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Potato's Role in Sustainable Agriculture and Agroecology

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Abstract As one of the most important non-cereal food crops in the world, potato plays a key role in sustainable agriculture and agricultural ecosystems. The literature review shows that potato can not only efficiently utilize limited resources and improve food security, but also promote ecosystem health and improve farmers' livelihoods through diversified planting and innovative management methods. The use of sustainable measures such as organic fertilizers, cover crops, ecological planting and biostimulants has significantly improved yield, quality and soil health, and reduced dependence on chemical inputs. Through the application of organic fertilizers in Shandong Province, China, potato has not only improved production efficiency and economic benefits, but also optimized the input structure and promoted the green transformation of regional agriculture. Innovative technologies such as hydroponics provide new paths to address climate change and land degradation. Potatoes have shown unique advantages in achieving nutritional security, ecological protection and sustainable rural development.
Keywords Potato (*Solanum tuberosum*); Sustainable agriculture; Agroecology; Organic fertilizer; Food security; Ecological planting; Hydroponics; Soil health

1 Introduction

The increasing population, volatile weather, deteriorating land, decreasing water resources, and the disappearance of many plants and animals have made global food security and ecological environment unstable (Barbeau et al., 2015; Djaman et al., 2021; Vilvert et al., 2022; Siamalube et al., 2025). The agricultural methods of the past, which were high-investment and wasteful, not only made the soil worse, but also polluted water sources and increased greenhouse gases in the air, which put increasing pressure on the environment (Khanal et al., 2024). There are still many places where people cannot get enough food, especially in developing countries, where the food production and transportation systems are very unstable, and many people are hungry or malnourished (Aksoy et al., 2021; Siamalube et al., 2025). In order to change this situation, agriculture must develop in a greener, more efficient and environmentally friendly direction. This requires the use of new technologies, more rational use of resources, and improving the resistance of crops to adverse environments, while also protecting the various functions of agricultural ecosystems (Aloo et al., 2020; Vilvert et al., 2022; Khanal et al., 2024; Siamalube et al., 2025).

In global food production, root and tuber crops such as potatoes, cassava and sweet potatoes are very important. They are not only staple foods in many countries, but also have high yields, good nutrition and strong adaptability, and are an important choice for ensuring food security (Aksoy et al., 2021; Khanal et al., 2024; Siamalube et al., 2025). Potato (*Solanum tuberosum*) is the fourth largest food crop in the world, second only to wheat, rice and corn. It is rich in carbohydrates, proteins, vitamins and minerals. It can supplement the various nutrients needed by the human body and is very helpful in reducing malnutrition and trace element deficiencies (Aksoy et al., 2021; Siamalube et al., 2025).

These crops are highly adaptable and can grow in cold, arid or poor soil areas, which allows some remote or poor areas to be used for farming, which is also beneficial to boosting the local economy (Barbeau et al., 2015; Khanal et al., 2024). Now that climate change is intensifying and resources are scarce, these diversified crops can enhance the risk resistance of agriculture and reduce dependence on a single type of crop (Barbeau et al., 2015; Khanal et al., 2024; Siamalube et al., 2025).

In recent years, as climate and land issues have become increasingly prominent, people have paid more and more attention to the environmental adaptability and resource conservation advantages of potatoes (Tunio et al., 2020; Aksoy et al., 2021; Siamalube et al., 2025). The potato industry can also extend downstream, such as developing by-products and recycling, providing new opportunities for green agriculture and circular economy (Khanal et al., 2024). In promoting sustainable agriculture and ecological agriculture, potatoes can not only help solve food problems, but also drive ecological protection and rural development (Aloo et al., 2020; Vilvert et al., 2022; Khanal et al., 2024; Siamalube et al., 2025).

This study sorts out the multifaceted role of potatoes in sustainable agriculture and agricultural ecology, and analyzes its performance and potential in global food security, ecological protection and rural development. We will evaluate the nutritional value of potatoes and see how they can help solve malnutrition and micronutrient deficiencies; we will also analyze their performance in various environments and how to enhance the risk resistance of agricultural systems. In addition, we will introduce some new sustainable planting methods, including the impact of pest and disease control, water-saving irrigation, and waste utilization on the environment. We will also combine actual cases to see the application effects and problems of potatoes in different regions, and propose future research directions and policy recommendations to provide reference for the green development of global agriculture.

2 Agroecological Characteristics of Potato Cultivation

2.1 Short growth cycle and adaptability to diverse climates

The growing period of potato (*Solanum tuberosum*) is relatively short, generally 70 to 120 days to mature, which is faster than many cereal crops (;et al., 2021; Nasir and Toth, 2022). Therefore, it can be planted several times a year, which can make more efficient use of land. Potatoes can also adapt to various climates, whether it is high-latitude temperate zones or low-latitude subtropical zones, and even some arid and semi-arid areas (Jennings et al., 2020; Nasir and Toth, 2022). In the context of global climate change, this adaptability is even more important. Studies have found that if the planting time is adjusted reasonably and suitable varieties are selected, the yield of potatoes may increase by 9% to 20% in the future, and its greenhouse gas emissions are not high, so it is regarded as a "climate-friendly" crop (Jennings et al., 2020). There are also new planting methods such as hydroponics and aeroponics, which allow potatoes to produce high yields in places with poor soil or extreme weather (Rajendran et al., 2024).

2.2 Low water and fertilizer requirements compared to cereal crops

Potatoes use less water and fertilizer than many traditional cereals, such as wheat and corn, which are more water- and fertilizer-intensive than them (Jennings et al., 2020; Nasir and Toth, 2022). Although potatoes are afraid of drought, their water efficiency is still quite high if combined with drip irrigation, cover crops and organic fertilizers (Nyawade et al., 2020; Ierna and Distefano, 2024). In places with drought or unstable rainfall, potatoes can also grow well by choosing the right variety, watering properly and maintaining good soil (Nyawade et al., 2020; Hill et al., 2021). In addition, the variety of microorganisms in its roots is strong, which can also help it adapt to the environment better when water and fertilizer are insufficient (Faist et al., 2023). In organic farming, the use of animal manure, green manure and biostimulants can not only provide nutrients, but also make the soil healthier and more biological (Ierna and Distefano, 2024).

2.3 Soil conservation and anti-erosion function

Potato planting can also help protect the soil, especially on slopes or in places that are easily washed away by rain. Traditional potato planting methods often turn the soil, leaving the soil exposed, prone to erosion and nutrient loss (Nyawade et al., 2019b). However, if intercropped with legumes, cover crops, or conservation tillage are used, these problems can be reduced (Nyawade et al., 2019b; Nyawade et al., 2020; Junge and Finckh, 2024). For example, in the East African highlands, after potatoes and beans were planted together, soil loss per hectare was reduced by more than half from 169 tons to 50 to 83 tons (Nyawade et al., 2019b) (Figure 1). Such a system can also reduce the loss of nutrients such as nitrogen, phosphorus and potassium, and improve soil fertility and yield

(Nyawade et al., 2019b; Nyawade et al., 2020). Conservation tillage and blanketing can also improve soil structure, retain moisture, and be more resistant to erosion (Junge and Finckh, 2024; Marjanović et al., 2024). Through these ecological management methods, potato cultivation can not only bring income but also protect the environment, which is a way worth promoting.

Figure 1 Runoff plots installed at right angle to the contours and parallel to the slope (Adopted from Nyawade et al., 2019b)

2.4 Biodiversity support in potato-based agricultural ecosystems

Potato cultivation also has many advantages in improving biodiversity. Traditional high-input planting methods can easily reduce the number of plants and animals in the field and reduce the ecological service function (Junge and Finckh, 2024). However, if ecological agricultural methods are adopted, such as diversifying species, using less fertilizers and pesticides, and strengthening soil management, the types and numbers of microorganisms, insects, plants, etc. can be increased (Ierna and Distefano, 2024; Junge and Finckh, 2024; Marjanović et al., 2024). The use of organic fertilizers, green manures, microbial agents, and intercropping with other crops can not only improve soil activity, but also enhance the ability of crops to resist diseases and insects and reduce the use of pesticides and fertilizers. Microorganisms in potato roots can also help it grow better in drought or fertilizer shortages (Faist et al., 2023). Intercropping potatoes and beans can also increase the number of above- and below-ground biological species, improve ecosystem stability and yield (Nyawade et al., 2019b; 2020). If a multi-level and systematic management approach is adopted, the potato agricultural system can not only increase production but also protect the ecological environment, which is a good direction for sustainable agricultural development (Nyawade et al., 2019b; 2020; Faist et al., 2023; Junge and Finckh, 2024; Marjanović et al., 2024; Ierna and Distefano, 2024).

3 Potatoes and Sustainable Resource Utilization

3.1 Water use efficiency and drought resistance

Potatoes have high water use efficiency and strong drought resistance. These two characteristics are particularly important as climate change is severe and water is becoming increasingly scarce. Studies have found that planting potatoes with legumes, such as sword beans and hairy vetch, and using silicon fertilizers can make the soil retain water better, the leaves contain more water, the yield naturally increases, and water is used more efficiently. Experiments in Kenyan fields have shown that this can increase water use efficiency by 45% to 67% (Nyawade et al., 2019c; 2020).

Intercropping can also cover the ground with plants, reduce soil temperature, reduce water evaporation, increase the water content in the soil by 38%, and improve drought resistance (Nyawade et al., 2019c). Silicon fertilizers can also help plants adapt to drought, such as increasing the amount of regulating substances in leaves and making cell membranes more stable (Nyawade et al., 2020). In arid areas such as northwest China, crop rotation and mulching can also make potato water more efficient, reduce water footprint, and increase yield and income (Liu et al., 2023).

3.2 Role in crop rotation and soil fertility maintenance

Potatoes play an important role in crop rotation. They can improve soil structure and maintain soil fertility, which is very helpful for sustainable agricultural development. If you only grow potatoes, the soil will deteriorate, organic matter will be reduced, nutrients will be unbalanced, and yields will decrease (Liu et al., 2023; Yang et al., 2024).

In northwest China, experiments have found that rotating potatoes with corn, flax, broad beans, etc. not only makes the plants taller, produces more dry matter, improves soil quality, saves water, and improves water use efficiency and income (Liu et al., 2023). With one rotation per year, the number of tubers per potato plant increased by 38.24%, the income increased by 9.7%, the water use efficiency increased by 41.86%, and the soil became fertile.

In the Mediterranean, rotating potatoes with durum wheat, adding organic fertilizers and conservation tillage, can increase soil organic carbon, reduce carbon dioxide emissions, and use less fertilizer and energy (Mancinelli et al., 2023). If there are leguminous crops in the rotation, it can also improve the activity and health of microorganisms in the soil (Yang et al., 2024).

3.3 Contribution to nutrient cycling and organic matter input

Potatoes are also useful in nutrient cycling and increasing soil organic matter, especially when planted or rotated with legumes. Planting potatoes alone for a long time can cause soil organic matter and microbial activity to deteriorate, but rotation and intercropping can improve this situation (Nyawade et al., 2019a).

In the experiment conducted in the highlands of Kenya, intercropping potato and leguminous crops increased light group organic matter in the soil by 12 to 28%, dissolved organic matter by 7 to 21%, microbial biomass by 15 to 38%, and soil enzyme activity and microbial respiration were enhanced.

These systems also promote nutrient transformation and cycling because there are more plant residues, so there is more organic matter in the soil, which is food for microorganisms (Nyawade et al., 2019a). In the North China Plain, the rotation of potatoes with sweet potatoes, peanuts, and soybeans has also increased equivalent yields and farmers' incomes, increased soil carbon by 8%, and improved soil health index by 45% (Yang et al., 2024) (Figure 2).

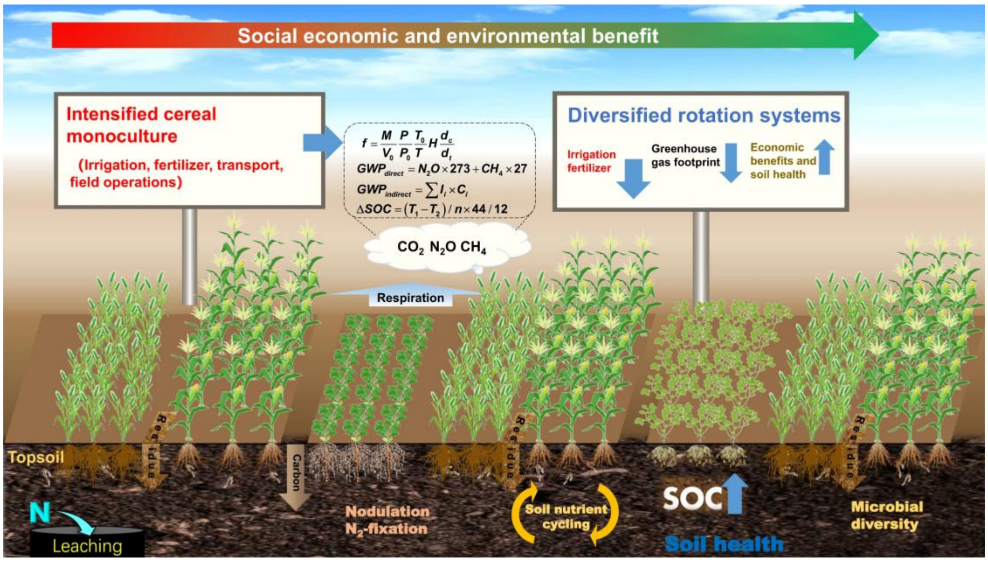

Figure 2 Schematic illustration of system integration from issues to outcomes (Adopted from Yang et al., 2024)

Image caption: In the North China Plain—the case study area, traditional cereal monoculture (such as wheat - maize double-cropping, i.e., two cereal crops per year) requires inputs of synthetic agrichemicals and irrigation in food production, causing large greenhouse gas (GHG) emissions; in contrast, rotation systems diversified with cash and legume crops can maintain crop yields, increase farmers' income, and reduce GHG emissions due to the biological N2 fixation by legumes partly substituting for synthetic N inputs. Legume-included rotations can also enhance soil health by stimulating soil microbial activities, increasing carbon sequestration, and enhancing nutrient cycles (Adopted from Yang et al., 2024)

Returning potato residues to the field and adding organic fertilizers can also help improve soil structure and carbon and nitrogen cycle efficiency, and reduce nutrient loss and pollution (Mancinelli et al., 2023).

3.4 Potential of intercropping and diversified planting systems

Potatoes have good ecological and economic effects in intercropping and multi-crop systems. For example, planting them with legumes such as sword beans (*Canavalia gladiata* (Jacq.) DC.), hairy vetch (*Vicia villosa*), peas (*Pisum sativum* L.), and common beans (*Phaseolus vulgaris* L.) not only enriches the above-ground and underground organisms, but also improves resource utilization efficiency and yield (Gitari, 2018; Nyawade et al., 2019c; 2020). The potato-legume intercropping system allows the ground to be covered with more plants, the soil to have more water, nutrients are not easily lost, the yield is also increased, and the income increases accordingly (Gitari, 2018; Nyawade et al., 2020).

In experiments in Kenya, the yield of this intercropping method is 2 to 3 times that of potato alone, and the land use efficiency is also higher (Nyawade et al., 2020). Intercropping can also help regulate soil temperature, improve photosynthesis and water use efficiency, make crops grow better, and make the system more stable (Nyawade et al., 2019c). This planting method can also increase the diversity and activity of soil microorganisms, help decompose organic matter and nutrient cycling, and improve soil health (Nyawade et al., 2019a).

In the arid regions of north China and northwest China, potato, corn and leguminous crops are rotated or intercropped to not only increase yield and economic benefits, but also reduce groundwater consumption and greenhouse gas emissions, making the system more resilient and sustainable (Liu et al., 2023; Wang et al., 2023; Yang et al., 2024).

4 Environmental Benefits of Potato-based Systems

4.1 Low greenhouse gas emissions per kilocalorie produced

Potatoes are a staple food crop. Compared with corn, wheat and rice, they emit less greenhouse gases per kilocalorie produced. In China, a systematic life cycle analysis was conducted and found that the carbon emissions and water consumption of potatoes were lower than those of these traditional food crops. With the advancement of the "potato staple food" policy, the carbon footprint, water footprint and land use of staple food crops are expected to be reduced by 17%~25% by 2030 (Liu et al., 2021). In industrial cultivation in Brazil, the carbon emissions of producing one kilogram of potatoes are 0.135 kg CO_2-eq, which is lower than vegetable crops such as tomatoes (Pereira et al., 2025). In southern China, the rotation of sweet potatoes and potatoes has also been shown to reduce emissions while ensuring yields (Tang et al., 2022).

4.2 Reduce dependence on pesticides and herbicides through integrated pest management

Traditional potato farming often uses a lot of chemical pesticides and herbicides, which affects the environment and water quality. But now many farmers are beginning to use integrated pest management (IPM) to reduce these chemical inputs. They prevent pests and diseases by rotating crops, intercropping, planting cover crops, reducing tillage and using organic fertilizers (Junge and Finckh, 2024). If regenerative agriculture or ecological planting methods are adopted, soil structure and biodiversity will improve, pests and diseases will be reduced, and pesticides and herbicides will be used less. The use of biostimulants and microbial fertilizers can also make crops healthier and reduce dependence on external chemicals (Ollio et al., 2025).

4.3 The potential of low-input and organic production systems

If organic fertilizers, biostimulants or microbial fertilizers are used to replace some or all chemical fertilizers, yields will not decrease, but tuber quality and soil health will improve (Mancinelli et al., 2020; Ollio et al., 2025). In field trials in the Mediterranean region, the use of organic fertilizers and conservation tillage to grow potatoes can increase soil carbon input, improve organic matter, and reduce CO_2 emissions (Mancinelli et al., 2020). In southern Spain, studies have found that combining microbial inoculants with reduced fertilizer use reduced CO_2 emissions by 25%~42% compared to traditional methods, and increased yield and quality (Ollio et al., 2025). Diversified planting, planting cover crops and using organic fertilizers increase soil biodiversity and ecological functions (Junge and Finckh, 2024; Henzel et al., 2025).

4.4 Improving soil health through cover crops

Planting cover crops and potatoes in rotation or intercropping can improve soil. For example, rotating legumes or grasses such as hairy vetch, rye, and clover with potatoes can increase soil organic matter, enhance microbial activity, and improve nitrogen supply and soil structure stability (Nyiraneza et al., 2021; Henzel et al., 2025). In experiments in eastern Canada, the use of cover crops and organic fertilizers increased soil nitrogen supply capacity by 44%, microbial respiration by 27%, and potato yield by 28% (Nyiraneza et al., 2021). In regenerative agriculture, these methods can significantly increase the number of microorganisms, soil respiration and fungal activity, and can decompose organic matter and nutrient cycles (Henzel et al., 2025). Cover crops can also reduce soil erosion and nutrient loss (Junge and Finckh, 2024; Henzel et al., 2025).

5 Socio-economic Dimensions of Sustainable Potato Production

5.1 Contribution to rural livelihoods and food security

Potato is the fourth largest staple food in the world and is very important for ensuring rural livelihoods and food security. It is a key crop in many developing countries to fight hunger and poverty due to its high yield, strong adaptability and rich nutrition (Devaux et al., 2020; Devaux et al., 2021). Potato can produce high yields with limited resources, and can meet the food needs of different regions through diversified planting, enhancing food availability and stability. It is widely distributed and has a flexible planting cycle, which helps to alleviate seasonal food shortages and improve the self-sufficiency of rural households (Devaux et al., 2020). The development of the potato industry chain has also created a large number of employment opportunities in rural areas, promoted farmers' income increase, and promoted rural economic development (Thuo and Maina, 2024). In developing regions such as Africa, Asia and Latin America, potato is a key crop for improving smallholder livelihoods, improving nutrition and achieving sustainable development (Devaux et al., 2020; Devaux et al., 2021; Thuo and Maina, 2024).

5.2 Role in smallholder and family farming systems

Smallholders and family farming systems play an important role in global potato production, especially in developing countries, where potato cultivation is the livelihood guarantee for many farmers (Devaux et al., 2021; Kangogo et al., 2024; Thuo and Maina, 2024). Potato is suitable for small-scale, diversified agricultural systems, and can be rotated or intercropped with other crops to improve land use efficiency and system resilience (Devaux et al., 2021; Thuo and Maina, 2024). In Kenya, Ethiopia and other places, potatoes are not only an important cash crop, but also an important part of farmers' family tables (Mijena et al., 2022; Thuo and Maina, 2024). However, many small farmers face difficulties in seed quality, climate change, pests and diseases, technical support and market access during production (Kangogo et al., 2024; Thuo and Maina, 2024). In order to improve the productivity and risk resistance of small farmers, research and policy recommendations include promoting high-quality seed potatoes, strengthening technical training, developing farmer cooperatives, improving infrastructure and enhancing information services. Promoting innovation in digital agriculture and climate-smart agriculture will help enhance the resilience and sustainable production capacity of small farmers (Thuo and Maina, 2024).

5.3 Market access and value chain potential in developing regions

Market access is limited by inadequate infrastructure, poor market information, price volatility, and shortages of seeds and agricultural resources (Kyomugisha et al., 2018; Wubet et al., 2022). In Uganda and Ethiopia, factors such as the contractual relationship between farmers and buyers, land size, planting varieties, and agricultural tool ownership significantly affect market access and sales efficiency. Farmers' income can be increased by more than 25% by participating in the value-added links of the value chain (such as primary processing, grading and packaging, etc.) (Kyomugisha et al., 2018). Collective marketing, contract farming and direct sales can improve market efficiency and farmers' bargaining power. In Ethiopia, the main participants in the potato value chain include producers, wholesalers, retailers and consumers. Wholesalers dominate the market through financial advantages, but farmers can significantly increase market supply and income by improving education levels, strengthening market connections and participating in farmers' organizations (Wubet et al., 2022). Policy recommendations include helping farmers obtain high-quality seed potatoes and agricultural inputs, improving market information services, and establishing a reasonable price mechanism and post-harvest management system (Kyomugisha et al., 2018; Wubet et al., 2022; Kangogo et al., 2024).

5.4 Gender and equity perspectives in potato-growing communities

Gender and equity issues are very important in potato-growing communities, especially in highland areas with rich native diversity. For example, in the Peruvian Andes, women play a central role in protecting and managing local potato diversity. They are not only responsible for planting, harvesting and preserving seed potatoes, but also participate in variety selection and knowledge inheritance (Molina et al., 2022). However, gender norms and social structures often limit women's opportunities in agricultural decision-making, resource access and market participation. Studies have shown that empowering women, promoting gender equality and inclusive management can help improve food security, nutrition and community well-being of farming families. External supporters such as governments, NGOs and scientific research institutions should take measures to help women overcome institutional barriers and increase their participation and benefits in the potato industry chain.

6 Breeding and Technological Innovation Promote Sustainable Development

6.1 Development of climate adaptability and pest-resistant varieties

Now climate change is becoming more and more serious, and agriculture is under increasing pressure. In order to make potatoes more adaptable to the environment and reduce pests and diseases, scientists have begun to breed some new potato varieties. These varieties are resistant to high temperatures, drought, and pests, which are very helpful for agriculture (Devaux et al., 2021; Waheed et al., 2023; Siamalube et al., 2025).

Potatoes themselves are highly adaptable and have high nutritional value, making them a good helper in solving food problems. However, the problem now is that the weather is extreme, the drought is severe, and there are many pests and diseases, which affect both yield and quality. By breeding high-yield, drought-resistant, and late blight-resistant varieties, not only can the yield be increased, but also less pesticides can be used, which is more environmentally friendly (Waheed et al., 2023; Siamalube et al., 2025). Some people are now working on nutritional fortification, such as increasing the content of trace elements such as iron and zinc in potatoes (Siamalube et al., 2025).

6.2 Application of traditional knowledge and participatory breeding

Farmers have accumulated a lot of experience from generation to generation, especially knowing which varieties are more adaptable to the local environment. This knowledge now plays a big role in breeding (Devaux et al., 2021; Tedesco et al., 2023).

Participatory breeding is to let farmers and researchers select and improve varieties together. The varieties bred in this way are more suitable for farmers to use and more suitable for the local climate (Devaux et al., 2021). In many developing countries, farmers have not only increased their yields but also retained local specialty varieties by participating in seed selection and field management (Devaux et al., 2021; Tedesco et al., 2023). Traditional agricultural methods, such as the use of organic fertilizers, crop rotation, and intercropping, are also helpful for ecological agriculture (Junge and Finckh, 2024; Zhang et al., 2024).

6.3 Advances in biotechnology and precision agriculture tools

Today's scientific and technological progress is very fast, especially biotechnology and precision agriculture, which have brought many new methods to potato cultivation. Methods such as molecular markers, gene editing, and biofortification can be used to improve disease resistance, nutritional value, and yield (Rajendran et al., 2024; Siamalube et al., 2025).

Gene editing can specifically change genes that are prone to disease, making potatoes more resistant to diseases such as late blight (Siamalube et al., 2025). Biofortification can increase vitamins and minerals, which is also helpful in solving malnutrition problems.

In field management, farmers can also use remote sensing, artificial intelligence, and big data. These tools can monitor soil, water, pests and diseases in real time, helping farmers to arrange watering, fertilization, and pest control more scientifically (Tedesco et al., 2023; Rajendran et al., 2024). Soilless cultivation techniques such as hydroponics are also suitable for breeding seed potatoes in areas with poor soil or extreme weather (Rajendran et al., 2024).

6.4 Seed system and sustainable breeding model

In the past, the traditional method of breeding seed potatoes often accumulated diseases and the problem of seed potato degradation was also serious (Rajendran et al., 2024). Now, some new methods are beginning to be adopted, such as the production of micro potatoes using hydroponics and the rapid propagation technology of healthy seed potatoes, which have improved the health and reproduction speed of seed potatoes.

The advantage of hydroponics is that it saves water and land, and can also avoid disease infection in the soil, which is very suitable for mass production of high-quality seed potatoes (Rajendran et al., 2024). If a sound seed supply chain and local breeding system can be established, farmers will have easier access to good seed potatoes, which can also reduce costs and improve planting efficiency (Devaux et al., 2021; Rajendran et al., 2024).

In order to make these practices more popular, the government and relevant units also need to provide technical training, arrange resources reasonably, and encourage everyone to use organic fertilizers and adopt ecological planting methods (Rajendran et al., 2024; Zhang et al., 2024).

7 Challenges and Constraints

7.1 Vulnerability to pests and diseases (e.g. late blight)

Potatoes are very susceptible to pests and diseases, especially serious diseases such as late blight (*Phytophthora infestans*). Potato diseases not only reduce yields, but also reduce tuber quality and affect farmers' income (Waheed et al., 2023; Siamalube et al., 2025). Potatoes are also easily attacked by various pests and pathogens, so farmers often have to use a lot of pesticides and fungicides, which increases the cost of planting, pollutes the environment, and affects food safety (Junge and Finckh, 2024; Siamalube et al., 2025). Climate change also makes the problem of pests and diseases more serious, such as more extreme weather and increasingly unstable climate. Although the impact can be mitigated by planting disease-resistant varieties or using some ecological methods, there are still many difficulties in actual promotion, such as insufficient technology, insufficient investment, and farmers' lack of understanding.

7.2 Post-harvest losses and storage limitations

Potatoes are easy to spoil after harvest. Because of its high water content and strong respiration, it is easy to rot, sprout or deteriorate during storage, and as a result, many of them are wasted (Devaux et al., 2020; 2021). Especially in developing countries or places with limited resources, the lack of cheap and easy-to-use storage technology and equipment has caused great losses and affected farmers' income. Sometimes it is destroyed by pathogens or insects during storage, and the loss is even greater (Siamalube et al., 2025). The old storage method can no longer meet the quality and safety requirements of modern agriculture, while new technologies and cold chain systems require a lot of money and technology, and are not easy to promote (Devaux et al., 2020). These post-harvest losses not only waste food resources, but also increase carbon emissions, which is detrimental to the environment and affects the important role of potatoes in sustainable agriculture.

7.3 Policy and market barriers hinder agricultural ecological transformation

At present, the agricultural policies of many countries are still mainly encouraging high yields and the use of more fertilizers and pesticides, but the support for ecological planting and sustainable methods is not enough (Devaux et al., 2020; 2021). Ecologically grown potatoes often cannot be sold at a good price, and farmers have no motivation to change their original planting methods. Government subsidies, loans, insurance, etc. are still concentrated on traditional agriculture, while the technology promotion, certification, and market access related to ecological planting are still imperfect. In addition, the potato industry chain is long, with many participants, information asymmetry, and uneven distribution of benefits, which makes it more difficult to promote ecological agriculture.

7.4 Knowledge gap and insufficient institutional support

Many farmers do not know much about new technologies such as ecological planting, pest and disease control, and post-harvest management, and lack training and technical services (Zhang et al., 2024; Siamalube et al., 2025). There is a disconnect between scientific research and production, and good technologies are difficult to promote and farmers cannot use them. In some places, agricultural education and training resources are insufficient, and farmers have few opportunities to acquire new knowledge, which affects their learning and adaptability. The government and relevant institutions have limited investment in technical research, extension and services, and the support mechanism is imperfect, making the development of ecological agriculture more difficult. In addition, there are also some institutional problems in terms of policy implementation, capital investment, and departmental coordination, which affect the realization of sustainable development goals.

8 Case Studies

8.1 Andean Plateau: indigenous knowledge and agroecology

The Andean Plateau is the origin of the potato, with a rich indigenous knowledge system and diverse agroecological practices. The cultivation techniques passed down from generation to generation by local indigenous communities emphasize diversity, crop rotation and ecological balance, and diversify risks and enhance system resilience by planting a variety of potato varieties. These practices not only enhance the resistance of crops to extreme climate and pests and diseases, but also promote soil health and biodiversity (Devaux et al., 2021). Indigenous farmers use traditional knowledge to select adaptable varieties, combined with organic fertilizers and natural resource management, to achieve a low-input, high-efficiency sustainable production model. The potato cultivation system in the Andes demonstrates the core concept of agroecology, that is, to improve productivity and ecological service functions through harmonious coexistence with the natural environment.

8.2 Sub-Saharan Africa: potato as a strategic food security crop

In sub-Saharan Africa, the population is growing rapidly, and food shortages and malnutrition are prominent problems. Potatoes, with their high yield, short growth period and strong adaptability, have become the key to improving food accessibility and diversity (Devaux et al., 2020; 2021; Siamalube et al., 2025). Potatoes can not only achieve high yields under limited land and water resources, but also bring economic benefits to farmers and improve their livelihoods. In recent years, many African countries have introduced improved varieties, promoted efficient planting techniques and strengthened seed potato supply systems. Potatoes have shown unique advantages in responding to climate change, alleviating hunger and promoting nutritional diversity.

8.3 Europe: sustainable intensification model of potato system

In recent years, European countries have widely adopted agricultural ecological measures such as conservation tillage, microbial inoculation, organic fertilizers and cover crops. Field trials in Hungary have shown that conservative tillage and beneficial microbial inoculation can increase potato yield and tuber quality, although some ecological benefits require long-term observation to appear (Marjanović et al., 2024). The European agricultural system focuses on systematic thinking, and through measures such as crop rotation, intercropping and returning organic matter to the field, it improves soil structure, enhances biodiversity, and effectively reduces pest and disease pressure (Junge and Finckh, 2024).

8.4 Asia: rice-potato rotation and climate adaptation

Integrated cropping patterns such as rice-potato rotation are widely adopted in Asia, especially in China. Rice-potato rotation can not only break the cycle of pests and diseases and improve soil structure, but also improve soil fertility and crop yields through straw return and organic fertilizer application (Waheed et al., 2023; Zhang et al., 2024) (Figure 3). The use of organic fertilizers and straw mulching can significantly improve the production efficiency, economic benefits and resource utilization of potatoes. Innovative technologies such as hydroponics have been promoted in parts of Asia, providing new ideas for potato seed production and efficient use of limited land resources (Rajendran et al., 2024).

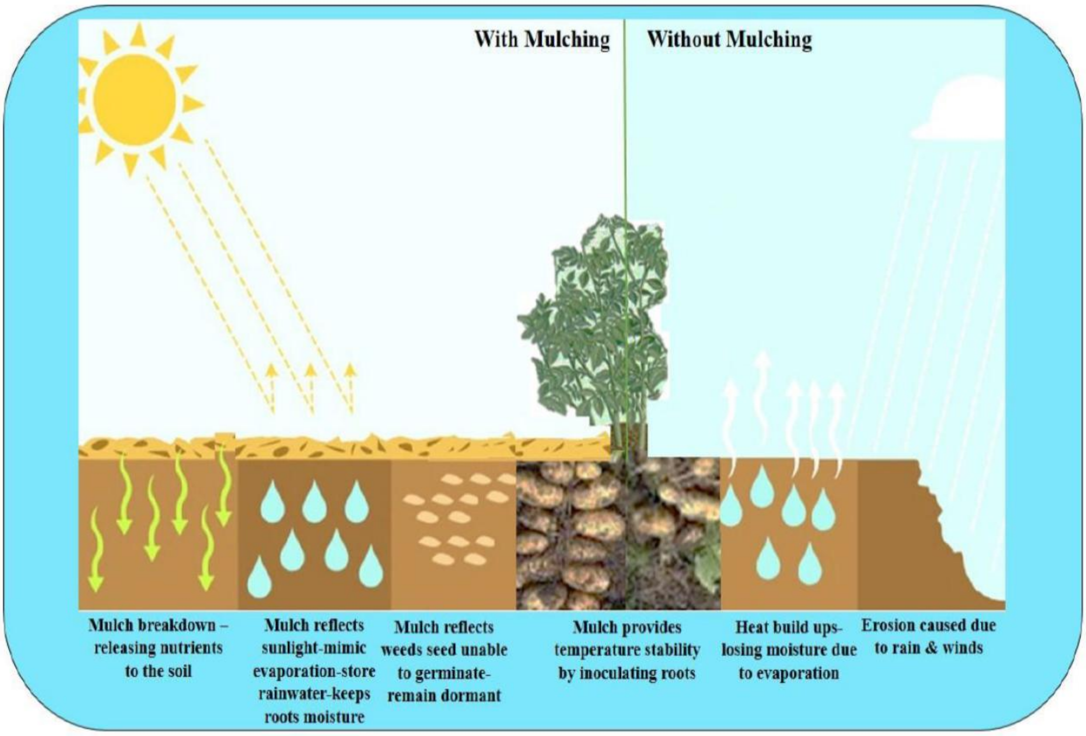

Figure 3 Mulching can dramatically increase soil nutrition and stop the weed population, as it prevents sunlight from reaching the seeds. By reducing evaporation, it protects plant roots against temperature fluctuations and retains moisture in the soil. As a result, wind and/or rain erosion can be reduced (or prevented) (Adopted from Waheed et al., 2023)

9 Future Directions and Policy Recommendations

9.1 Research priorities for sustainable potato systems

We need to improve potato yields and resource utilization efficiency. Soil can be improved and yields can be increased by using organic fertilizers, laying straw, and adding beneficial microorganisms (Ekin, 2019; Waheed et al., 2023; Junge and Finckh, 2024; Zhang et al., 2024). At the same time, it is also necessary to select disease-resistant and drought-tolerant varieties, strengthen pest and disease control, and study better post-harvest processing technologies, which are important for stable yields and food safety (Devaux et al., 2020; 2021; Siamalube et al., 2025).

Soilless cultivation such as hydroponics, as well as artificial intelligence and remote sensing technologies, are also being used in potato breeding and management. These technologies can make planting more efficient and water-saving, and can better cope with extreme weather (Rajendran et al., 2024). In addition, potatoes can also play a role in nutrition fortification, biodiversity conservation and ecological services, helping to promote global food security and sustainable development.

9.2 Integrate into national and international agricultural ecological strategies

Potatoes are highly adaptable and can be planted in a wide range of areas. They can be used to ensure food and ecological security in different places (Devaux et al., 2020; 2021). Therefore, national policies should incorporate potatoes into food security strategies and encourage ecological planting, rotation and intercropping, which can improve land use efficiency and make planting systems more resilient (Devaux et al., 2021; Junge and Finckh, 2024; Zhang et al., 2024).

Internationally, potatoes can also serve as a typical example of South-South cooperation and ecological agricultural development. Countries can jointly promote agricultural progress by sharing varieties, exchanging technologies, and spreading experiences (Devaux et al., 2020; 2021). International organizations should also increase policy and financial support to promote the development of ecological agriculture on a global scale.

9.3 Policy tools to support sustainable planting (subsidies and promotion)

The government can make farmers more willing to use organic fertilizers, water-saving technologies, and ecological planting methods by issuing subsidies, reducing taxes, etc. (Waheed et al., 2023; Junge and Finckh, 2024; Zhang et al., 2024). At the same time, agricultural extension services should also keep up to help farmers understand and master new technologies, new varieties, and ecological management methods (Junge and Finckh, 2024; Zhang et al., 2024; Siamalube et al., 2025).

It is also necessary to build a better seed supply system and post-harvest management mechanism, provide training and market information, which will help improve the efficiency and risk resistance of the entire industry (Devaux et al., 2020; Zhang et al., 2024; Siamalube et al., 2025). In addition, special attention should be paid to the actual needs of small farmers and remote areas, and resources should be allocated rationally to achieve equitable development (Devaux et al., 2020; 2021). At the international level, cooperation can also be strengthened to promote technology to developing countries and help them develop the potato industry.

9.4 The role of education and knowledge sharing platforms

At present, many farmers do not know much about ecological agriculture, pest and disease control and post-harvest processing technologies, and need to strengthen training and technical services (Zhang et al., 2024; Siamalube et al., 2025; Junge and Finckh, 2024). A hierarchical agricultural education system can be established to comprehensively improve farmers' capabilities from basic knowledge to practical skills (Zhang et al., 2024; Siamalube et al., 2025).

It is also important to develop digital platforms and information service systems, which can help researchers, extension workers and farmers better communicate and share experiences, and accelerate the promotion and application of new technologies (Junge and Finckh, 2024; Rajendran et al., 2024). International cooperation and networked learning also provide more opportunities, which will help countries learn from each other and make progress together (Devaux et al., 2020; 2021).

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Conflict of Interest Disclosure

The authors affirm that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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