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CONTRIBUTION OF RENEWABLE ENERGY TECHNOLOGIES WITH CLIMATE RESILIENT APPROACH IN AGRICULTURAL SYSTEMS

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ABSTRACT

The integration of Renewable Energy Technologies (RETs) in agricultural systems is increasingly recognized as a pivotal approach to building climate resilience, enhancing productivity, and promoting sustainability in agriculture. The global agricultural sector faces significant challenges due to climate change, which affects crop yields, water availability, and overall food security. RETs, including solar, wind, biomass, and other renewable sources, offer sustainable solutions to mitigate these impacts while reducing dependency on fossil fuels and minimizing greenhouse gas emissions. Studies have shown that solar-powered irrigation systems, particularly in drought-prone regions they have successfully enhanced food security and agricultural productivity by providing reliable water sources for crops. Similarly, the application of RETs in greenhouse climate control has been reviewed as an effective method to maintain optimal growing conditions while reducing energy costs. Biomass energy, derived from agricultural residues, presents an opportunity for farmers to generate additional income while contributing to waste management and energy production. In India and other developing regions, RETs have the potential to revolutionize rural agriculture by improving access to energy, thus enabling the adoption of modern agricultural techniques. The role of RETs in climate-smart agriculture is underscored by their ability to reduce emissions and enhance the resilience of agricultural systems to climate variability. However, the widespread adoption of these technologies requires supportive policies, financial incentives and capacity-building initiatives to overcome barriers such as high initial costs and technical challenges. In completion, RETs play a crucial role in advancing climate-resilient agriculture by offering sustainable energy solutions that support food security, environmental protection and rural development. The successful integration of RETs into agricultural systems is essential for achieving long-term sustainability and resilience in the face of global climate challenges.

Key words : Agricultural Productivity, Agricultural Systems, Renewable Energy Technologies (RETs), Sustainability.

Introduction

Energy is essential for human life, as it supports basic needs such as food production and economic development (Oyedepo, 2012). Key activities that rely on energy include agriculture (like irrigation, land preparation, fertilization, and livestock rearing), household tasks (such as lighting, cooking and food preservation), commercial operations (including lighting and processing) and community services (like water pumping, refrigeration in health centers and lighting communal spaces) (Babatunde, 2018). Agriculture, in particular, is energy-intensive, requiring power for irrigation, refrigeration, drying crops, and livestock management to produce food for people (Oyedepo, 2013). However, these energy demands raise concerns for stakeholders, as it's important to find a balance that is both technically and economically sustainable to protect the environment.

Thus, it is crucial to explore collective and integrated efforts to address what are considered complex and interconnected multidisciplinary issues, which pose significant threats to human civilization and existence. Many of these challenges are closely linked to energy, water, and food production, particularly in developing countries. These areas of concern form the foundation of global security, prosperity, and equity. In light of this, energy, water, and food security have been recognized as key elements in achieving the United Nations' aspirational Sustainable Development Goals (SDGs). The water–energy–food nexus is therefore proposed as a conceptual framework for promoting sustainable development. Developing countries, however, face the difficult task of meeting the increasing demands for food, clean water, and sustainable energy, a challenge that is further intensified by climate change. As noted by Rasul and Sharma (2016), "effective adaptation to change requires the efficient use of land, water, energy, and other vital resources, and coordinated efforts to minimize trade-offs and maximize synergies." Failing to follow this approach may lead to a decrease in food production.

Water, energy, and food are essential for human survival, poverty eradication, and sustainable development (Oyedepo, 2014). The demand for these resources is expected to increase significantly in the coming decades due to pressures from population growth, urbanization, dietary changes, technological advancements, shifts in social status and culture, increased mobility, economic development, and climate change (Hoff, 2011). Water plays a crucial role in various agricultural processes, such as fisheries, irrigation, forestry and is also used in different forms to produce or transport energy (FAO, 2011b). As a result, 70% of the world's freshwater withdrawals are attributed to agriculture, making it the largest consumer of freshwater globally. Additionally, food production and supply account for 30% of the world's energy consumption (FAO, 2011a). Energy is vital for daily agricultural activities, including irrigation, extraction, collection, pumping, and water treatment.

With the development of new cities, there is a growing demand for water, energy and land resources, leading to environmental consequences and resource scarcity in many cases. This challenge is expected to escalate as the global food demand is predicted to increase by 60% by 2050 (FAO, 2011b). Moreover, global energy demand is projected to rise by approximately 50% by 2035 (IEA, 2010). According to a report by the FAO, "Total global water withdrawals for irrigation are projected to increase by 10 percent by 2050" (FAO, 2011b). The interconnectedness of energy, water, and food security is likely to face significant challenges in the future. For example, South Africa, once a major food exporter between 1985 and 2008, has become a major importer due to population growth and a decline in agricultural activities in recent years (Bazilian *et al*, 2011). Furthermore, between 2009 and 2010, the South African government and Eskom announced a 31% increase in electricity tariffs, with an expected rise of 25% for three consecutive years.

As a result, the agricultural sector is likely to be significantly impacted by future electricity price increases, given its high energy demands for irrigation and other farming activities. Transitioning from irrigation-based farming to rain-fed agriculture could help alleviate the pressure from rising tariffs, but it may also pose a risk to national food security, particularly during droughts. This concern arises because 25% of the country's primary food supply is produced on irrigated farmlands (Bazilian *et al*., 2011).

Similarly, in India, farmland irrigation accounts for approximately 15-20% of the country's total electricity consumption (Bazilian *et al*., 2011). In India, irrigation systems are connected to the electrical grid due to subsidized electricity prices, which are often too low to reflect the true cost of energy. This, combined with the lack of effective energy management in irrigation systems, leads farmers to over-extract groundwater faster than it can be naturally replenished. As water levels drop, the energy required for irrigation increases, further straining an already overburdened and inefficient grid (Hussain *et al*., 2010; Sallem *et al*., 2009).

One potential solution to these challenges is the adoption of standalone renewable energy-powered water pumps, coupled with effective management practices that could introduce more accurate pricing signals. The adoption of renewable energy technologies in agricultural activities holds great potential for addressing trade-offs and leveraging the interactions between water, energy, food security and climate change to promote sustainable agriculture. The fluctuating energy demand, coupled with the need for safe, reliable and environmentally sustainable energy sources, necessitates a transformation of the energy sector through the rapid adoption of renewables. The United Nation's "Sustainable Energy for All" initiative aims to double the global share of renewable energy by 2030 (Griggs *et al*., 2013). This shift presents both challenges and opportunities for the energy, water, and food sectors.

However, research into the role of renewable energy within the water-energy-food nexus, as well as the broader understanding of how expanding renewables impact these sectors, remains limited and fragmented (Bazilian *et al*., 2011). One promising opportunity is the use of renewable energy for farmland and grassland irrigation. Nevertheless, agricultural irrigation places significant pressure on both water and energy security, especially since the demand for food and energy is closely tied to population growth and climate change. The main technical challenges to farmland irrigation are access to clean, affordable electricity, and effective energy and water management within these systems. Implementing renewable energy technologies alongside proper management techniques can help alleviate the strain on the grid, reduce energy and water consumption in the agricultural sector, and lower the costs associated with irrigation.

Energy demands in the Agricultural sector

In recent decades, the demand for energy, especially in the agricultural sector, has significantly increased. Before the widespread availability of fossil fuels, most agricultural tasks around the world were performed manually. The industrial revolution marked a turning point, driving humanity to rely heavily on fossil fuels (Giampietro and Ulgiati, 2005). The Green Revolution in the 1960s further spurred the use of energy in agriculture, leading to today's mechanized farming practices aimed at maximizing yields, which are now highly dependent on fossil energy sources (Johansson *et al*., 2012).

Understanding agricultural production systems is essential to accurately assess the energy requirements in the sector (Jordan, 2013). Agriculture's energy demands are varied, covering inputs such as fertilizers, water pumping, irrigation systems, machinery and labour that are vital for production processes (Wiedmann, 2009). The continuous global rise in energy demand has driven up costs across numerous sectors, including agriculture. Agriculture, as the backbone of rural economies and a primary resource for many nations, depends heavily on energy. Much of the world's food production comes from rural populations involved in the cultivation, processing, and storage of agricultural goods, all of which require energy.

Water supply and irrigation systems, long recognized as crucial to agricultural productivity (Shinde and Wandre, 2015), present a significant energy requirement. The energy-intensive task of pumping water from underground or surface sources is vital for irrigation, livestock management, and various on-site operations such as cleaning. This process often accounts for one of the largest energy expenditures in agriculture, emphasizing the role of water pumping as a key contributor to the sector's overall energy consumption.

The cost of irrigation is primarily influenced by three main factors: water availability, energy and usage patterns. However, these costs can be reduced through the use of water and energy-efficient irrigation systems (Chandel *et al*., 2015). Traditionally, water pumping for irrigation has relied on conventional energy sources such as diesel and grid electricity. With the depletion of fossil fuels and the unreliability of power supplies, researchers are exploring alternative solutions. In addition to rising costs, the environmental impact of conventional energy use is a significant concern. Renewable energy sources have shown great potential in addressing these challenges, offering a more sustainable solution for irrigation.

As the global population continues to grow, food consumption will inevitably increase, emphasizing the need to improve agricultural productivity for food security. Reducing food waste is another critical strategy. Food loss typically occurs at three stages: during harvest, post-harvest, and in the marketing phase. In India, for instance, a case study revealed that significant food waste happens post-harvest, leading to substantial economic losses (Prakash *et al*., 2016 and Lakhani *et al*., 2024). Perishable goods are especially vulnerable to spoilage, and one solution to preserve their freshness is through low-temperature storage. However, this method is costly and requires a stable energy supply.

Drying agricultural products is one effective preservation technique that can reduce food loss. Dried goods can be stored for extended periods, yet the drying process is highly energy-intensive, involving both heat and mass transfer (Kumar and Tiwari, 2007). In developed countries, about 10% of total energy consumption is dedicated to drying operations (Kudra, 2004). Until the 1970s, these processes primarily relied on fossil fuels. The oil crises of the 1970s, however, spurred a shift toward alternative energy sources for agricultural drying. Renewable energy has since emerged as a viable and eco-friendly option, providing an economically sustainable alternative for drying agricultural products (Akinbulire *et al*., 2014; Babatunde *et al*., 2018).

Today, farming is predominantly conducted using mechanized methods, with machinery playing a crucial role in various agricultural tasks. These machines require either direct or indirect energy to function. They are utilized in field preparation, crop planting, chemical application, and even crop harvesting. Additionally, the production of fertilizers and chemicals, which occurs off the farm but is essential to agricultural processes, is also energy-intensive.

Overall, the energy requirements in agriculture can be divided into two main categories: direct and indirect energy demands (Table 1).

Table 1 : Energy demand in the agricultural sector.

S. no.	Direct energy demand	Indirect energy demand
1	Pumping of water/ irrigation	Farm machinery and buildings
2	Drying	Pesticides production
3	Other farm activities	Fertilizer production

The relationship between Water-energy-food Nexus and Climate change

The water-energy-food nexus was introduced at the 2011 Bonn Nexus Conference by the German government. This concept emerged in response to the challenges posed by climate change, as well as societal shifts such as population growth, globalization, economic development and urbanization (Hoff, 2011). Water, energy, and food are essential resources for human survival and societal development. Despite efforts to reduce resource losses, the demand for these vital resources is expected to rise due to factors such as population growth, climate change, and other global trends. In recent years, the water-energy-food nexus has gained significant attention and has become a recognized technical term in discussions around sustainability.

While the water-energy-food nexus concept may have its limitations, its value in fostering a systematic approach to sustaining the future of humanity cannot be overstated. It is crucial to consider the theoretical, practical, policy, and management strategies required to address the Nexus, which remains in its early stages of development. According to the literature, an optimal policy framework for water, energy and food systems has been described in three main phases.

The first phase involves integrating water resources with other sectors, such as agriculture, industry, and more. This is followed by the incorporation of diverse energy sources, including gas, oil, coal, nuclear, and renewable energy. The second phase focuses on safeguarding the nation, public health, and essential livelihood services. Prior to the development of the Nexus concept, water, energy, and food security were often addressed separately. The third phase establishes policies that account for the interconnectedness of the water, energy, and food systems.

The water-food nexus aims to reduce water consumption in food production and enhance the efficiency of water use in food preparation. A 2007 study examined environmental aspects of the water-food nexus, including an analysis of food imports (Qadir *et al*., 2007). Another study by Karimi *et al*. (2012) explored the use of green water and strategies to prevent the depletion of residual soil moisture post-harvest while maintaining low water consumption. Additionally, Akangbe *et al*. (2011) conducted research on environmental, social, economic, and governance approaches, focusing on climate protection models in agriculture.

The relationship between water and energy, often referred to as the water-energy nexus has been understood for many years. Water plays a vital role in energy production, such as in hydropower generation and biofuel production. Conversely, energy is required for processes like pumping water for agriculture and treating wastewater. A study by Hardy *et al*. (2012) highlighted that agricultural irrigation in Spain's water sector consumes a significant amount of energy.

The water-energy-food nexus has gained importance, with integrated water resource management being a key strategy to enhance synergy between these sectors. Karimi *et al*. (2012) found that increased irrigation leads to higher energy consumption, but also lowers the carbon emissions from groundwater extraction. Another study by Yang *et al*. (2009) explored the land and water needs for bioethanol production using maize. Additionally, Granit *et al*. (2012) discussed various perspectives on regional integration, including hydropower investment, irrigation reform and power market development.

Concerns about climate change have grown significantly and are frequently discussed across sectors impacted by climate variability. The increasing effects of climate change can be attributed to activities in key sectors like agriculture and industry (Pardoe *et al*., 2018). Rainfall, as a critical water source, plays an essential role in both food production and the agricultural sector, while also being vital for hydropower generation. However, climate change may alter rainfall patterns, affecting its quantity, timing and intensity.

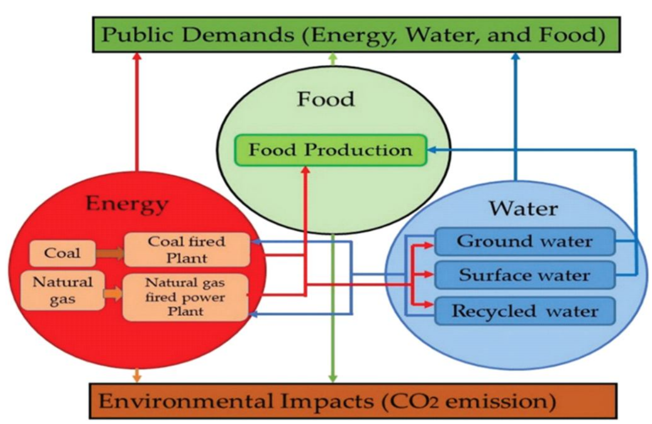

Fig. 1 : A schematic representation of interactions of water, energy, food and climate change (Zhang and Vesselinov, 2017).

In response, several climate-related initiatives aim to reduce the vulnerability to climate-induced disasters and environmental degradation in the long term. Fig. 1 illustrates the interconnectedness of these essential resources water, energy and food with climate change.

Sustainability in agriculture

Climate change stands as one of the most significant threats to humanity in the 21st century. The rise in global temperatures is a primary driver behind disruptions in the Earth's natural systems. This increase in temperature is causing shifts in the regular cycles of ecosystems, leading to natural disasters such as droughts, floods, and unseasonal frosts. These extreme weather conditions pose a serious threat to the long-term sustainability of agriculture and food security. According to reports from the United Nations, a global temperature increases of 3°C could have devastating consequences for water resources, food supply, biodiversity, and the proliferation of pests and diseases, particularly during planting and harvesting periods. This would, in turn, significantly impact crop production and livestock, potentially leading to a failure to meet global food demands.

Researchers have emphasized the critical need for global agriculture and food security to achieve the long-term goal of limiting the rise in global temperature to below 2°C compared to pre-industrial levels in order to prevent catastrophic consequences. Climate change is expected to have severe negative impacts, particularly on small-scale farmers in rural areas, further jeopardizing food security. Therefore, it is crucial to build resilience to the effects of climate change and reduce agriculture-related greenhouse gas emissions. Agriculture is responsible for nearly 24% of global greenhouse gas emissions (Lenka *et al*., 2015). As a result, the sector holds significant potential in the fight against climate change by adopting sustainable and smart agricultural practices. Implementing green agriculture techniques can enhance farm-level resilience, helping to mitigate the adverse effects of climate variability and contributing to global efforts to combat climate change.

The integration of renewable-powered technologies in agriculture has the potential to significantly mitigate the effects of climate change. Biochar, derived from agricultural crop residues through thermo chemical processes, aids in effective crop waste management. Its growing significance stems from distinctive features like high organic carbon content, stability, ample surface area, and cation exchange capacity. Renewable energy is derived from natural resources that are continually replenished, making it a sustainable solution. The use of renewable energy technologies (RETs) in agriculture not only prevents the depletion of natural resources but also reduces emissions. Renewable energy offers effective, long-term solutions to various conservation challenges in agriculture, with solar, wind, biomass, hydropower and geothermal energy being prime examples. These technologies serve as viable alternatives to fossil fuels, providing energy for heating and electricity, thus promoting sustainable agricultural practices.

Agricultural sustainability hinges on the principle of enhancing crop productivity and maintaining economic stability, while simultaneously minimizing the exploitation of natural resources and combating the adverse impacts of climate change (Yunlong and Smit, 1994). Achieving sustainable agriculture requires collective societal responsibility, governed by widely accepted regulations and principles (McPherson, 2011). The essential principles and practices that underpin sustainable agriculture are outlined in Table 2.

Table 2 : Principles of Sustainability in agriculture.

Principles of sustainable agriculture (McPherson, 2011)	**Sustainable practices of agriculture (Tilman *et al*., 2002)**
A sustainable agricultural system ensures the continuous protection of the natural environment through the conservation of natural resources.	The use of rotational grazing which reduces the costs of animal feeds while providing high quality animal feed.
A sustainable system of agriculture is dependent on the efficient management and utilization of renewable energy resources.	The use of management practices for nutrients used for the nourishment of crops such as fertilizer and manure. This ensures a cheap and cost-effective use of nutrients.
A sustainable system of agriculture is based on environmental ethics which ensures the protection of all water, soil, biotic and air species.	The use of information technology for efficient management of crops and use of water conservation practices for the protection of wetlands
Sustainable practices possess techniques which are non-toxic and harmless.	The use of agroforestry practices for conservation of the natural environment.
A sustainable system of agriculture provides profits for agricultural users and investments.	Renewable energy can also be used to implement sustainable practices of agriculture.

Applications of Renewable Energy in Agriculture

Renewable technologies are increasingly being utilized in agriculture to fulfil a wide range of energy needs, from water pumping to space heating. The adoption of renewable energy in agriculture addresses several challenges associated with fossil fuel use, as it generates minimal to no environmental emissions and reduces reliance on imported fuels. As a result, incorporating renewable energy into agricultural practices offers significant financial benefits. Renewable energy sources are sustainable, providing a long-term revenue stream for farmers and agriculturists.

In many cases, farmers and ranchers are now producing and selling surplus energy, which plays a vital role in enhancing energy security within the agricultural sector. This leads to an independent energy supply, reduced environmental pollution and the use of various renewable energy sources. Renewable energy technologies such as solar, wind, geothermal and biomass have diverse applications in agriculture, as further discussed in the following section.

Solar Energy

Solar energy plays a crucial role in agriculture, offering numerous benefits such as enhancing self-sufficiency, reducing costs, and minimizing environmental pollution. By lowering electricity consumption, solar energy helps save significant amounts of money for farmers. Its advantages in agricultural applications are highlighted by Chel and Kaushik (2011) and include the following:

- Reduced operational costs: Solar energy eliminates the need for fuel or diesel, lowering the cost of farm operations.
- Low maintenance: Solar panels, having no moving parts, require minimal maintenance, which contributes to cost savings.
- Reliability: Solar systems offer consistent and dependable power, ensuring the smooth operation of agricultural activities.
- Environmental benefits: Solar energy is a clean source of power that eliminates harmful gas emissions, promoting environmental conservation.

Photovoltaic (PV) systems, in particular, offer a cost-effective solution for generating electricity on farms, ranches, and orchards. These systems are often more economical than using transformers or power lines, especially for tasks like lighting agricultural fields, pumping water for crop irrigation or livestock, and setting up electric fencing (Carbone *et al.*, 2011). One of the simplest and most common uses of PV technology in agriculture is for water pumping. PV-powered water pumps can serve a wide range of needs, from irrigating crops to watering livestock and domestic uses (Schwarz, 2006). These systems also feature water storage capabilities, which allow for continuous operation even when sunlight is not available, eliminating the need for batteries and simplifying the system while reducing operational costs.

In addition to water pumping, PV systems can be utilized in a variety of agricultural operations, including (Xue, 2017):

- Refrigeration of agricultural products.
- Low-cost electricity for grinding agricultural goods.
- Egg collection and handling through photovoltaic systems.
- Solar-powered pumps and compressors for fisheries.
- Solar-powered feeding equipment for livestock.
- Photovoltaic fencing to protect livestock.

Solar energy can also be harnessed to produce heat for various agricultural applications. These applications include (Chikaire *et al.*, 2010):

- Solar water heaters for cleaning livestock in animal production.
- Sun drying of grains and crops.
- Solar-powered dryers for efficient and hygienic crop drying.

By utilizing solar energy, the agricultural sector can reduce reliance on fossil fuels, cut operational costs, and promote sustainability, all while minimizing the environmental footprint of farming activities.

Solar energy offers valuable applications in greenhouse heating, extending beyond its conventional use for lighting. Traditional greenhouses typically rely on oil or gas heaters to maintain the necessary temperatures for plant growth during colder months (von Zabeltitz, 1986). However, solar greenhouses can leverage solar energy for both lighting and heating purposes (Bellows and Adam, 2008). These specialized greenhouses are designed with thermal mass to collect and store solar heat and include insulation to retain this heat on cloudy days and at night.

In the northern hemisphere, solar greenhouses are strategically oriented to maximize southern exposure, enhancing their ability to capture solar energy (Taki *et al.*, 2017). This design reduces the reliance on fossil fuels for heating, contributing to more sustainable greenhouse operations.

An innovative approach in solar greenhouse design involves integrating a filter system that reflects near-infrared radiation (NIR). Sonneveld *et al*. (2009) provide a detailed analysis of such a system, which includes a spectral-selective cover that blocks approximately 35% of external solar energy. This reduces the cooling capacity required for the greenhouse. The NIR coating can be paired with solar energy systems, as the reflection of solar energy by photovoltaic cells helps in generating electricity. Sonneveld *et al*. (2009) also developed a computer program to model light rays, optimizing the geometry of the reflector to improve collecting efficiency.

Addressing the challenge of high global radiation and elevated outdoor temperatures is crucial for effective greenhouse cooling. By incorporating these advanced technologies, solar greenhouses can achieve better energy efficiency and reduce dependency on traditional heating methods, thus promoting sustainable agricultural practices.

Wind Power

Wind power offers a continuous energy supply, operating around the clock unlike solar power, which depends on sunlight. Wind energy technologies generate both mechanical and electrical energy, making them highly valuable for agricultural applications. Wind power is one of the fastest-growing renewable energy technologies, surpassing even bioenergy in its expansion. In the United States, the Department of Energy (DOE) has set ambitious plans for wind energy to account for 5% of the nation's electricity by 2020 (U.S. Department of Energy, 2010).

Technological advancements, including the development of hybrid energy systems, are enhancing the economic efficiency of wind energy. These improvements are expected to encourage agricultural producers to invest more in wind power infrastructure, leading to reduced energy costs and greater self-sufficiency. Wind energy is not only reliable but also cost-effective, addressing various energy needs on farms and ranches. Wind turbines can be used to power water pumps for irrigation and generate electricity, eliminating the need for conventional infrastructure such as transformers, electric poles, and power lines (Clark, 1991).

Windmills powered by wind energy are also employed to grind grains and legumes on farms (Halliday and Lipman, 1982). As an environmentally friendly option, wind energy does not require diesel or fuel, which reduces noise and air pollution. Additionally, it prevents the formation of toxic and radioactive waste, reduces greenhouse gas emissions, and minimizes acid rain by decreasing the concentration of oxide compounds (Kondili and Kaldellis, 2012). Economically, wind-powered farms are highly feasible due to their low maintenance and operational costs and the reduced need for fuel imports (Leung and Yang, 2012).

Small wind generators can produce electricity ranging from 400 watts to 40 kilowatts or more, sufficient for various farm operations (Ali *et al*., 2012). Farmers and ranchers can thus become wind energy producers with minimal land requirements. Net metering offers significant benefits by allowing farmers and ranchers to use excess power generated by wind turbines for other farm operations or to return it to the grid. This process results in a backward movement of the electric meter when surplus power is generated and a forward movement when additional power is needed (Poullikkas *et al*., 2013).

Biomass Energy

Biomass energy, derived from organic waste and plant materials such as trees, crops, manure and crop residues, represents a valuable renewable energy source. The large volumes of crops and biomass waste generated from agricultural activities can be converted into energy. This converted energy is utilized by energy companies for producing vehicle fuel, electricity for homes, and power for businesses. According to the U.S. Department of Energy, biomass energy has the potential to reduce greenhouse gas emissions and generate over $20 billion in revenue for rural communities and farmers (U.S. Department of Energy, 2003).

While crop and animal residues are commonly used for soil erosion control, nutrient recycling and cost reduction, they can also be effectively used for energy production without harming soil quality (Jovanovski *et al*., 2005). Biomass energy is particularly advantageous for small-scale farming, where it enhances the sustainability of agricultural practices without requiring extensive artificial processing.

Additionally, biomass plays a crucial role in the development of biorefineries, which have diverse applications in agriculture. A biorefinery is an industrial facility that converts biomass into energy and various valuable products, including electricity, ethanol, steam, biodiesel and high-value chemicals (Elmekawy *et al*., 2013). These products serve as efficient alternatives to petroleum-based chemical feedstocks and fuels, contributing to reduced greenhouse gas emissions and enhanced energy security. For example, a biorefinery can transform corn into animal feed, corn syrup, and ethanol, while trees can be processed into wood products, heat and electricity. This multifaceted use of biomass supports both sustainable agricultural practices and energy diversification.

Conclusion and Recommendations

The use of renewable energy in agriculture presents numerous opportunities, including enhanced energy efficiency, self-sufficiency and independence from traditional energy sources. However, there are also significant challenges associated with adopting renewable energy in the agricultural sector. These include difficulties in obtaining accurate data in developing and undeveloped nations, high initial investment costs, a lack of technical expertise for installation and maintenance, limited societal awareness of the benefits of renewable energy, and insufficient incentives for agriculturists and stakeholders to embrace these technologies.

Addressing these challenges requires concerted efforts, such as partnerships between governments and the private sector, as well as international collaboration. Through these measures, the barriers to renewable energy adoption in agriculture can be effectively mitigated.

In summary, renewable energy offers a pathway to clean and sustainable farming practices that not only protect the environment, but also improve energy efficiency, ultimately leading to financial savings. The following recommendations are proposed to enhance the adoption of renewable energy in agriculture:

Reduction of Energy Costs : Utilizing renewable energy sources to power agricultural activities can significantly reduce energy expenditures, thereby boosting overall business profitability. It is important to develop flexible and cost-effective methods to facilitate the adoption of these technologies.

Reduction of Emissions : By using renewable energy to power farming operations, emissions from agricultural activities can be reduced, which would help mitigate the sector's contribution to global warming. Research into environmental incentives that could encourage the adoption of renewable energy in agriculture is essential.

Legislative Support : Governments should pass business-friendly legislation that promotes the adoption of renewable electricity generation in the agricultural sector. Additionally, the creation of an innovative public benefits fund could leverage private investment in renewable energy projects that benefit the agricultural community.

Small-Scale Energy Systems : Encouraging the installation of small-scale renewable energy systems within agricultural businesses is critical. These systems would not only help combat climate change but also enhance the viability and sustainability of agricultural enterprises.

By implementing these recommendations, the agricultural sector can play a significant role in the transition to renewable energy, while simultaneously improving environmental stewardship and business profitability.

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