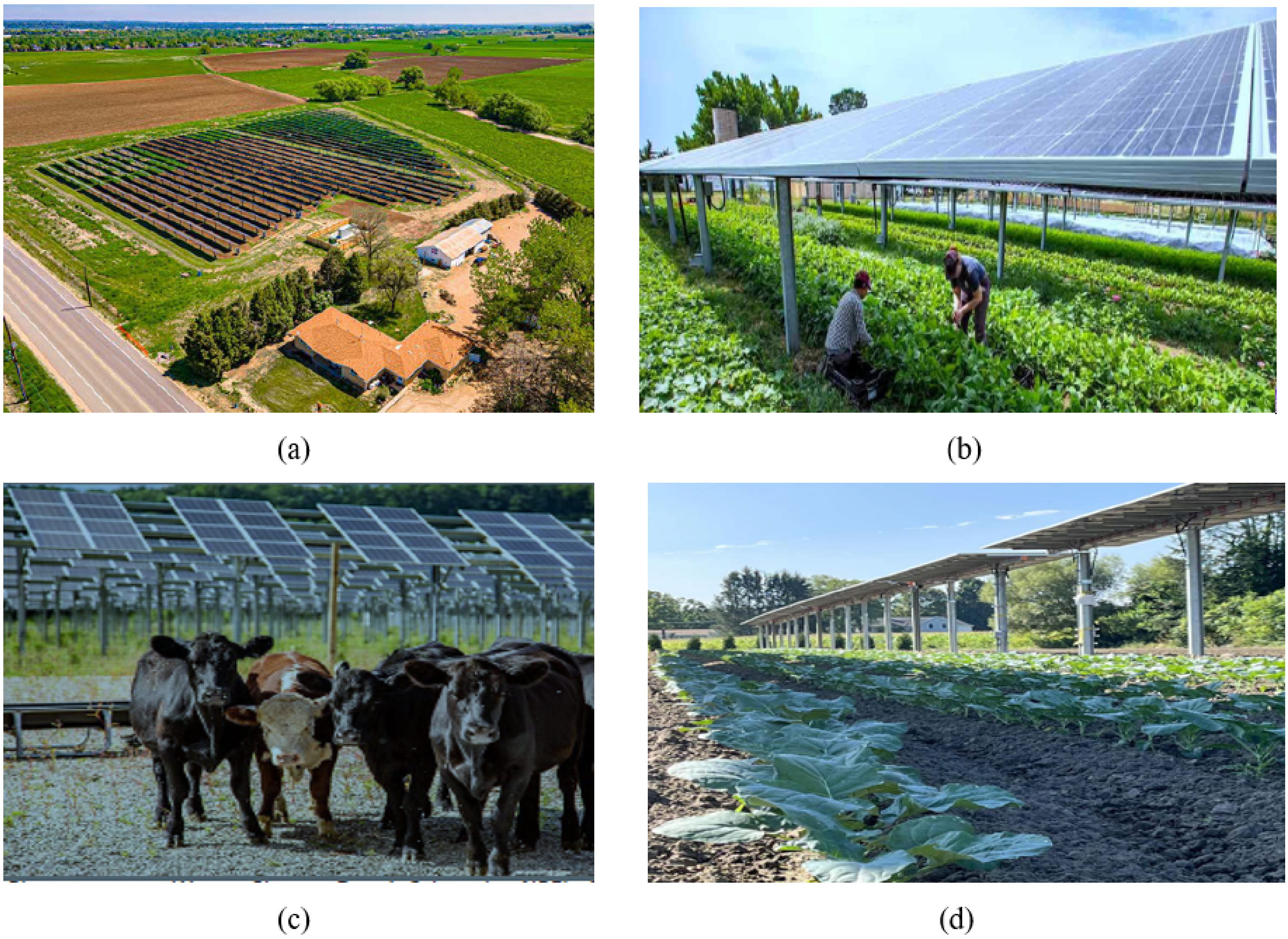

Figure 3. Modern applications of energy from the sun – (a) Solar farm for generating and supplying electricity to rural areas, (b) Photovoltaic systems for generating energy used in the husbandry of horticultural plants, (c) Photovoltaic systems integrated to livestock production, and (d) Photovoltaic systems for commercial cultivation of vegetable plants.

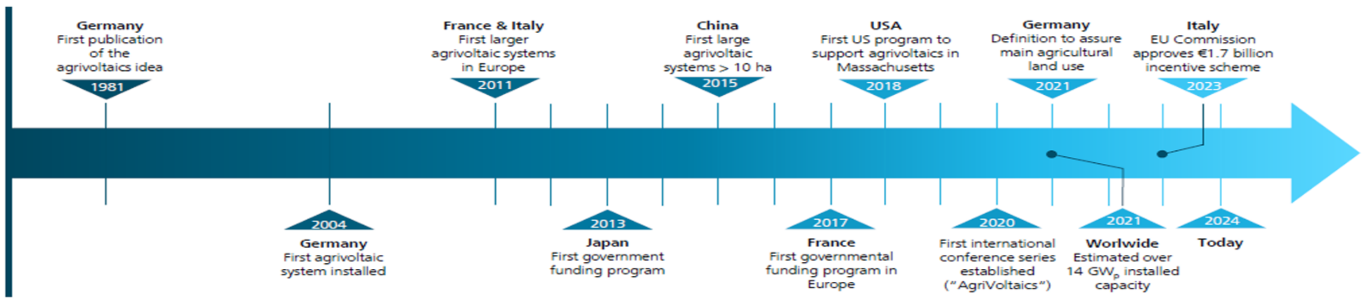

Figure 4. Agrivoltaics development timeline [31].

of erosion and generate jobs for the rural populace, the government of China has developed series of projects that pair photovoltaics with shrub crops and grazing animal production, especially in arid regions. India has stepped a bit further in solarizing agriculture to institute policies that are focused on establishing alliance, pilots, incentives, financier, and standardized best practices to Agrivoltaics schemes.

Crops are cultivated in between arrays of solar panels, and power tillers or small agricultural machinery can be adopted as mechanization options to further improve the timeliness of operation and productivity. Crop productivity is dependent on the location of the farm and the configuration of the solar system incorporated in the agrivoltaic field. For integrating solar primed energy generation with crop production, the design considerations include optimized photovoltaic panels height and spacing for

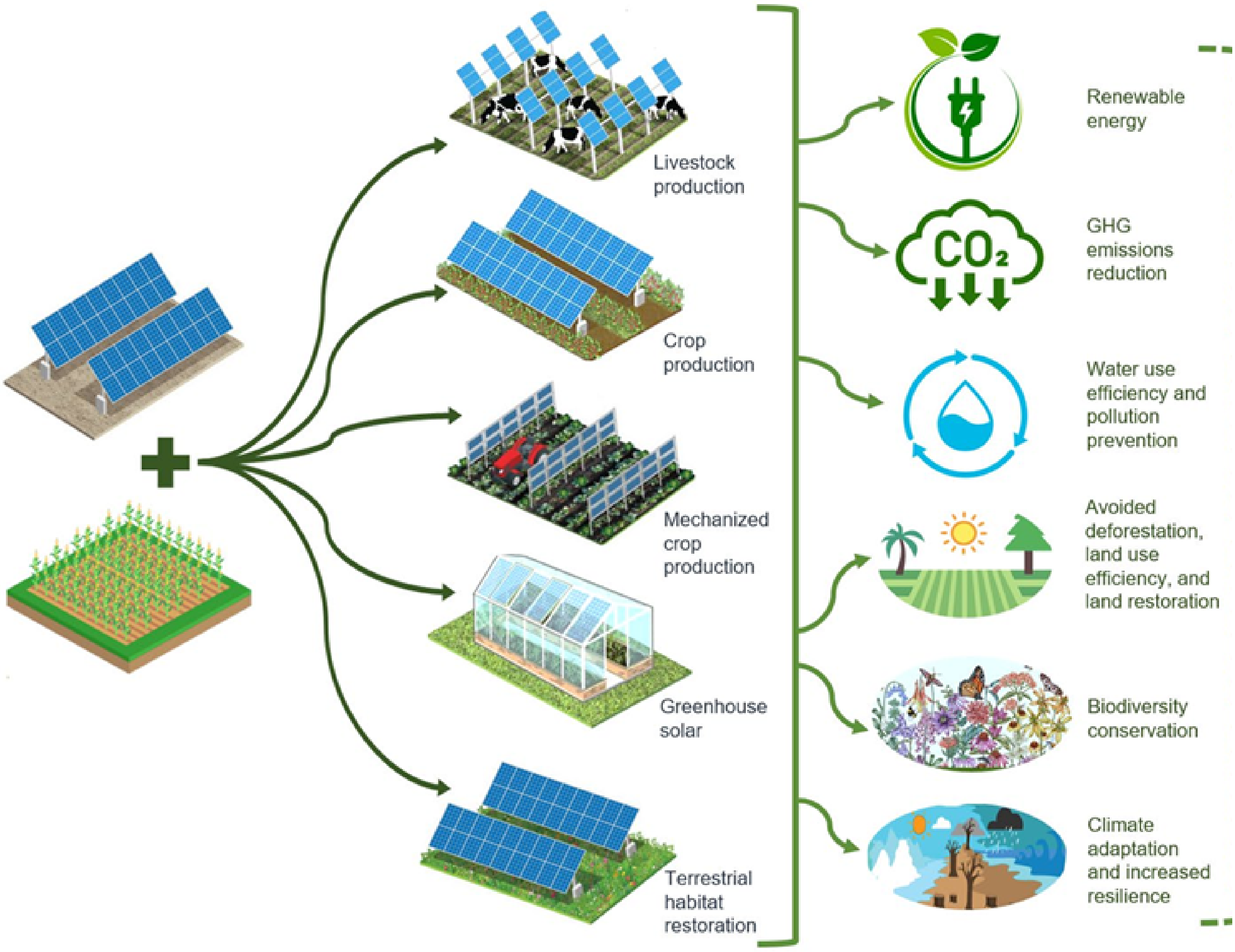

Figure 5. Applications and importance of agrivoltaic technologies.

effective growth of relatively shade-tolerant plants to extremely non-shade-tolerant plants, on-site operation and maintenance variability, water accessibility and agricultural returns on investment. Doubleday [36] maintained that grazing animals like cattle and sheep are reared to forage underneath or in between adjacent photovoltaic panel systems. Solar energy and the integrated grazing concept promote sustainable animal grazing practices, enable research studies for pasture land optimization, farm environment tending cost reduction, and attune to other habitats, especially pollinator habitat compatibility. The major design considerations for integrating photovoltaic energy generation to cattle rearing are costs for erecting fence structures around the farm, accessing good water and developing adjustable solar panels to accommodate larger livestock. According to Dreves [37], the applications and importance of the system in modern-day agriculture are as outlined in Figure 5.

Agrivoltaics is also integrated in greenhouses by incorporating photovoltaic units on the top or around the structure for the generation and direct application of electricity in the system. Automated tilt-varying hoods are usually used in mounting the solar panels to vary shading within the greenhouse. The design and operational factors that are considered for applying agrivoltaic technology to greenhouses include photovoltaic technology materials, optimized use of generated electricity, optimized lighting and structural configuration of the greenhouse. Also, it is adopted to provide habitat for pollinators, native vegetation, as well as taming the mutual benefits of vegetative resources.

Agrivoltaics is fast being developed globally with diverse applications in crop husbandry, horticulture, aquaculture, greenhouse, ecosystem services and bee-keeping. The design, layout and specification vary with farming requirements and practical conventions. For sustainability and effective advancement of the agrivoltaic technologies, there is a need for widened research on real-time adapting solar technology configurations, standardized implementation techniques, long-term experimentation, characterization and evaluation, intensive mutual and integrated beneficial partnership, multi-sectoral mutual prospects, geographical diversification of pilot projects, and international agrivoltaics data transmission. In modern agriculture, agrivoltaics hold great prospects and significance (see Figure 6).

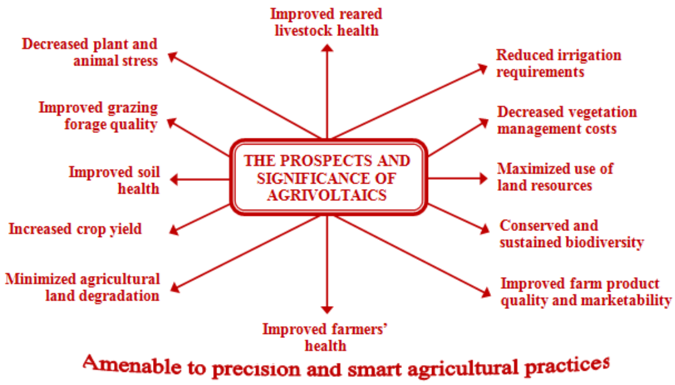

Figure 6. The prospects and significance of agrivoltaics in modern agriculture.

To a huge extent, agrivoltaic has been very significant for the reduction of competition for limited agricultural land, minimization of loss of water from the soil and plant resources, protection of cultivated crop and reared animals from the vagaries of weather, reduction of agricultural carbon-footprints, preservation of biodiversity and ecosystem, minimization of fossil-fuel energy sources dependence, improvement of the welfare and dignity of rural farmers and sustainability of revenue generation for farmers [38–40].

3.1 Reduction of Competition for Limited Agricultural Land

Agrivoltaics fosters the combined production of photovoltaic systems generating energy and agricultural products in the same area of land at a time. It is a viable alternative technology to remedy the effects of the reduction in cultivatable areas due to the establishment of solar farms with several hoods, racks and panels for electricity generation [31]. The farm technique promotes land use optimization. It also plays a vital role in curbing the lives and properties threatening crises that often arise from the struggles for the limited land, as driven by the increased demand for sustainable food and energy resources by the ever-growing global population [41]. In practice, photovoltaic cells are mounted in raised frameworks or rack systems to provide enabling space for such agricultural purposes as plant and animal husbandry.

Agrovoltaics is a modern technique that promotes the production of food products and industrial raw materials with limited resources. Edouard et al. [42] reported that this technique increases land use efficiency to about 180% while Global Environment Facility [39] maintained that research has shown that with agrivoltaics favours about 1.7 land equivalent ratio (LER), that is, the application of agrivoltaics to 1 ha of land can generate the quantity of food and energy resources that a 1.7 hectares of farmland can service when split into two for separate "farm field" for crop production and "solar farm" for electricity generation. In the concepts of reclamation, Li et al. [43] reported that agrivoltaic systems improve the growth and development of native plants. This has led to the discovery of several applications in the reclamation of abandoned agricultural lands.

3.2 Minimization of Loss of Water from the Soil and Plant Resources

Agrivoltaics systems provide shade to the underlying space to minimize the rate of evapotranspiration – loss of moisture from the soil and plant parts. Also, livestock reared under agrivoltaic systems are prone to consume less water than those raised in the open system [38, 44]. As the photovoltaic panels require intermittent washing operations for sustained radiation efficiency, the resulting wastewater is reused for crop irrigation. Jaine et al. [45] reported that in recent configurations, channels and piping systems are incorporated in the photovoltaic rack assembly to harvest rainwater into a reservoir for use.

3.3 Protection of Cultivated Crops and reared Animals from the Vagaries of Weather

The photovoltaic panel assembly in an agrivoltaic setup protects crops and animals from extreme weather conditions emanating from direct insolation, high temperature and heavy precipitation. It intercepts rain droplets to impede accelerated runoff and minimizes evapotranspiration in the farm. Despite the fact that excess shading effects from photovoltaic panels mounted close to the ground reduce the productivity of shade-intolerant crops, the system tends to generate a unique micro-climate around its expanse that improves the yield, marketability and seasonality of so many categories of crops. Literature [40] opined that the compatibility of desired crops and animals must be duly considered in agrivoltaic designs should take into account the compatibility of desired crops.

3.4 Reduction of Agricultural Carbon-Footprints

For successful and sustainable global agricultural practices, carbon footprint reduction is paramount [46]. Despite the rapid variations in climate and higher demands for food due to the ever-rising population growth effects, ways of addressing the cataclysmic impact of carbon footprint on the earth are of great concern to the agricultural sector. By adopting renewable energy and other strategies, carbon emissions can be reduced, leading to more sustainable agriculture. Such a climate-smart endeavour as agrivoltaics is germane in reducing carbon emissions. Also, the technology offers renewable energy that does not in any way cause the discharge of carbon into the environment. Global Environmental Facility [39] upholds that with an adequate energy storage facility on the ground, the deployment of agrivoltaic systems to just 1% of the approximately 1 billion hectares of the world's agricultural lands could potentially sustain the global energy demand with drastically reduced emission of greenhouse gases. Sarr et al. [31] stated a prediction that by the year 2050, about 25% of the electrical energy that will be required globally will be furnished through photovoltaic systems, with an expected 4.9 Gt (≈21%) reduction in CO_2 emission across the energy sector.

Rural development and industrialization activities through conventional deforestation and burning of cleared bush products have been reported to be contributing significantly to carbon emissions into the environment [38]. According to Hassanpour et al. [47], plants grown in agrivoltaic systems tend to build up more biomass content with higher carbon content and sequestration prospects. The adoption of techniques that foster agricultural emissions reduction and carbon sequestration increases is capable of cutting down the contributory effects of agriculture to climate change to about 5.5 – 6.0 Gt of carbon dioxide equivalent annually. Terrones [48] and Macknick et al. [49] reported ways of addressing agricultural carbon footprint issues to include:

i. Effective implementation of the "4Rs nutrient management" – Manure and other crop nutrient resources are adopted with keen emphasis on 'right source – denoting the type of manure', 'right time –applying when needed by plants', 'right rate – optimal quantity for effective crop nutrient uptake' and 'right place – precise location for effective plant utilization'.

ii. Adoption of renewable energy and energy-efficient systems for agricultural operations to economically reduce carbon footprint.

iii. Minimizing tillage practices to disturb the soil less and relatively reduce Carbon dioxide (CO_2) emission.

3.5 Preservation of Habitat, Ecosystem and Biodiversity

The concurrent utilization of a land for both agricultural purposes and renewable energy generation helps in conserving land resources with other benefits relating to the improvement of native habitat and protection of terrestrial ecosystem, as well as the conservation of biodiversity [50, 51]. Global Environmental Facility [39] reported that the shades emanating from photovoltaic panels optimizes absorption of nitrogen and phosphorus, thereby minimizing the chances of water bodies pollution when such nutrients are washed or eroded into them. Agrivoltaic systems impose a microclimate that enables cultivated crops and reared livestock to effectively cope with the high-temperature conditions posed by climate change. The covering and shield provided by the photovoltaic assembly protects farmers, plants, and livestock against climate change-induced frequent extreme weather events – heavy precipitation/storm, heat waves and drought [52].

3.6 Minimization of Dependence on Fossil-fuel Energy Sources

Agrivoltaics is potentially attentive to providing solutions to the food, energy and water security problems of Nigeria. It eradicates the dependence on fossil-fuel-operated power-generating sets in farms. Dhonde et al. [53] reported that the electrical energy generated from the photovoltaic unit could be used for operating water pumps to supply water and powering other equipment in the farm.

3.7 Improvement of Income, Welfare and Dignity of Rural Farmers

The acceptance, adoption and implementation of agrivoltaics hold great prospects in expanding the occupational opportunities of farmers and optimizing their revenue-earning chances [54]. Agrivoltaics accommodate mechanization techniques that tend to improve the dignity of farmers, reduce drudgery and increase productivity (see Figure 7).

Figure 7. A farmer executing farm operations in between solar panel rows with a tractor [40].

In recent times, the configuration and design have been done to accommodate the use of agricultural machinery and equipment for cultivating tall food and horticultural crops chances [54]. Agrivoltaics is closely related to precision farming, and it is likely to improve productivity through the application of technologies such as Artificial Intelligence, sensors and yield monitoring platforms. While the system is prone to higher productivity, it promotes timely access to self-generating electricity for the execution of storage, processing other operations. Li et al. [55] stated that with respect to different crops, agrivoltaic technologies are capable of producing 9%–20% return on investments annually. McKinsey et al. [56] indicated that agrivoltaic technology fosters sustained market timing for increased income within the agricultural value chains. Incorporating a water channel and storage facility into the systems, water use efficiency and overall operational costs are improved. Dinesh et al. [57] conducted an investigative study on the economic benefits of agrivoltaic systems and reported that the system was 30% more economically significant than the conventional agricultural practices.

Generally, for the effective planning and deployment of agrivoltaics, keen consideration is made to the compatibility of the technique vis-à-vis site design, farming equipment, availability of solar technology, previous agricultural practices, and operation and maintenance schedules; flexibility of the technique, farming patterns and practices and support plans; and remunerations from sustainable operations and financial breakthrough. Agrivoltaic technology enhances farmers' economic resilience through innovative multiple uses of land resources, diversified income earning, and optimized use of water and energy. The communities around the farm are serviced with such benefits as workforce development, reduced land-related conflicts, and food and energy resources resilience. In the same light, the corporate or industrial benefits to having established agrivoltaic projects include increased interest and access to landed resources, advanced regional acceptance and adoption, minimized operation and maintenance requirements, and improved benefits from the constituent systems. Despite these sectoral benefits, agrivoltaics presents concerns towards effective planning and implementation, security and preservation of farmland, effects on soil, productivity and land availability, cultural heritage, cost-benefit uncertainties, and technical and economic liabilities.

4 Enabling Conditions for Agrivoltaics Deployment in Nigeria

Nigeria is endowed with photovoltaic power potentials (see Figure 8). The northern and central regions enjoy some of the strongest solar exposure, with annual averages ranging between 1,800–2,500 kWh/m² [58]. These areas are highly favorable for agrivoltaics, not only for electricity generation but also for improving crop performance under harsh, dry conditions. In contrast, the southern forest and coastal States receive lower solar irradiance (around 1,200–1,600 kWh/m² annually) and face heavier rainfall and cloud cover. While this reduces large-scale generation prospects, it creates opportunities for smaller systems that protect and enhance shade-loving or rain-sensitive vegetables, spice crops and beverage seedlings [59].

Successful agrivoltaic implementation in Nigeria is controlled by such conditions as land tenure and community acceptance, investment costs and funding sources, and policy and legal support requirements.

4.1 Land tenure and community acceptance

Land access has continued to pose critical challenge in Nigeria. Although the Land Use Act gives the State governors formal authority, rural lands are still so much influenced by customary rights and in situ local authorities [61]. In the northern and middle

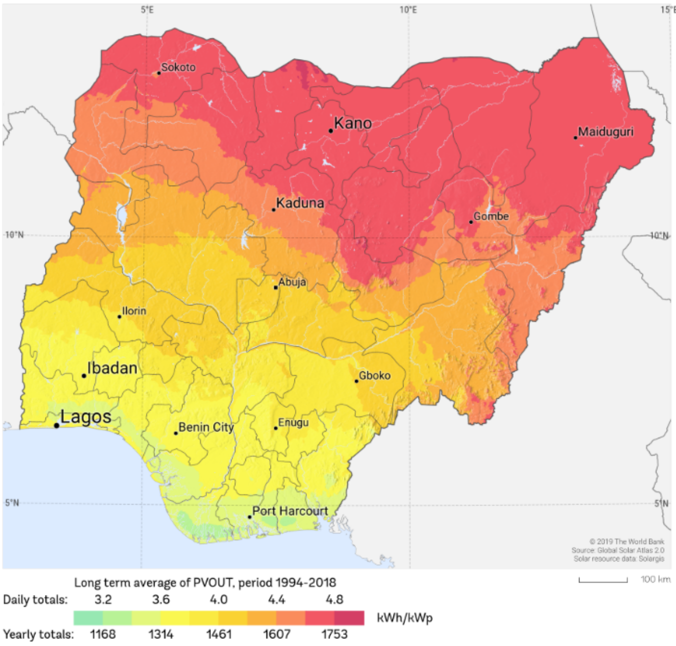

Figure 8. Photovoltaic power potentials across different regions in Nigeria [60].

belt regions, coinciding farmer and herder claims add sensitivity, which implies that agrivoltaic designs should incorporate grazing considerations, and such designs are subject to local negotiations. In the south where there is fragmented landholdings, farmer cooperatives or household-scale agrivoltaic schemes may work better than large-scale projects. Irrespective of the region, the sustenance of long-term success in agrivoltaics acceptance, adoption and implementation is dependent on clear treaties, visible community benefits, and inclusive ownership models.

4.2 Investment costs and funding sources

Agrivoltaics amount to higher installation costs than the conventional photovoltaics because of taller mounting structures, stronger supports, and wider spacing requirements [62]. The Northern regions of Nigeria that have larger expanses of flat land, are more liable to hybrid-finance projects that integrate private equity, concessional loans from development banks and climate adaptation grants or funds [65]. Potentially, the systems could serve as power vendors to agro-processing centres, mini-grids, or even the regional grid while still promoting crop/animal production. In the southern regions of Nigeria that are characterized with smaller farms and limited capital, the relative financing options are more attuned to pay-as-you-grow models, cooperative lending, or donor-assisted pilot projects [64]. Across all zones, there is a need to develop repayment schedules that are agreeable to existing farming revenue patterns.

4.3 Policy and legal support requirements

Presently, there is no agrivoltaics regulatory framework in force in Nigeria [65]. In order to advance the development and deployment of the technology, the States in the regions, especially the north and Middle Belt, require bilateral approval processes. Such approval processes must effectively adjust to statutory and customary land rights, as well as sustainable conflict-resolution mechanisms. In southern regions, streamlined permits for farmer or cooperative owned agrivoltaic systems, and subsidized import duties on specialized agrivoltaics hardware, can go a long way to accelerate acceptance and adoption. In the nation scale, agrivoltaics blueprint variables should be integrated into the existing renewable energy policy, agricultural climate-smart agriculture initiatives, and extension programs to formally position the technology to sustained recognition and incentive gains [66, 67].

5 Agrivoltaics and Livestock Integration in African Regions

There are proofs of technical feasibility of agrivoltaics that already exists in African countries. Although large-scale adoption in Africa is still at nascent stage, several experimental projects and pilot studies provide valuable insights into how the technology can be adapted to African agro-ecological and socio-economic contexts. Livestock integration is the most immediate and low-risk pathway for dual-use projects. Policy and finance support are essential as adoption of agrivoltaics is highly dependent on conflict-sensitive land management, benefit-sharing arrangements, and incentives to offset higher capital costs. It becomes convincing to establish pilot trials that will explicitly combine grazing access with energy and crop production to maximize acceptance and impact. The following instances strengthen the case for exploring agrivoltaics in Nigeria.

5.1 On-farm agrivoltaics demonstrations in Kenya and Tanzania

Research sites in Kenya and Tanzania have set-up agrivoltaics test projects that integrated elevated photovoltaic arrays with crops and water-harvesting structures. The findings show that partial shading reduces evapotranspiration and, in many cases, maintains or improves yields of staple crops such as maize and beans. The attraction point for farmers was in the instances when energy access and water benefits were built into the model, especially where they were involved in co-design [68, 69].

5.2 Experimental agrivoltaic fields in Ghana

Vast areas of rangeland suitable for agrivoltaics was mapped out and several solar farms have begun partnering with local sheep farmers, using grazing for vegetation control under PV arrays. This tends to reduce operating costs while offering herders stable access to pasture [71–73].

6 The Feasibility of Agrivoltaics in Different Regions of Nigeria

The potential for agrivoltaics in Nigeria is shaped by regional differences in solar resources, land management practices, financing capacity, and supportive policies. Agrivoltaics holds the greatest promise regions where abundant sunlight and water stress create strong incentives for dual land use. In other regions of lesser solar variable endowments, there is prospects in smaller and crop-specific agrivoltaics applications. There is a dire need for sustainable financing models that befit regional cash flows, communal engagement, and explicit policy backing to bridge the gap between technical feasibility and long-term adoption.

6.1 Feasibility of Agrivoltaics in North West Nigeria

The North West region of Nigeria which comprises of Sokoto, Katsina, Zamfara, and Kano States has high solar resource and solar power generation profiles. The region has the highest global horizontal irradiance (GHI) with longer dry seasons and clear skies [74, 75]. These remarkable solar features position it as one of the best regions for maximizing agrivoltaics-electricity output. Lands in the regions are principally overseen by customary rights. With the widespread farmland and grazing areas, the communities are likely to embrace agrivoltaics opportunities for extra income. But in situations where the such projects are likely to block their grazing access, the risk of resistance becomes obvious. These potential impasses define the need for timely engagement with local authorities and efficient integration of pastoral mobility considerations. Although system costs are increased by imported hardware and elevated structures, the very high solar yield improves project economics. Potential financiers may include development finance institutions (DFIs), distributed renewable energy programs, and private developers, particularly where power can be sold to mini-grids or industries [76]. Clear lease frameworks that reconcile statutory and customary rights, provisions for pastoral access, and simplified licensing for mini-grids and grid-connected agrivoltaics are equally needed.

6.2 Feasibility of Agrivoltaics in North East Nigeria

In Borno, Yobe and Adamawa States that make up the North Eastern region of Nigeria there is strong availability of solar resources [77]. Despite the high agrivoltaics potentials, the insecurity menace in the regions adds to the risk premiums that tends to limit practical deployment of agrivoltaics in many areas. The available lands in the region are principally under customary control. Community acceptance and adoption towards agrivoltaics is essentially tied to visible local benefits. The investment costs that are applicable to North East include insurance, security arrangements, and civil works raise costs. Humanitarian-development blended finance and resilience-focused energy programs are the scalable financing options that are suitable in this context [78, 79]. Due to the insecurity problems, commercial equity-only models cannot work in North East. Beyond policy and legal support, there is a critical need for effective coordination among State governments, security agencies, and the local authorities. This is so because, every investor needs guarantees that are linked with community development obligations.

6.3 Feasibility of Agrivoltaics in North Central/Middle Belt Nigeria

This region is the hotspot of farmer–herder conflicts, with substantial displacement and declining agricultural output [80]. Although slightly lower than those of the far northern States, there is good solar resource and power generation potential in Benue, Plateau, Niger and Kaduna States that make-up the Middle Belt region of Nigeria [81]. The shading that might result from the agrivoltaic systems can minimize the incidence of heat stress in crops, and improve water retentiveness during drier months. The development of large agrivoltaic systems that could cause obstruction to grazing access can trigger serious anxious reaction amongst herders. Pliable models that integrate livestock pathway, elevated racks, or water-sharing infrastructure are vital for effective implementation. Also, early engagement of both farming and pastoralist groups is essential. The investment costs of agrivoltaics is preferable when the technology is alternating expensive diesel for irrigation, storage, or processing. The ideal source of funding is the integrated financing that combines climate funds, agricultural grants, and concessional loans. The policy and legal frameworks pertaining to the establishment of agrivoltaics in the regions must consider conflict-sensitive approvals, mandatory community benefit-sharing, and grazing-access clauses, as part of such project regulation. Besides, there should be sound synergy between agriculture, livestock, and energy ministries in the region.

6.4 Feasibility of Agrivoltaics in South West Nigeria

The South Western region of Nigeria comprises of Oyo, Ogun, Lagos and Osun States which are characterized with coastal, forest and moderate solar radiation attributes that tend to reduce insolation. Peri-urban agrivoltaics for economic crops and small farm holdings are more feasible in the region than large-scale systems. The lands are highly fragmented, mostly urbanized, and owned through stringent statutory land systems than observed in the northern regions [82]. The likely inducement for acceptance of agrivoltaics by farmers and communities in this region lies in effective generation of electricity and productive land use [83]. There is a greater chance of smallholder agrivoltaic systems which in no doubt costs more per watt but remains devoid of larrge land disputes. The likely funders for such project in the region include local banks, energy service companies, venture capital in agri-tech, and concessional green credit lines. The practicable policy and legal frameworks for the adoption of agrivoltaic remain those that promotes simplified smallholder permits, and reduced import duties on essential hardware.

6.5 Feasibility of Agrivoltaics in South South Nigeria

The South Southern region of Nigeria is made up of three States (Rivers, Delta and Bayelsa). It is characterized by reduced solar yields due to high cloud cover and rainfall intensity. While the solar power generation potential of agrivoltaics for the region remain modest compared to the northern regions, the system remains viable for productive uses such as fisheries cold chains and agro-processing. The land rights are highly complex and strongly contested due to oil industry legacies [84]. The establishment of such projects will require strong transparency, community involvement, and job creation to gain acceptance [84]. The incidents of corrosion in the dominant coastal environments tend to increase maintenance costs, and the resulting lower yield also reduces derivable revenue. The adaptable funding option for the region is the blended finance that integrates corporate social responsibility (CSR) funds, development finance institutions (DFIs), and donor-assisted projects. The applicable policy and legal support require strong environmental standards, enforceable community benefit frameworks, and targeted incentives for diesel replacement projects [85].

6.6 Feasibility of Agrivoltaics in South East Nigeria

The southeastern region of Nigeria which is made up of Abia, Anambra, Ebonyi, Enugu and Imo States is endowed with moderate solar radiation, and this limits the potential of agrivoltaics to vegetables, nurseries, and rooftop systems for processing facilities [86, 87]. Land ownership is under strong customary family control, but relatively well-structured. The featured fragmented plots encourage cooperative or cluster-based agrivoltaic models. Just like the South West region, small and medium enterprise finance, energy service company (ESCO) partnerships, and donor-assisted agri-energy programs the most adaptable funding options [88]. Due to the high trade disposition of this region, productive-use electrification strengthens business cases. The State governments could provide agrivoltaics policy and legal framework that create cooperative loan schemes, standardized lease templates for smallholder clusters, and integrating agrivoltaics into rural electrification plans [89].

7 Potential challenges to the Implementation of Agrivoltaic Systems and mitigation strategies

Introducing agrivoltaics into cattle rearing systems in Nigeria offers a promising model for dual land use, yet its practical deployment is constrained by several technical, economic, and socio-cultural barriers. A structured analysis of these challenges, alongside context-appropriate mitigation strategies, is essential to enhance feasibility and ensure community acceptance [90].

One of the foremost technical risks lies in the potential for physical damage to photovoltaic infrastructure. Unlike sheep or goats, cattle exert far greater force, making behaviors such as rubbing against posts, pushing against frames, or trampling cables especially hazardous to solar arrays [91]. Moreover, cattle movement can generate dust and organic debris, accelerating panel soiling and reducing efficiency. These risks can be mitigated through elevated racking systems, with panels installed at heights of at least three meters and supported by galvanized steel posts anchored in concrete foundations [92]. Sensitive components, such as inverters and cables, should be enclosed with fencing or protective barriers, while rotational grazing systems can distribute pressure on the land and infrastructure more evenly. Together, these design and management practices reduce the likelihood of costly damage [93].

Electricity utilization also presents technical and economic difficulties. Grid connections in rural Nigeria are often weak or non-existent, while stand-alone systems must rely on expensive storage technologies to balance fluctuating demand [94]. A practical response is to prioritize productive, cattle-related energy uses, such as water pumping, milk cooling, feed processing, or cold storage, that provide immediate economic value while stabilizing demand. Hybrid systems that pair solar generation with battery banks or diesel backup can ensure continuity of critical services, especially in dry seasons when water access is paramount [95]. Clustering agrivoltaics systems into micro-grids that serve groups of herders or cooperatives can further spread costs and benefits, while training programs delivered through extension services can build local expertise in maintenance and troubleshooting.

The economic dimension represents another major obstacle. Livestock-oriented agrivoltaics requires taller, stronger, and more complex infrastructure than standard solar farms, substantially raising capital costs [96]. For many herders with limited access to affordable finance, the long payback period discourages investment. Addressing this challenge requires innovative financial approaches. Blended finance, supported by concessional loans, climate adaptation funds, and development bank facilities, can de-risk investments and attract private participation. Cooperative models that pool resources among herders allow cost-sharing and collective ownership, while leasing or service-based arrangements; where energy companies install and manage the systems and sell electricity or services under long-term agreements, can eliminate the need for large upfront payments [97]. Equally important is diversifying revenue streams: energy sales, livestock productivity gains from shaded grazing, and payments for vegetation management can all contribute to faster returns and improved financial sustainability.

Beyond technical and financial issues, socio-cultural acceptance is perhaps the most complex challenge. Cattle herding in Nigeria is not merely an economic activity but also a cultural identity, particularly among nomadic pastoralists. Agrivoltaic infrastructure, if introduced without consultation, may be perceived as restrictive or imposed. To overcome this, participatory engagement is vital. Herders should be directly involved in the planning of site layouts, grazing corridors, and access rights to ensure that agrivoltaic systems fit into existing practices rather than disrupt them [98]. Community sensitization sessions led with pastoralist associations can build trust by demonstrating tangible benefits such as shade, reduced cattle stress, and improved water access [99]. Training modules, designed in simple and practical formats, can equip herders with skills for managing grazing within solar sites, monitoring infrastructure, and maintaining basic safety practices. Moreover, reframing roles through titles such as "agrivoltaic stewards" can provide recognition and dignity, positioning herders as active partners in technological innovation rather than passive beneficiaries [100].

While agrivoltaic cattle ventures face higher risks than crop/ small-ruminant based models, these impediments are resolvable. Elevated and reinforced designs minimize structural vulnerability, productive on-site energy use strengthens local value creation, innovative financing lowers capital burdens, and participatory engagement ensures cultural alignment. Together, these strategies can transform agrivoltaics from a theoretical concept into a resilient and socially embedded solution for Nigeria's pastoral sector.

8 Solution Prospects of Agrivoltaics Technology to the Nomadic Cattle Rearing Crisis in Nigeria

The old-fashioned nomadic practice of rearing cattle has continued to face serious condemnation and opposition from the farming populace in different regions of Nigeria, and the apprehensive resistance of the herders has always culminated in conflicts that have led to loss of lives and properties. In some instances, the quest of herdsmen to ensure that pasture and water bodies are accessible for tending to their grazing livestock is viewed in the negative perspective of an attempt to conquer and dominate. This breeds fear, ignites unlawful confrontations, and causes societal degradations that impede sustainable national development. Reports from several scholars have opined that in the present era, the "ranching system" remains the most feasible and veritable solution to the age-long nomadic cattle rearing crisis in Nigeria [101]. However, most of the citizens, who viewed cattle rearing as a private enterprise, are of the view that it is wrong for any central or regional government to propose the establishment of ranches in specified places across the nation for "a particular set of people" with collectively owned funds. They further insisted that the government must also commit commensurate funds to farmers and other occupational businesses to sustain equity in its administration. This impasse accentuated the quest for other options to sustain the cattle-rearing business with drastically reduced possibilities of conflict eruptions.

On the other hand, several researchers have reported the causes of the nomadic cattle rearing crisis in Nigeria to include unpredictable variability in climate, increased population growth, desertification advancements, spreading flooding incidences and other extreme meteorological events. The ever-growing population causes depletion in land for agricultural and grazing ventures, and there is competition between native farmers and nomadic herdsmen for land. The competition often escalates to a serious crisis that poses a threat to national development and food security. For a nation that has risen from a population of 33 million in 1950 to over 200 million in the present day and was reported by United Nation to attain the projected population sizes of 364 million and 480 million by 2030 and 2050 respectively [101], there must be devoted concerns on the effective management of limited resources, especially agricultural lands.

The infusion of the concepts of such green technological applications as agrivoltaics remains a dependable approach to maximize the use of land for simultaneous varied product output, high productivity, environment preservation, ecosystem and biodiversity sustenance, process mechanization and automation, remote and smart technology adaptability, and soil protection [102]. The International Crisis Group [103] reported the steps to resolving herdsmen-farmers' conflicts to include security improvement, community-based conflict resolution advocacy, grazing reserves creation, ranching system adoption, desertification reduction and strengthened regional collaboration, but every other one of the enlisted steps has been debased over time except the adoption of the ranching system. The population increase pressures foster the need for introducing technological aids for enforcing dual or multiple mutually related ventures on a piece of land instead of apportioning different lands for related enterprises. To this end, the conceptualization of an aspect of agrivoltaics that shoulders solar energy harnessing and subsequent generation of electricity, and rearing of animals on a piece of land is undoubtedly attainable and practicable. This concept was borne when cows were led to graze underneath the photovoltaic panels in solar farms [40].

With respect to cattle ranching, agrivoltaics embodies the design and setup of photovoltaic units to also shelter reared cattle in addition to generating and transmitting electrical energy for other utilities in the farm. Depending on the breed of the cattle and their physiological requirements, the solar panels are either placed low or elevated to provide shade for the comfort of the animals and the farmers. The technology reduces the incidence of heat stress for the domesticated animals, as well as reducing the quantity of water required. Several research studies are being devoted to ascertaining the effectiveness of agrivoltaics for the rearing of different livestock [104]. Sharpe et al. [105] state that agrivoltaics is categorized into open systems (interspaced photovoltaics and overhead photovoltaics) and closed systems (photovoltaic greenhouse). The different configurations of photovoltaic systems that can be adopted for cattle rearing business include the fixed tilt continuous, fixed tilt partitioned, single axis tracking without elevated panels, single axis tracking with elevated panels, and vertical bifacial or agricultural photovoltaic fence (see Figure 9). Except for the vertical bifacial configuration, all the other configurations are adopted by farmers to provide overhead shelter and shade for the reared animals. In complex applications, two or more configurations can be used in combination in a particular farm for rearing different livestock. The vertical bifacial photovoltaic panels are developed into a solar perimeter fence around the farmland to protect the animals, and save the cost of setting up conventional fence works.

Several studies have been directed towards the combination of agrivoltaics with grazing livestock (cattle and sheep) to, on one hand, provide shelter for the animals and, on the other hand be produce renewable energy. Sharpe et al. [105] reported a comparative evaluation study carried out at the University of Minnesota to determine the effect of imposing shade on pasture-based dairy herd and herds reared in the open system (see Figure 10). Handler et al. [106] conducted a study to determine the effect of agrivoltaic systems used to rear sheep at the Sustainable Futures Institute located at the Michigan Technological University. Also, Andrew et al. [107]

Figure 9. Different photovoltaic configurations for agrivoltaic systems – (a) Fixed tilt continuous, (b) Fixed tilt partitioned, (c) Single axis tracking without elevated panels, (d) Single axis tracking with elevated panels, (e) and (f) vertical bifacial. Source: Staie and Mirletz [40].

reported a comparative study of the growth of lamb and pasture production in an agrivoltaic system and conventional open pasture carried out at Oregon State University in Corvallis (see Figure 11).

Figure 10. The University of Minnesota experimental agrivoltaic site.

The findings obtained from these studies showed that the agrivoltaic systems pose no harmful effects on the reared animals. The system promoted the reduction of heat stress in the livestock and improved their well-being, in addition to increasing land use efficiency. Also, the agrivoltaic systems amounted to reduced need for tending to grasses through herbicide

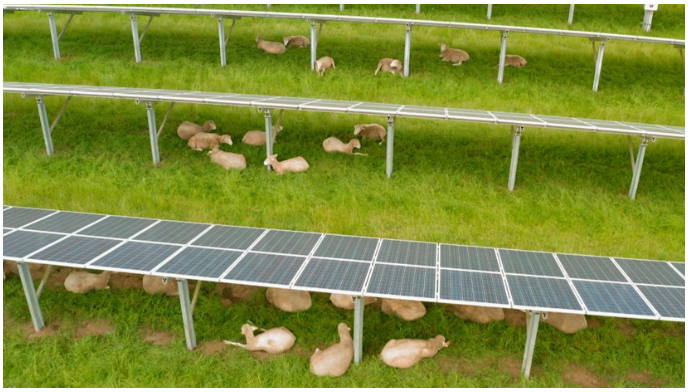

Figure 11. The Oregon State University experimental agrivoltaic site [108].

applications and slashing operations. The mean rate of water consumption by the animals reared under the agrivoltaics system was far lower in the late spring period, but relatively the same in the early spring at the time of conducting the study.

In Nigeria, the prospects of the practice of dual combination of installed photovoltaic systems and cattle farming are great, as cattle rearing constitutes the highest source of her meat protein. However, Evans [109] maintained that the anticipated combination effects and corresponding value addition obtained per area when compared with other applications of agrivoltaics (crop production, bee-farming, greenhouse, etc.) are relatively low. The shade that the photovoltaic panels provide serves a great welfare benefit by protecting the cattle from direct solar radiation on hot days and direct water droplets during rain incidence. The animal being reared may develop an interest in the presence of solar panels and decide to attack the structure until it becomes obvious to them that the photovoltaic system does not pose any threat to them.

Agrivoltaic systems protect the livestock from the sun, facilitate the harvest and treatment of water, and reduce the chances of soil degradation. It promotes grassroots generation of electrical power that is of great benefit to the rural dwellers who are usually not able to access the national grids. Agrivoltaics is amenable to the year 2020 Nigeria agriculture promotion policy because it is subject to regular and well defined methodological surveys, responsive to the adoption of improved breeds, attune with the improved methods of production, agreeable to the modern day pest and disease infestation control, aligned to technologically facilitated livestock identification and traceability, adjustable to automated disease monitoring and quarantine techniques, and

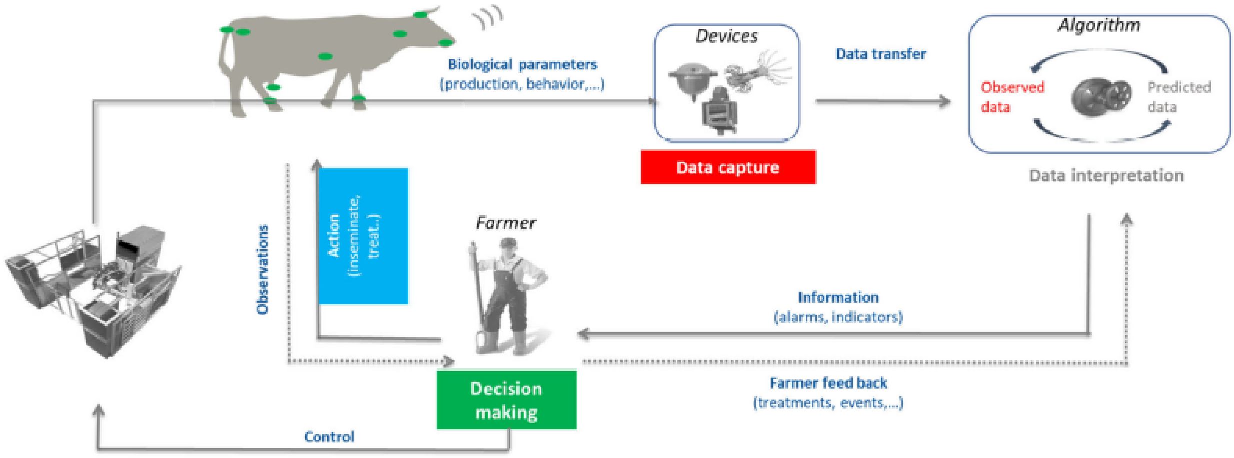

Figure 12. Precision livestock farming components adaptable to an agrivoltaic system [114].

attendant to novel ranching concepts [110]. With these policies' inclined characteristics, agrivoltaics is capable of providing a permanent solution to the nomadic cattle rearing-related crisis in Nigeria. In addition to providing shelter, photovoltaic systems are incorporated into the grazing range system for:

i. Simultaneous production of electrical energy and protein food resources.

ii. Generation and supply of electricity for operating agricultural machines that handle and process hay materials from other crop fields into supplemental feed.

iii. Provision of electricity for powering underground water pumps to continually fill water to designated water drinking areas in the range.

iv. Provision of electricity for powering underground water pumps to fill water reservoirs in the range of other utilities.

v. Provision of electricity for operating electric fence units to deter intrusion and unguided animal movements.

vi. Provision of electricity for lighting the environment of the range and sustaining farmers' electric power needs.

vii. Establishment of a unique microclimate that reduces heat stress on and excessive loss of water from the reared animal to foster sound physiological dispositions.

viii. Provision of eco-friendly energy that will foster the powering and incorporate novel smart technologies.

ix. Establishment of a site for intensive research and experimentation.

x. Promotion of direct soil nutrient addition and preservation of the environment.

The major challenges to awareness creation, acceptance, adoption, pilot project establishment and full-scale implementation of agrivoltaics in cattle production are novel photovoltaic panel development, system performance evaluation, process and operation modelling, operation and maintenance requirements, pliable agrivoltaics legal structures and social acceptability. These challenges can be tackled through enlightenment workshops, seminars and conferences organized with scholars from regions where knowledge of agrivoltaics has advanced.

8.1 Effects of agrivoltaic systems to crop and animal health

Photovoltaic systems do not pose an inherent threat to crops or livestock; the outcomes largely depend on how the systems are designed and managed. Studies show that solar panels can actually support agriculture when integrated thoughtfully. For livestock, the shade created by panels reduces heat stress, improves comfort, and allows farmers to cut vegetation control costs through managed grazing [111]. For crops, the altered microclimate under panels helps conserve soil moisture, lowers daytime temperatures, and can lengthen the growing season, especially for shade-adapted plants such as leafy greens and certain forages. Research from regions as varied as Arizona, Spain, and Germany has demonstrated that yields often remain stable or even rise under partial shade, with added benefits in water-use efficiency and resilience during hot or dry periods [112]. Risks such as livestock injury from poor fencing, yield reductions in high-light crops, or damage to panels are tied to poor

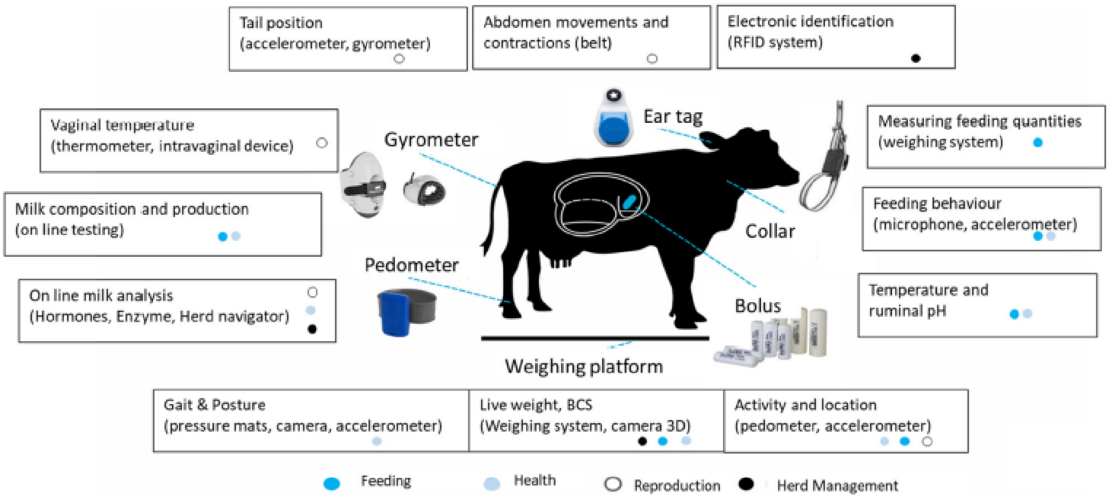

Figure 13. The sensing devices for capturing biological data from animals for agrivoltaic applications [113].

infrastructure and planning, not the solar technology itself. By applying safeguards like elevated panel heights, robust fencing and cabling, proper water access, and careful crop selection, these risks can be effectively managed. In practice, well-designed agrivoltaic systems can improve both animal welfare and crop productivity rather than hinder them.

9 Compliance of Cattle Rearing Agrivoltaics to Industry 4.0 and 5.0 Technologies

Agrivoltaics is adaptable to frontier technologies (artificial intelligence, machine learning, big data, robotics, machine vision and internet of things). These technologies can be integrated into cattle rearing agrivoltaics (range-voltaics) to foster the automation of water pumping and other operations within the range. With automatic sensing and surveillance components incorporated in the agrivoltaic system, real-time insights on the feeding habits and reproductive health of the animals help the farmers to make viable decisions towards the animal care and productivity (see Figure 12). The observed signs facilitate effective forecasting of disease outbreaks that promote improved animal welfare and the sustainability of the farms. While the sensors capture and relate the measurable parameters, the relative programmed algorithms recognize the obvious changes and interpret them, supplementary information from other sources assists in the exact categorization of the occurrences, and the resulting predictions are relayed to the farmer for effective decision making [113].

With the integration of biometric sensing devices, Industry 4.0 and 5.0 technologies are fast gaining momentum in livestock management, especially in the aspects of continuous surveillance and monitoring of domesticated animals' health status and behavioral dispositions. The sensing devices (see Figure 13) that can be used for capturing biological data from domesticated cattle include, thermometer, an intra-vaginal device, a gyrometer, a pedometer, a weighing system, an accelerometer, a 3D camera, a herd navigator, a pressure mat, a microphone and a ruminal pH meter.

10 Conclusion

There is a lack of empirical evidence in relation to the impact of agrivoltaics in a Nigerian context due to the non-existence of agrivoltaic systems in the country. Following the findings obtained from research conducted overseas, agrivoltaics is technically and economically feasible as a solution to the nomadic cattle rearing crisis. There are good prospects and potential benefits in combining solar energy harness and electrical power generation with cattle rearing enterprise. These include improved cattle comfort and productivity, and the simultaneous generation of electricity for other secondary applications and maximized use of land without posing any negative environmental effects. However, there is a dire need for sensitization and awareness on the effectiveness and viability of agrivoltaics for sustainable cattle rearing. The adaptability of the technology to industry 4.0 and 5.0 technologies helps in eliminating the the drudgery of physical, real-time surveillance of the herd.

11 Recommendations

To establish agrivoltaics as a practical and lasting response to the challenges of pastoralism in Nigeria, the recommendations outlined below present a structured pathway that blends policy support, cross-sector collaboration, academic research, grassroots pilot projects, and the use of digital technologies designed to fit the country's diverse social and environmental contexts.

i. Agrivoltaics should be formally incorporated into the National Livestock Transformation Plan (NLTP) and the National Renewable Energy Action Plan, while the Federal Government introduces measures such as temporary tax reliefs, duty-free importation of key equipment, and conditional grants to ease start-up costs and stimulate private investment.

ii. A National Agrivoltaics Taskforce should be created to bring together the Ministries of Agriculture, Power, Environment, and Land Resources, ensuring coordinated policies that reduce land-use disputes, simplify regulatory processes, and align agrivoltaic projects with broader goals of agricultural modernization and climate resilience.

iii. Dedicated Agrivoltaics Innovation Centers should be set up within universities and polytechnics across Nigeria's ecological regions, where local researchers, in collaboration with international partners and private firms, can develop context-specific designs and simultaneously build local expertise through training programs for engineers, extension workers, and young professionals.

iv. Pilot agrivoltaic farms should be rolled out in all six geopolitical zones, with strong participation from traditional leaders, pastoral associations, and farmer cooperatives, while also integrating solar-powered boreholes, cold storage, and small-scale processing units to ensure immediate, visible benefits and measurable outcomes for local communities.

v. Gradual introduction of affordable digital tools, including IoT sensors, GPS-enabled livestock tracking, and predictive data models, should be prioritized within pilot sites, with outputs made accessible through mobile platforms in local languages and integrated into Nigeria's Digital Agriculture Strategy to support the transition to data-driven, climate-smart livestock management.

Data Availability Statement

Not applicable.

Funding

This work was supported without any funding.

Conflicts of Interest

The authors declare no conflicts of interest.

Ethical Approval and Consent to Participate

Not applicable.

References

[1] Ajayi, M. O., Herbert, E. B., Imosemi, A., Nyekwere, N., Eyongndi, D. T., & Oladele, O. O. (2023, August). Legal implications of free-range system of rearing cattle in Nigeria: A Review. In *IOP Conference Series: Earth and Environmental Science* (Vol. 1219, No. 1, p. 012013). IOP Publishing. [CrossRef]

[2] Kubkomawa, H. I. (2017). Indigenous breeds of cattle, their productivity, economic and cultural values in sub-Saharan Africa: A review. *International Journal of Research Studies in Agricultural Science*, *3*(1), 27–43. [CrossRef]

[3] Sasu, D. D. (2022). Solar energy capacity in Nigeria from 2014 to 2022. Statista. Retrieved from https://www.statista.com/statistics/1278096/solar-energy-capacity-in-nigeria/

[4] Amadi, N. S., & Aleru, P. D. (2021). Influence of open cattle grazing on crop production among rural farmers in rivers state. *Global Journal of Scientific and Research Publications (GJSRP)*, *1*(2).

[5] Jinadu, L. A. (2021). Resolving the Herdsmen-Farmers Conflicts in Nigeria. Societal Futures, Future Africa Forum. Retrieved from https://forum.futureafrica.com/resolving-the-herdsmen-farmers-conflicts-in-nigeria

[6] Ogboru, T., & Adejonwo-Osho, O. (2018). Towards an effective cattle grazing and rearing legal framework: An imperative for environmental protection. *Journal of Sustainable Development Law and Policy (The)*, *9*(1), 58-79. [CrossRef]

[7] Oghuvbu, E. A., Oghuvbu, O. B. (2020). Farmers-herdsmen conflict in Africa: The case of Nigeria. Vestnik RUDN. *International Relations*, *20*(4), 698–706. [CrossRef]

[8] Ukase, P. I., & Ityonzughul, T. T. (2020). Policy Options/StrategiesTowards a Resolution of Farmers-Nomadic Cattle Herders Conflicts in Nigeria. *Covenant University Journal of Politics and International Affairs*, *8*(2).

[9] Okojie-Okeiyi. (2019, January 8). Resolute 4.0 seen as solution to Nigeria's farmers-herders crisis. Businessday NG. Retrieved from https://businessday.ng/agriculture/article/resolute-4-0-seen-as-solution-to-nigerias-farmers-herders-crisis/

[10] ISE, F. (2022). Agrivoltaics: Opportunities for Agriculture and the Energy Transition. Fraunhofer Institute for Solar Energy Systems. *Freburg, Germany: Fraunhofer Institute for Solar Energy Systems*. Retrieved from https://www.ise.fraunhofer.de/en/publications/studies/agrivoltaicsopportunities-for-agriculture-and-the-energy-transition.html

[11] Olayoku, P. A. (2014). *Trends and patterns of cattle grazing and rural violence in Nigeria (2006-2014)* (Doctoral dissertation, IFRA-Nigeria).

[12] Oluwaleye, J. M. (2020). The challenge of herders-farmers crisis and its implication on peace building and sustainable development in Nigeria. *Journal of Public Administration and Development Alternatives (JPADA), 5*(2), 49-67.

[13] Nnoruga, N. J. (2021). Open grazing in Nigeria: A threat to human life and environmental degradation. *Journal of African Studies and Sustainable Development*.

[14] *UNHCR web archive*. (n.d.). Refworld | UNHCR's Global Law and Policy Database. Retrieved from https://www.refworld.org/docid/54ef03904.html

[15] Punch Editorial Board. (2023, January 4). FG should end herdsmen attacks now. Punch Newspapers. Retrieved from https://punchng.com/fg-should-end-herdsmen-attacks-now/

[16] Egbuta, U. (2018). Understanding the herder-farmer conflict in Nigeria. *Conflict Trends, 2018*(3), 40-48. Retrieved from https://www.accord.org.za/conflict-trends/understanding-the-herder-farmer-conflict-in-nigeria/

[17] Ilo, U. J., Jonathan-Chaver, I., & Adamolekun, Y. (2019). The deadliest conflict you've never heard of: Nigeria's cattle herders and farmers wage a resource war. *Foreign Affairs, 23*.

[18] Atobatele, A. J., & Moliki, A. O. (2022). Herdsmen's/Farmers' conflicts and sustainable national development in Nigeria. *Ethiopian Journal of Social Sciences, 8*(1), 28-40.

[19] Ndubuisi, C. I. (2018). A critical analysis of conflicts between herdsmen and farmers in Nigeria: Causes and socioreligious and political effects on national development. *HTS Teologiese Studies/Theological Studies, 74*(1).

[20] Blench, R. (2018). Towards a Peaceful Coexistence between Herders and Farmers in Nigeria: Conclusions drawn from the field. *Misereor DPS, Catholic Secretariat of Nigeria, Abuja*.

[21] Doherty-Odueko, F. (2019). Panacea for herdsmen-farmers conflicts in Nigeria. *Journal of Dairy, Veterinary & Animal Research, 8*(2), 111-113.

[22] Nassef, M., Eba, B., Islam, K., Djohy, G., & Flinta, F. (2023). Causes of farmer-herder conflicts in Africa: A systematic scoping review. *Supporting Pastoralism and Agriculture in Recurrent and Protracted Crises (SPARC) Report, 50*.

[23] Bella, F., Ilemobola, O., Udoh, O., Ndulue, J. C., & Iyamah, J. O. (2024). Farmer-Herder Crisis And The Ekiti State Anti Grazing Law: The Human Rights Question. *Migration Letters, 21*(S7), 624–639. Retrieved from https://migrationletters.com/index.php/ml/article/view/8788

[24] Ibrahim, S. G., Gimba, Z., & Collins, O. (2018). The lingering problem of herders-farmers relations in Nigeria: A crisis of political development. *African Journal of Law, Political Research and Administration, 1*(1), 28-37.

[25] Akinyetun, T. S. (2016). Staff to gun: Fulani herdsmen in Nigeria. *Asian Journal of Multidisciplinary Studies, 4*(8), 38-44.

[26] Nkwunonwo, U. C., Okeke, F. I., Chiemelu, E. N., & Ebinne, E. S. (2019). Geospatial technology potentials in reawakening the consciousness of soil distribution in Nigeria's north-central region and mediating the herdsmen-farmers conflicts. *Journal of Geoscience and Environment Protection, 7*(02), 156. [CrossRef]

[27] ACAPS, 2017. Nigeria: Farmer-Herder Conflict in Benue, Kaduna, and Plateau States (2017), ACAPS. Switzerland. Retrieved from https://coilink.org/20.500.12592/2pckm1 on 01 Dec 2025.

[28] Dimelu, M. U., Salifu, E. D., & Igbokwe, E. M. (2016). Resource use conflict in agrarian communities, management and challenges: A case of farmer-herdsmen conflict in Kogi State, Nigeria. *Journal of Rural Studies, 46*, 147-154. [CrossRef]

[29] 360, R. M. (2025, July 24). *RMRDC to explore Agrivoltaics for sustainable farming and local solar panel production*. Raw Materials 360. Retrieved from https://360.rmrdc.gov.ng/rmrdc-to-explore-agrivoltaics-for-sustainable-farming-and-local-solar-panel-production

[30] *Raising livestock and crops under solar panels*. (n.d.). Extension at the University of Minnesota. Retrieved from https://extension.umn.edu/livestock-operations/what-are-agrivoltaics

[31] Sarr, A., Soro, Y. M., Tossa, A. K., & Diop, L. (2023). Agrivoltaic, a synergistic co-location of agricultural and energy production in perpetual mutation: A comprehensive review. *Processes, 11*(3), 948. [CrossRef]

[32] Fraunhofer, I. S. E. (2019). Agrophotovoltaics: High Harvesting Yield in Hot Summer of 2018.

[33] Saand, A. S., Jamali, M. I., Koondhar, M. A., Kaloi, G. S., Albasha, L., Aoudia, M., & Touti, E. (2025). A comparative review: floating photovoltaic, agrivoltaics, and ground-mounted PV systems. *IEEE Access, 13*, 45853-45873. [CrossRef]

[34] *What is the regulatory framework for agrivoltaics ?* (2025, November 19). TSE | Expert in photovoltaic and agrivoltaic development. Retrieved from https://www.tse.energy/en/articles/le-cadre-reglementaire-de-lagrivoltaisme-pour-preserver-lagriculture-francaise

[35] Gambetta, R. (2024, December 10). Harvesting the sun: How Italy is pioneering the future of

Agrivoltaics. greenCrowd. Retrieved from https://www.greencrowd.energy/post/harvesting-the-sun-how-italy-is-pioneering-the-future-of-agrivoltaics

[36] Doubleday, K. (2024). *Introduction to the 3-Part Agrivoltaics Knowledge Series: Agrivoltaics 101* [*Slides*] (No. NREL/PR-6A40-90584). National Renewable Energy Laboratory (NREL), Golden, CO (United States).

[37] Dreves, H. (2022). Growing Plants, Power, and Partnerships Through Agrivoltaics. *National Renewable Energy Laboratory (NREL)*.

[38] Agrivoltaics: Solar and agriculture Co-location. (n.d.). Energy.gov. Retrieved from https://www.energy.gov/eere/solar/agrivoltaics-solar-and-agriculture-co-location

[39] *Agrivoltaics.* (n.d.). Global Environment Facility. Retrieved from https://www.thegef.org/council-meeting-documents/gef-stap-c-66-inf-04

[40] SAREP Agrivoltaics knowledge series: Agrivoltaics groundwork. (n.d.). National Renewable Energy Laboratory. Retrieved from https://research-hub.nrel.gov/en/publications/sarep-agrivoltaics-knowledge-series-agrivoltaics-groundwork/

[41] Nakata, H., & Ogata, S. (2023). Integrating agrivoltaic systems into local industries: A case study and economic analysis of rural Japan. *Agronomy, 13*(2), 513. [CrossRef]

[42] Edouard, S., Combes, D., van Iseghem, M., Tin, M. N. W., & Escobar-Gutiérrez, A. J. (2023). Increasing land productivity with agriphotovoltaics: Application to an alfalfa field. *Applied Energy, 329*, 120207. [CrossRef]

[43] Li, Z., Sun, X., Zhou, J., Wu, L., Bi, D., Zhao, J., Zhu, R., & Christie, P. (2023). Sustainable phytoextraction of metal-polluted agricultural land used for commercial photovoltaic power generation. *Journal of Cleaner Production*, *391*, 136093. [CrossRef]

[44] Proctor, K. W., Murthy, G. S., & Higgins, C. W. (2020). Agrivoltaics align with green new deal goals while supporting investment in the U.S. rural economy. *Sustainability, 13*(1), 137. [CrossRef]

[45] Jain, P., Raina, G., Sinha, S., Malik, P., & Mathur, S. (2021). Agrovoltaics: Step towards sustainable energy–food combination. *Bioresource Technology Reports*, *15*, 100766. [CrossRef]

[46] Coolfarm1. (2024, October 21). How to reduce carbon footprint in agriculture. Cool Farm Tool | An online greenhouse gas, water, and biodiversity calculator. Retrieved from https://coolfarm.org/how-to-reduce-carbon-footprint-in-agriculture/

[47] Hassanpour Adeh, E., Selker, J. S., & Higgins, C. W. (2018). Remarkable agrivoltaic influence on soil moisture, micrometeorology and water-use efficiency. *PloS one*, *13*(11), e0203256. [CrossRef]

[48] Terrones, C. (2025, January 21). 10 best practices to reduce carbon footprint in agriculture. ICL. Retrieved from https://www.icl-group.com/blog/blog-best-practices-to-reduce-carbon-footprint-in-agriculture/

[49] Macknick, J., Hartmann, H., Barron-Gafford, G., Beatty, B., Burton, R., Choi, C. S., Davis, M., Davis, R., Figueroa, J., Garrett, A., Hain, L., Herbert, S., Janski, J., Kinzer, A., Knapp, A., Lehan, M., Losey, J., Marley, J., MacDonald, J., … Walston, L. (2022). *The 5 Cs of agrivoltaic success factors in the United States: Lessons from the InSPIRE research study* (Report No. NREL/TP-6A20-83566; Contract No. AC36-08GO28308). National Renewable Energy Laboratory (NREL). U.S. Department of Energy Office of Scientific and Technical Information. [CrossRef]

[50] Yang, Y., Tilman, D., Furey, G., & Lehman, C. (2019). Soil carbon sequestration accelerated by restoration of grassland biodiversity. *Nature Communications*, *10*(1), 718. [CrossRef]

[51] *Sweet deal: Beekeeping at solar sites offers economic and environmental benefits – AgriSolar Clearinghouse*. (2022, April 5). AgriSolar Clearinghouse. Retrieved from https://www.agrisolarclearinghouse.org/sweet-deal-beekeeping-at-solar-sites-offers-economic-and-environmental-benefits/

[52] Barron-Gafford, G. A., Pavao-Zuckerman, M. A., Minor, R. L., Sutter, L. F., Barnett-Moreno, I., Blackett, D. T., ... & Macknick, J. E. (2019). Agrivoltaics provide mutual benefits across the food–energy–water nexus in drylands. *Nature Sustainability*, *2*(9), 848-855. [CrossRef]

[53] Dhonde, M., Sahu, K., & Murty, V. V. S. (2022). The application of solar-driven technologies for the sustainable development of agriculture farming: a comprehensive review. *Reviews in Environmental Science and Bio/Technology*, *21*(1), 139-167. [CrossRef]

[54] Agostini, A., Colauzzi, M., & Amaducci, S. (2021). Innovative agrivoltaic systems to produce sustainable energy: An economic and environmental assessment. *Applied Energy*, *281*, 116102. [CrossRef]

[55] Li, C., Wang, H., Miao, H., & Ye, B. (2017). The economic and social performance of integrated photovoltaic and agricultural greenhouse systems: Case study in China. *Applied Energy*, *190*, 204–212. [CrossRef]

[56] McKinsey & Company. (2024, September 19). Saving Southeast Asia's crops: Four key steps toward food security. Retrieved from https://www.mckinsey.com/industries/agriculture/our-insights/saving-southeast-asias-crops-four-key-steps-toward-food-security

[57] Dinesh, H., & Pearce, J. M. (2016). The potential of agrivoltaic systems. *Renewable and Sustainable Energy Reviews*, *54*, 299–308. [CrossRef]

[58] Salihu, M. K., Danladi, A., & Medugu, D. W. (2024). Regional-based potential assessment for solar photovoltaic generation in northern part of Nigeria using satellite imagery data. *Bulletin of the National*

Research Centre, *48*(1), 132. [CrossRef]

[59] Energy Tracker Asia. (2023). *Solar energy in Nigeria: Current status and future potential*. Retrieved from https://energytracker.asia/solar-energy-nigeria/

[60] Solargis. (2021). Solar resource map [Data set]. Solargis. Retrieved September 8, 2025, from https://solargis.com/maps-and-gis-data/download/nigeria

[61] Babalola, K. H., & Hull, S. A. (2019). Examining the Land Use Act of 1978 and its effects on tenure security in Nigeria: A case study of Ekiti State, Nigeria. *Potchefstroom Electronic Law Journal/Potchefstroomse Elektroniese Regsblad*, *22*(1). [CrossRef]

[62] BIS Research. (n.d.). Agrivoltaics: A global and regional focus - product. MarketResearch.com. Retrieved December 2, 2025, from https://www.marketresearch.com/BIS-Research-v4011/Agrivoltaics-Global-Regional-Focus-Product-36722604

[63] The Cable. (2025, May 8). FG signs $158m financing deal to boost agriculture in Northern Nigeria. Retrieved from https://www.thecable.ng/fg-signs-158m-financing-deal-to-boost-agriculture-in-northern-nigeria

[64] Lawal, R. (2025, January 29). *Heifer launches finance leasing scheme to support Nigerian farmers*. TheCable. Retrieved from https://www.thecable.ng/heifer-launches-finance-leasing-scheme-to-support-nigerian-farmers

[65] Salis, A., Ezekwu, L., & Badmus, S. (n.d.). Strengthening Nigeria's legal framework to advance sustainable green electricity practices. Mondaq. Retrieved December 2, 2025, from https://www.mondaq.com/nigeria/renewables/1565924/strengthening-nigerias-legal-framework-to-advance-sustainable-green-electricity-practices

[66] Adeshina, M. A., Ogunleye, A. M., Suleiman, H. O., Yakub, A. O., Same, N. N., Suleiman, Z. A., & Huh, J. S. (2024). From potential to power: advancing Nigeria's energy sector through renewable integration and policy reform. *Sustainability*, *16*(20), 8803. [CrossRef]

[67] iTelemedia. (n.d.). 2025 *outlook: Renewable energy investments and what it means for Nigerians*. Retrieved December 2, 2025, from https://itelemedia.com/2025-outlook-renewable-energy-investments-and-what-it-means-for-nigerians

[68] Forests News, CIFOR-ICRAF. (2023, July 27). *Working on sunshine: Agrivoltaics in East Africa*. https://forestsnews.cifor.org/86194/working-on-sunshine-agrivoltaics-in-east-africa

[69] World-Energy. (2024, November 23). Agrivoltaics Can Improve Water Conservation in Africa. *The World Energy*. https://www.world-energy.org/article/46262.html

[70] The National Academies of Sciences, Engineering, and Medicine. (2025). *Agrivoltaic technology in drylands of West Africa: Strengthening national innovation systems for diffusion and market development at the water-energy-food nexus* (PEER Project No. 9-117). In Partnerships for Enhanced Engagement in Research (PEER), U.S. Agency for International Development. Retrieved from https://sites.nationalacademies.org/PGA/PEER/PEERscience/PGA_364175

[71] Brent, A., Chapman, N., & de Kock, I. (2023). Agrivoltaic Systems: Potential Opportunities for South Africa: A GIS Analysis. In *AgriVoltaics Conference Proceedings* (Vol. 2). [CrossRef]

[72] Green Building Africa - Net Carbon Zero Buildings and Cities. (2021, May 3). Agrivoltaics increases land productivity, improves animal welfare. Green Building Africa. Retrieved from https://www.greenbuildingafrica.co.za/agrivoltaics-increases-land-productivity-improves-animal-welfare

[73] Stewart, W. C., Scasta, J. D., Maierle, C., Ates, S., Burke, J. M., & Campbell, B. J. (2025). Vegetation management utilizing sheep grazing within utility-scale solar: Agro-ecological insights and existing knowledge gaps in the United States. *Small Ruminant Research*, 107439. [CrossRef]

[74] Bawonda, F. I., Oricha, J. Y., & Sanni, S. O. (2023). Estimating global horizontal irradiance in Nigeria: An empirical modelling perspective. *Journal of Solar Energy Research*, *8*(4), 1701-1714. [CrossRef]

[75] Okoye, C. O., Taylan, O., & Baker, D. K. (2016). Solar energy potentials in strategically located cities in Nigeria: Review, resource assessment and PV system design. *Renewable and Sustainable Energy Reviews*, *55*, 550–566. [CrossRef]

[76] Reuters. (2025, March 10). Nigeria strikes $200 million deal to power rural areas with renewable mini-grids. *Reuters*. Retrieved from https://www.reuters.com/world/africa/nigeria-strikes-200-million-deal-power-rural-areas-with-renewable-mini-grids-2025-03-10

[77] Solar resource maps & GIS data for 200+ countries. (n.d.). Data, software and services for solar projects | Solargis. Retrieved from https://solargis.com/maps-and-gis-data/download/nigeria

[78] *Blended finance solutions for clean energy in humanitarian and displacement settings*. (2022, January 13). NRC. Retrieved from https://www.nrc.no/resources/reports/blended-finance-solutions-for-clean-energy

[79] International Finance Corporation. (2025). IFC and Canada invest in Husk to catalyze solar-powered economic growth in rural Nigeria. International Finance Corporation. Retrieved from https://www.ifc.org/en/pressroom/2025/ifc-and-canada-invest-in-husk-to-catalyze-solar-powered-economic-growth-in-rural-nigeria

[80] Food crises, instability loom as middle belt output plummets over unresolved farmer-herder Clahes. (2025, March 31). THISDAYLIVE – Truth and Reason. Retrieved from https://www.thisdaylive.com/2025/03/31/food-crises-instability-loom-as-middle-belt-output-plummets-over-unresolved-farmer-herder-clahes

[81] Buremoh, B. S., Ezenwora, J. A., & Moses, A. S. (2025). Assessment of Solar Energy Potentials in Parts of North-Central Nigeria using Geospatial Method.

[CrossRef]

[82] Obayelu, A., Ogunmola, O., & Oyewole, K. (2019). Land fragmentation and its determinants in Nigeria: A case study of smallholder farmers in Ikenne Agricultural Zone, Ogun State, Nigeria. *Journal of Agribusiness and Rural Development*, *52*(2), 147–155. [CrossRef]

[83] Essiet, D. (2024, August 15). Expert urges solar-powered farming for food security. *The Nation Nigeria*. Retrieved from https://thenationonlineng.net/expert-urges-solar-powered-farming

[84] Sanni, S. (2021, December 18). Bayelsa, Delta boundary communities bicker over ownership claims, threats to shutdown oil wells. *Vanguard Nigeria*. Retrieved from https://www.vanguardngr.com/2021/12/bayelsa-delta-boundary-communities-bicker-over-ownership-claims-threats-to-shutdown-oil-wells/

[85] Emeseh, E., Obani, P., Okukpon, I., Imoedemhe, O., & Olokotor, P. N. (2023). Just Transition and Environmental Justice: Principles, Practice and Implementation Strategies for a Post-Oil Future (Hybrid).

[86] Amadi, S. O., Eze, I. A., Enyi, V. S., Nwokolo, S. C., & Kalu, P. N. (2025). Multi-Parameter Based Models for Estimating Global Solar Radiation in Selected Locations in Ebonyi State, Southeastern Nigeria. *Trends in Renewable Energy, 11*(2), 213-236. [CrossRef]

[87] Adelakun, A. O., & Adelakun, F. M. (2024). Mathematical modeling and seasonal solar radiation variability in Nigeria's geo-political zones: A recurrence and multifractal analysis. *Journal of Atmospheric and Solar-Terrestrial Physics, 261*, 106290. [CrossRef]

[88] The Cable. (2025, March 11). NSIA, firms create $500m fund to finance renewable energy projects in Nigeria. The Cable. Retrieved from https://www.thecable.ng/nsia-firms-create-500m-fund-to-finance-renewable-energy-projects-in-nigeria

[89] Channels Television. (2025, March 11). Nigeria secures $950m funding to boost renewable electricity supply. Channels Television. Retrieved from https://www.channelstv.com/2025/03/11/nigeria-secures-950m-funding-to-boost-renewable-electricity-supply

[90] Reden Solar. (n.d.). *Agrivoltaic sites for livestock and arable farming*. Retrieved December 2, 2025, from https://reden.solar/en/our-expertise/agrivoltaic-sites-for-livestock-and-arable-farming-2/

[91] How sheep are reshaping solar farm maintenance. (2023, August 30). Maintenance World | Useful Reliability and Maintenance Resources. Retrieved from https://maintenanceworld.com/2023/08/30/landscape-to-lambscape-how-sheep-are-reshaping-solar-farm-maintenance

[92] Silicon Ranch. (n.d.). CattleTracker. Retrieved December 2, 2025, from https://www.siliconranch.com/cattletracker

[93] MT Solar. (2023, August 30). Landscape to lambscape: How sheep are reshaping solar farm maintenance. Retrieved from https://www.mtsolar.us/solar-grazing-challenges-and-possibilities/

[94] Williams, N., Raji, T., & Ekoh, C. (2024, August 7). Illuminating Nigeria: Blurring the lines between the grid and off-grid electricity. Georgetown Journal of International Affairs. Retrieved from https://gjia.georgetown.edu/2024/08/07/illuminating-nigeria-blurring-the-lines-between-the-grid-and-off-grid-electricity/

[95] Ismaila, Z., Falode, O. A., Diji, C. J., Kazeem, R. A., Ikumapayi, O. M., Petinrin, M. O., ... & Akinlabi, E. T. (2023). Evaluation of a hybrid solar power system as a potential replacement for urban residential and medical economic activity areas in southern Nigeria. *AIMS energy, 11*(2), 319-336. [CrossRef]

[96] Randle-Boggis, R. J., Lara, E., Onyango, J., Temu, E. J., & Hartley, S. E. (2021, June). Agrivoltaics in East Africa: opportunities and challenges. In *AIP conference proceedings* (Vol. 2361, No. 1, p. 090001). AIP Publishing LLC. [CrossRef]

[97] Ibrahim, M. O., Amaka, F. A., & Adekunle, E. O. (2024). Modelling Cooperatives to Combat Energy Poverty in Ondo State in the Context of Renewable Energy Transition. *International Journal of Research and Innovation in Social Science*, *8*(8), 3608-3615. [CrossRef]

[98] Cinjel, N. D., & Oboromeni, W. (2024). The Fulani in Nigeria and their Herding System: Is it an Agro-Business or a Culture?. *Journal of Policy and Development Studies, 15*(1), 111-125. [CrossRef]

[99] Forging a path to peace for farmers and Herders in Adamawa state. (n.d.). Mercy Corps. Retrieved from https://nigeria.mercycorps.org/research-resources/peace-farmers-herders-adamawa

[100] Agrivoltaic opportunities: Grazing livestock in solar energy systems. (2024, September 25). Agricultural Bioenergy and Energy Conservation. Retrieved from https://www.canr.msu.edu/news/agrivoltaic-opportunities-grazing-livestock-in-solar-energy-systems

[101] Mamman, E. (2021). Resolving the farmers-herders conflict in Nigeria: A way forward for sustainable national development. *International Journal of Social Science and Human Research, 4*(7), 1714-1721.

[102] Chatzipanagi, A., Taylor, N., & Jaeger-Waldau, A. (2023). *Overview of the potential and challenges for agri-photovoltaics in the European Union* (p. 57). Luxembourg: Publications Office of the European Union. [CrossRef]

[103] Attention required! | Cloudflare. (n.d.). International Crisis Group. Retrieved from https://www.crisisgroup.org/africa/nigeria/252-herders-against-farmers-nigerias-expanding-deadly-conflict

[104] Gorjian, S., Bousi, E., Özdemir, Ö. E., Trommsdorff, M., Kumar, N. M., Anand, A., ... Chopra, S. S.

(2022). Progress and challenges of crop production and electricity generation in agrivoltaic systems using semi-transparent photovoltaic technology. *Renewable and Sustainable Energy Reviews*, *158*, 112126. [CrossRef]
[105] Sharpe, K., Heins, B., Buchanan, E., & Reese, M. (2021). Evaluation of photovoltaic systems to shade cows in a pasture-based dairy herd. *Journal of Dairy Science*, *104*(3), 2794–2806. [CrossRef]
[106] Handler, R., & Pearce, J. (2022). Greener sheep: Life cycle analysis of integrated sheep agrivoltaic systems. *Cleaner Energy Systems*, *3*, 100036. [CrossRef]
[107] Andrew, A., Higgins, C., Smallman, M., Graham, M., & Ates, S. (2021). Herbage yield, lamb growth and foraging behaviour in agrivoltaic production systems. *Frontiers in Sustainable Food Systems*, *5*, 659175. [CrossRef]
[108] Burns, J. (2022, July 21). Oregon researchers propose innovative path forward for farming's water woes. opb. Retrieved from https://www.opb.org/article/2022/07/21/oregon-research-agriculture-water-shortage-solar-panels-solution
[109] Evans, M. E., Langley, J. A., Shapiro, F. R., & Jones, G. F. (2022). A validated model, scalability, and plant growth results for an agrivoltaic greenhouse. *Sustainability*, *14*(10), 6154. [CrossRef]
[110] Manya, N. U. M., & Abdullahi, S. (2025). Assessing Nigeria's National Livestock Policy and Its Role in Enhancing Protein Security: A Qualitative Policy and Food-Security Assessment. *Public Management and Service*, *1*(1), 32-39. [CrossRef]
[111] Faria, A. F. P., Maia, A. S., Moura, G. A., Fonsêca, V. F., Nascimento, S. T., Milan, H. F., & Gebremedhin, K. G. (2023). Use of solar panels for shade for holstein heifers. *Animals*, *13*(3), 329. [CrossRef]
[112] Bryce, E. (2019, January 12). A tech revolution will help farmers harvest sunshine with their crops. WIRED. Retrieved from https://www.wired.com/story/energy-agrivoltaic-farms/
[113] Kleen, J. L., & Guatteo, R. (2023). Precision livestock farming: What does it contain and what are the perspectives? *Animals*, *13*(5), 779. [CrossRef]
[114] Neethirajan, S., Reimert, I., & Kemp, B. (2021). Measuring farm animal emotions – Sensor-based approaches. *Sensors*, *21*(2), 553. [CrossRef]

Chinedu Chukwuemeka Christian Anyene is a Lecturer in the Department of Agricultural and Bioenvironmental Engineering Technology at the Federal Polytechnic, Oko. With 12 years of academic and professional experience, he combines teaching, research, and technological innovation in agricultural engineering. He is currently pursuing a Ph.D. in Food and Bioprocess Engineering, with a focus on sustainable and efficient processing systems. His research interests include farm power and machinery development, renewable energy and green technology, food processing and bioprocess engineering, and waste conversion with value addition. Engr. Chinedu is dedicated to developing practical solutions that enhance agricultural productivity, environmental sustainability, and rural development. (Email: anyene.chinedu@federalpolyoko.edu.ng)

Daniel Olisaeloka Udorah is a Lecturer in the Department of Agricultural and Bioenvironmental Engineering Technology at the Federal Polytechnic, Oko. With six years of experience, he engages in teaching, research, and community-focused engineering solutions. His research interests span soil and water engineering, wastewater treatment and recycling, and wetland preservation. He also explores renewable energy integration and the optimization of rainwater harvesting systems. Daniel is committed to advancing sustainable water resource management and environmental conservation. (Email: udorah.daniel@federalpolyoko.edu.ng)

Patience Stella Nsofor is a Senior Technologist in the Department of Agricultural and Bioenvironmental Engineering at the Federal Polytechnic, Oko. With 12 years of professional experience, she specializes in supporting teaching, research, and innovation in agricultural engineering. Her research interests include agricultural machinery development, renewable energy integration, and food processing and bioprocess engineering. She is committed to advancing sustainable technologies that enhance agricultural productivity and rural livelihoods. Patience continues to contribute to capacity building and applied research in agricultural and environmental systems. (Email: stella.nsofor@federalpolyoko.edu.ng)

Nnaemeka R. Nwakuba is a Professor in the Department of Agricultural and Biosystems Engineering, School of Engineering and Engineering Technology of the Federal University of Technology, Owerri (FUTO), Nigeria where he earned his B.Eng (Hons), M.Eng, Ph.D degrees in 2005, 2011, and 2018, respectively. His career objective is to contribute substantially to teaching and research for development, particularly in the agri-food sector and be part of the dynamic team that works towards applying the basic sciences and natural laws to develop technologies and innovations to improve agricultural/food production.Engr. Dr. Nwakuba specializes in Power and Machinery Engineering as well as Crop Processing and Storage Engineering options of Agricultural Engineering. His research spans the technological process and system variables for the development of efficient and tecno-economic food and bio-processing equipment and technologies for value addition in the agri-food sector. (Email: nnaemeka.nwakuba@futo.edu.ng)