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REVIEW

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Potato production in the United States: Two-decade update and future sustainable pathways

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Abstract

In the United States, agriculture accounts for approximately 10% of total greenhouse gas (GHG) emissions, including contributions from potato (*Solanum tuberosum L.*) production, a staple crop in the American diet. However, limited research has focused on recent trends in US potato production, particularly the contribution of different agricultural inputs and their role in GHG emissions. This study analyzes trends in US potato production using over two decades (1999/2000–2022) of annual survey data from the United States Department of Agriculture/National Agricultural Statistical Service. Key areas of analysis include planted and harvested area, yields, total and unit sale prices, and input usage. The data are further used to estimate GHG from potato production through the Cool Farm Tool for 2000 and 2022. Our findings reveal a 34% and 32% decline in planted and harvested area, respectively, alongside a 22% reduction in total production across all market segments. Notably, yield increased by 15% in 2022 compared to 2000. The overall decrease in potato production aligns with sharp increases in unit price and total potato sales after adjusting for inflation, which rose by 54% and 20%, respectively. Inputs such as nitrogen, phosphorus, herbicides, and insecticides showed consistent reductions in per-hectare and total annual application, whereas potassium and fungicide usage increased. Yield improvements and reduced input usage led to a 39% decrease in total estimated emissions and a 20% reduction in emissions intensity by 2022 compared to 2000. The study highlights site-specific nutrient management and technologies like low-emission fertilizers, renewable energy, carbon sequestration practices, and breeding as future investment priorities.

Plain Language Summary

Agriculture significantly contributes to global greenhouse gas (GHG) emissions, with the United States sector accounting for about 10% of national emissions. Limited

Abbreviations: CFT, Cool Farm Tool; CPI, consumer price index; GHG, greenhouse gas; IPCC, Intergovernmental Panel on Climate Change; NASS, National Agricultural Statistics Service; USDA, United States Department of Agriculture.

research has explored recent trends in US potato production, especially the impact of various agricultural inputs on GHG emissions. This study analyzes US potato production trends from 1999/2000 to 2022 using United States Department of Agriculture data, focusing on land area, yields, prices, inputs, and emissions. Findings show a 34% decline in planted land area and a 22% drop in total production, offset by a 15% yield increase. Input reductions in nitrogen, phosphorus, herbicides, and insecticides, alongside increased potassium and fungicide use, led to a 39% emissions cut and a 20% drop in emissions intensity. The study highlights the need for site-specific nutrient management and the integration of technologies like low-emission nitrogen fertilizers, renewable energy, carbon capture, and advanced breeding techniques as future investments.

1 | INTRODUCTION

Agriculture and other land uses (including forestry) account for approximately 13% and 21% of global greenhouse gas (GHG) emissions, respectively (Nabuurs et al., 2022). In the United States, agriculture contributes about 10% of the country's total GHG emissions (EPA, 2024; USDA, 2023, 2024), which includes emissions from on-farm potato (*Solanum tuberosum L.*) production activities. The United States is a top potato producer globally with a farm gate value of 5.39 billion in 2023, which is a 3% increase from 2022 (USDA & NASS, 2024). Major potato-growing states in the United States include Idaho, Washington, Wisconsin, and North Dakota. According to a 2022 survey and census data from the United States Department of Agriculture (USDA), potato products are distributed across processing markets (65%), table stock (22%), and smaller markets or non-sales (11%) (USDA & NASS, 2024). The economic value and significance of the potato crop make it a compelling horticultural commodity for various stakeholders, including consumers, producers, researchers, industry, and government agencies like the USDA. Historically, potato production has focused on topics such as crop protection, variety developments, crop nutrition, and best management practices. However, in the last decade, sustainability has emerged as a key area of discussion, driven by the growing recognition of agriculture's role in climate change, either as a contributor, a victim, and/or a potential solution to environmental challenges. Farmers are currently going through challenges such as the impacts of climate change, regulatory pressures, price volatility, and increasing demands from the food industry and governments to meet sustainability metrics for decarbonization targets. Despite these hurdles, they continue to view farming as a solution rather than a problem (Hatfield et al., 2024; USDA, 2023; USEPA, 2022).

Although potatoes generate relatively lower agricultural emissions compared to many other crops (Clune et al., 2017; Haile-Mariam et al., 2008; Nemecek et al., 2012), it is crucial to understand their potential to sustain adequate production while minimizing GHG emissions at the same time. Key sources of emissions in potato production include fertilizer production and application, soil management practices, energy consumption, land-use changes, residue management, pesticide and chemical use, post-harvest losses, and transportation. Blanket application of nitrogen fertilizers, whether under-applied or over-applied, can lead to nutrient imbalances and inefficient utilization. This not only reduces nutrient-use efficiency and profitability but also heightens environmental risks due to the potential loss of unused nutrients through emissions or leaching, further increasing the contribution of agriculture to GHG emissions (Singh et al., 2005). Inappropriate tillage practices disrupt soil structure, leading to increased CO_2 emissions into the atmosphere (Rakotovao et al., 2017). Conservation tillage practices enhance carbon inputs from crop residues (Stewart et al., 2016) while reducing CO_2 emissions from the soil. Reduced soil tillage offers advantages over the conventional tillage, including a 35% decrease in diesel fuel consumption, a 10% reduction in fossil energy use, enhanced carbon sequestration, and increased nitrogen accumulation in the soil (Küstermann et al., 2013).

The United States Vision 2030 Climate Mitigation Pathways, based on available scientific data, estimates that United States agriculture has the potential to achieve a 23% reduction in GHG emissions (Eagle et al., 2022). Also, in a recent report by Hatfield et al. (2024), United States agriculture has the potential to be GHG emissions negative with key drivers such as managing soil carbon, nitrogen fertilizer, animal production, closing crop production yield gap, and efficient energy use in agriculture (Hatfield et al., 2024). To attain this target, the USDA has developed a framework to measure, monitor, report, and verify GHG emissions and removals in the agriculture and forestry sectors. This strategy is part of a broader approach to advance an integrated United States GHG monitoring and information system, reflecting ongoing efforts and the future direction for achieving emission reductions. Such measurement and monitoring of inventories under potato production using GHG emissions modeling tools can help farmers, consumers, and stakeholders understand the sources of GHG emissions from production and show opportunities for potential mitigation.

Several models and tools have been developed to estimate GHG emissions (Vetter et al., 2018). These GHG calculators are designed for various users and purposes, with some being reviewed and compared by Colomb et al. (2012) and Whittaker et al. (2013). The models address different aspects of agricultural emissions and range from Intergovernmental Panel on Climate Change (IPCC) Tier 1 approaches (IPCC, 2006) to detailed biogeochemical models like DeNitrification—DeComposition (Li et al., 2010). They also vary in scale, focusing on individual processes such as soil microbial decomposition or broader regional analyses, such as the Ex-Ante Carbon-balance Tool (EX-ACT, 2010) and Comet-Planner for the United States (Comet-Planner, 2012). The Cool Farm Tool (CFT) is one of the most widely utilized tools by farmers and food supply chain stakeholders (e.g., academia, universities, private corporations, and non-governmental organizations) for estimating GHG emissions (Hillier et al., 2011). It employs a comprehensive set of empirical models to calculate full farm-gate product emissions, integrating a combination of Tier 1, Tier 2, and simplified Tier 3 approaches, as defined by the IPCC (1997) for GHG estimation in national inventories (Hillier et al., 2011).

This study aims to provide a systematic review of potato yields and GHG emission trends under potato production in the United States of America to highlight a positive outlook toward achieving the set GHG reduction target. It raises the question of whether periodic, sector-specific reviews at the crop level, utilizing existing historical data, can effectively highlight realistic performance and outline pathways for sustainable food production in the United States while reducing negative environmental impact through efficient agronomic practices that optimize input use and enhance or stabilize yields. To address this question, this study analyzes USDA survey and agriculture census data to examine US potato production trends from 1999/2000 to 2022, focusing on factors such as land area (planted and harvested), yield (per hectare and total), economic metrics (unit and total sales), fertilizer use (nitrogen, phosphorus, and potassium), and crop protection inputs (fungicides, herbicides, and insecticides). The data are also utilized to estimate GHG emissions from potato production using the CFT (Version 2.11.0), aiming to assess whether the observed trends have influenced production-related emissions at the farm level.

Core Ideas

- The US potato production trends (2000–2022) were analyzed using United States Department of Agriculture and agricultural census data.
- Potato land area and input use declined, but yields rose steadily over two decades, reducing greenhouse gas emissions.
- Reduced potato land area decreased production volumes and led to an increase in real prices from 2000 to 2022.
- Achieving net-zero potato emissions demands innovative strategies and advanced breeding for resilience and efficiency.

2 | MATERIALS AND METHODS

2.1 | Potato production data sources

Data on potato production from 2000 to 2022 was obtained from the census of agricultural data (USDA & NASS, 2024) and extracted online with Quick Stats 2.0. The data span land area (planted and harvested hectares), yield (per hectare and total production), and economics (unit and total sales). Data on agricultural chemical use in potato production, including fertilizers, pesticides, and herbicides, was gathered from USDA-National Agricultural Statistics Service (NASS) surveys conducted between 1999 and 2022. The chemical data analysis focused on nine states (Colorado, Idaho, Maine, Michigan, Minnesota, North Dakota, Oregon, Washington, and Wisconsin), which collectively represent over 90% of the total potato land area planted annually (USDA & NASS, 2024). The chemical use survey lacked data for the year 2000; instead, the 1999 data were used as the baseline.

2.2 | Price of potato production

The price of potatoes was adjusted using the consumer price index (CPI) to account for the year-by-year changes in purchasing power and inflation relative to the base year. This allows for a meaningful comparison of potato prices across the 20 years, offering a clearer picture of price trends and economic value.

Similarly, potato sales data were adjusted using the annual CPI based on all goods (1982–1984 = 100) using the Federal Reserve Bank of Dallas guidelines (Federal Reserve Bank of Dallas, 2024) to current 2023 dollar values.

2.3 | Estimation of GHG emissions

2.3.1 | Cool Farm Tool

The CFT (http://coolfarmtool.org) is an online science-based calculator that enables farmers and food supply chain companies to estimate GHG emissions and explore mitigation strategies for agricultural production (Schipanski et al., 2024). It was originally developed as a Microsoft Excel model by the University of Aberdeen in collaboration with Unilever and the Sustainable Food Lab (Hillier et al., 2011). It allows users to input soil and climate characteristics and agricultural production practices for a specific crop or food product to estimate its environmental impact. The CFT tool calculates emissions based on empirical (data-driven) models, and the prediction is based on IPCC-defined climate zones (Jabbour et al., 2021). It primarily relies on Tier 1 emission factors for GHG estimation, as higher-tier data are often unavailable for many regions and emission sources. Originally designed for national-scale accounting, Tier 1 methods were intended for less significant emission sources (e.g., those contributing under 5% of total emissions) (Richards et al., 2016). Nevertheless, many GHG calculators, including the CFT, use Tier 1 factors as the default approach due to the lack of alternative data. Emissions are reported for CO_2, CH_4, and nitrous oxide (N_2O) for the major sources of on-farm emissions associated with the production of agricultural products. Data input requirements for CFT are moderate (Jabbour et al., 2021), capturing all on-farm activities related to potato production through seven input sections (crop, soil, inputs, fuel and energy use, irrigation, carbon, and transport) (Figure 1). The CFT was selected for this review because it is a practical and commonly used GHG calculator in both corporate and development sectors. It estimates net emissions using simplified IPCC Tier 1 methods and empirical models, relying solely on fundamental climate, soil, and agricultural management inputs.

2.3.2 | Data input for GHG estimation under potato production

Each section of the CFT related to potato production was properly fed with inputs according to specific plot conditions to get a rough estimation of CO_2, N_2O, and CH_4 emissions separately as well as total GHG emissions in terms of equivalents of carbon dioxide emissions. The year 2000 served as the baseline for land area, yield, and sales, while 1999 data were used as the baseline for chemical use due to the unavailability of chemical data for 2000. Data from 2022, provided by USDA and NASS, was the most recent included in the model. The CFT provides diverse options on agroecological conditions for users to select specific parameters that reflect their cropping systems and conditions. Since potato production in the United States occurs in very diverse environments and management practices, this review focused on data on national trends provided by the USDA. Information provided on the crop data section includes details such as crop area, harvested quantity, seed amount, and reporting year. No information was provided regarding sowing and harvesting dates. To calculate emissions from potato cultivation, the tool utilizes data on potato yields and the management of residues. It subsequently determines the nitrogen content in the residues along with the corresponding N_2O emissions. Furthermore, the tool estimates the CH_4 emissions generated by potato residues. Since soil characteristics influence GHG emissions from fields, and these vary by location and field, the CFT categorizes soil properties based on texture, organic matter, drainage, moisture, and pH. The selected soil inputs were chosen to represent typical United States potato-growing conditions. The CFT uses an exponential model to calculate N_2O emissions, accounting for soil and climate factors while incorporating both background soil emissions and those from crop residues (Bouwman et al., 2002; Stehfest & Bouwman, 2006). Agricultural inputs impact GHG emissions through fertilizer production, crop protection products, and soil-derived N_2O emissions. Different fertilizer and crop protection types entered in the tool were based on US potato production. The tool estimates emissions from the production and use of fertilizers and agrochemicals, with inputs reflecting common practices in US potato farming, as per USDA census data. The tool uses multivariable empirical models (Bouwman et al., 2002; Stehfest & Bouwman, 2006) to compute N_2O emissions from fertilizers (Richards et al., 2016). The fuel and energy section covers machinery operations like field preparation, planting, harvesting, and herbicide application, along with energy used for irrigation.

In view of these, some consistent assumptions were applied in the CFT for both the 2000 baseline and 2022. The model incorporated the following assumptions:

1. All tillage, pesticide applications, and other field operations were treated as single operations for both the baseline year and 2022.
2. All nitrogen fertilizer forms were assumed to be urea ammonium nitrate produced in North America in 2014 as the most representative nitrogen used in United States potatoes, while the phosphorus and potassium emission factors used were world production (2014) for both years, as built-in CFT. The 2014 production year was selected because those are the public emission factors available in CFT based on Fertilizer Europe data (Brentrup et al., 2018).
3. The most representative soil properties used were well-drained sandy soils with a pH range of 5.5–7.3, 1.75%

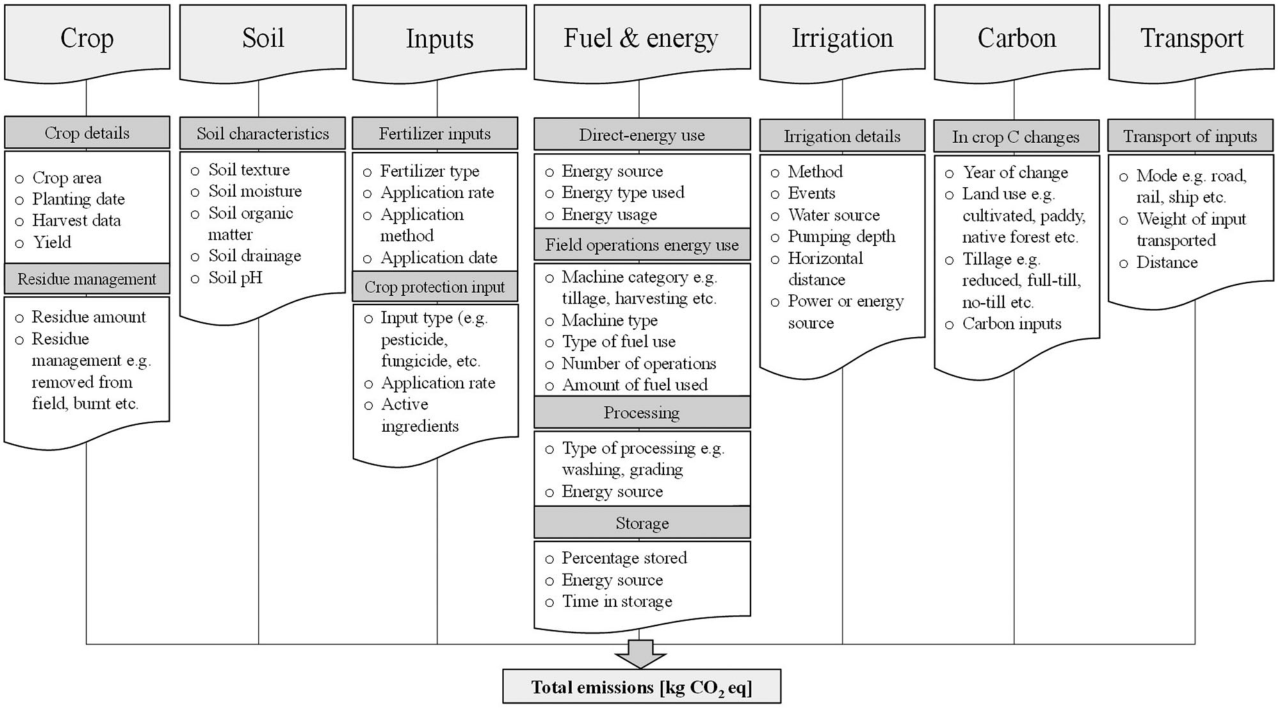

FIGURE 1 A flow chart representing how data are entered in the Cool Farm Tool (CFT) for greenhouse gas (GHG) emission estimation. The CFT model estimates emissions by accounting for all relevant sources and processes that contribute to GHG output, as shown above. This was adapted from the Cool Farm Alliance (2024) online application, CFT v2.42.0. All irrigation-related information for this review was input exclusively in the fuel and energy section, meaning no entries were made in either the designated irrigation section or the carbon and transportation categories.

organic matter, and 0.50% soil organic carbon for both years.

4. Based on USDA census data, groundwater irrigation using pressure sprinkler systems was assumed for both years' production, as this represents the most common practice. Energy consumption for irrigation was calculated using USDA census data (2001 and 2022) combined with Crop-Watch estimates of 19 gallons (0.072 m^3) of fuel per 20.32 cm of water per hectare (Klein, 2008). Since water source and irrigation method data were only available from 2012 to 2022, the predominant approach during this period (groundwater with pressure sprinklers) was applied to both years due to a lack of reliable baseline data for 2000.

3 | RESULTS

3.1 | US potato production, yield, and economic trends from 2020 to 2022

The USDA data revealed a declining trend in both planted and harvested land areas from 2000 to 2022 (Figure 2A). By the end of 2022, the planted and harvested areas had decreased by an average of 34% and 32%, respectively. In contrast, potato yields experienced an upward trend from 2003 to 2022, following an initial decline between 2000 and 2003. On average, potato yields increased by 15% by the end of 2022 relative to the baseline year (Figure 2A). While this study primarily investigates national-scale observations, we recognize the considerable variability present in state and county data, which reflects diverse climate conditions and predominant local practices.

The trends in potato product distribution in the United States market showed a reduction on average from 2000 to 2022. The trends were not consistent across the years, with some years showing a reduction and an increment for some of the product categories. Overall, when the 2022 data were compared to the 2000 data, table stock was reduced by 22%, processing (the biggest share of the market) was reduced by 34%, other uses (including seeds) were reduced by 9%, and non-sales were reduced by 49% (Figure 2B).

In contrast to the decreasing trends in various potato product distribution in the United States market, unit sales price and total production sales increased at the national level by 54% and 22%, respectively, at the end of 2022 compared to 2000 (Figure 3A,B). The trend shows that as total potato production decreased from 2000 to 2010, the sales price saw an upward trend. Similarly, an increase in total production from 2010 to 2016 saw a decrease in sales price (Figure 3A,B). The market trends analyzed in this study are limited to national data, with the understanding that local variations exist at the state and county levels.

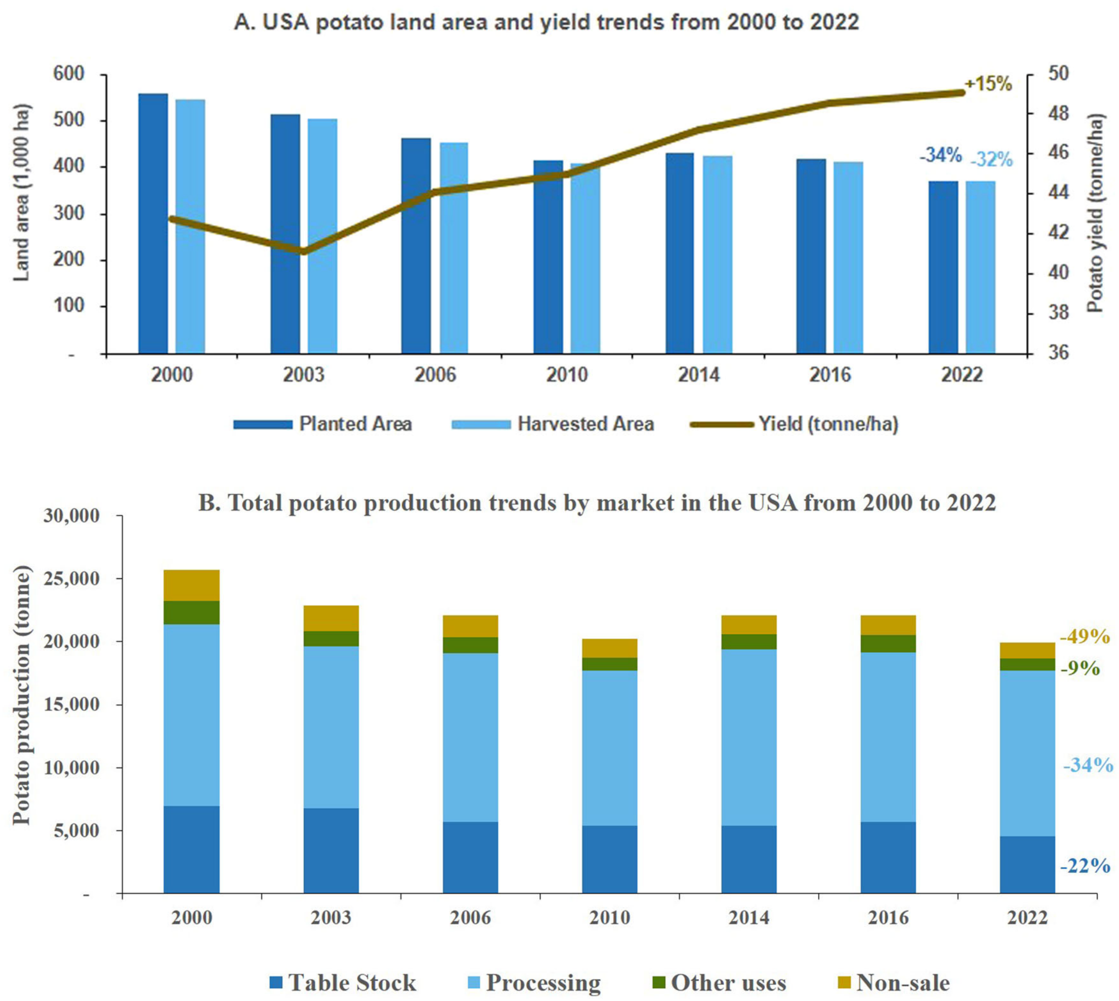

FIGURE 2 US potato production land area, yield, and production by market segments based on United States Department of Agriculture (USDA) survey data from 2000 to 2022. (A) land area and yield; (B) total potato production by market segment.

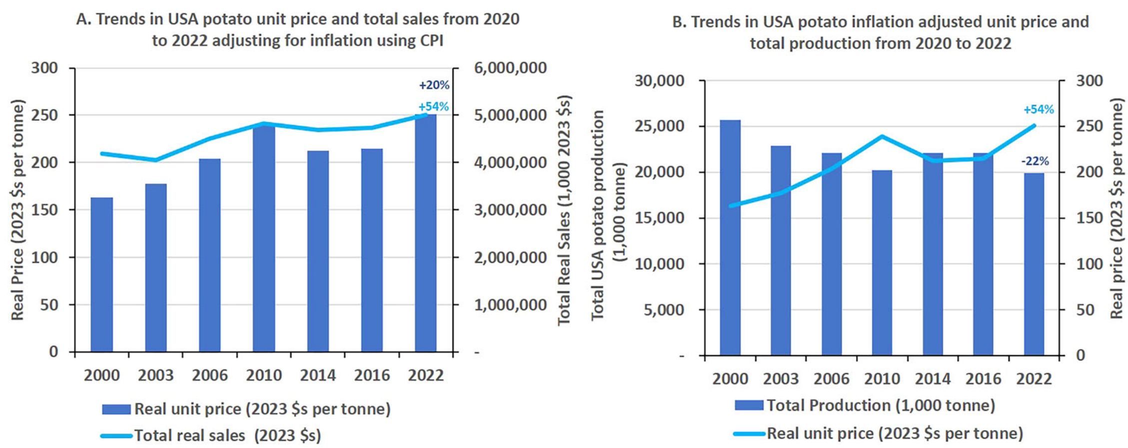

FIGURE 3 US potato production and sales trends based on CPI adjustment for United States Department of Agriculture (USDA) survey data from 2000 to 2022. (A) Unit and total production sales; (B) total potato production and unit sales.

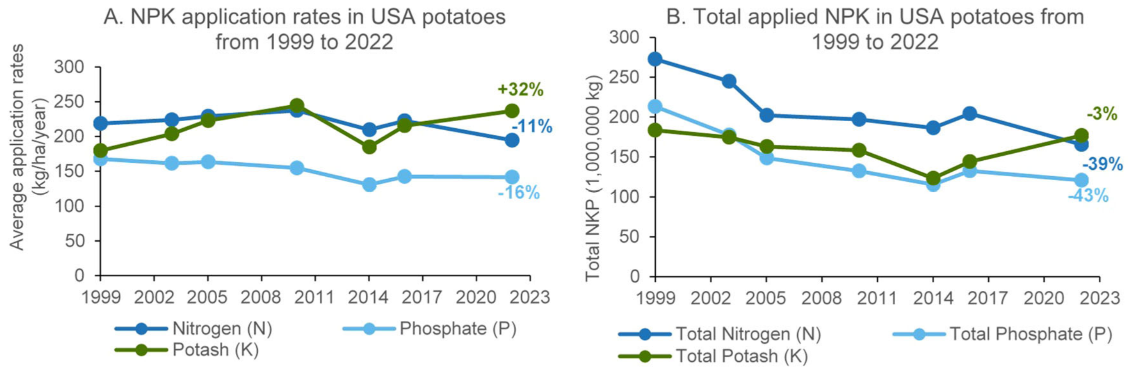

FIGURE 4 US NPK fertilizer application trends under potato production based on United States Department of Agriculture (USDA) survey data from 2000 to 2022. (A) NPK applied per hectare per year; (B) total NPK applied.

3.2 | Fertilizer (nitrogen, phosphorus, and potassium) use trends in US potato production from 1999 to 2022

Over two decades of mineral fertilizer application under potato production in the US, the rates of application of nitrogen (N) and phosphorus (P) fertilizers recorded reductions of 11% and 16%, respectively, while potassium (K) application rate increased by 32% over the period (Figure 4A). The N and K rates increased consistently from 1999 to 2010 and, thereafter, declined until 2014 before an upward trend was observed again in 2016. Phosphate fertilizer however saw a gradual decline in the rate of application from the baseline year until 2014, before a gradual increase from 2016. The total N, P, and K applied consistently decreased from 1999 to 2014 (Figure 4B). After 2014, the total K fertilizer applied increased sharply until 2022. Total N and P on the other hand increased slightly from 2014 to 2016 and thereafter decreased until 2022. On average, the total N, P and K fertilizer applied reduced at the end of 2022 relative to the baseline year at −3%, −44%, and −39%, respectively.

3.3 | Crop protection inputs use trends

Among the US crop protection input utilization under potato production, fungicide was the most applied, followed by herbicides and insecticides (Figure 5A). The average application rate trends showed that only fungicides reported an increase (+16%) at the end of 2022 compared to the baseline year. The USDA potato survey data from 1999 to 2022 also revealed that herbicide and insecticide application rates decreased by 13% and 78%, respectively. In terms of the total crop protection input, the available data show decreasing trends for all the inputs (Figure 5B). The total insecticides applied were reduced by 67% at the end of 2022. This was followed by fungicide (37%) and total herbicides declined by 16% at the end of 2022. The total fungicides recorded a sharp increase from 2010 to 2017 before a drastic reduction again to the lowest point, whereas total insecticides and herbicides had a consistent decline (Figure 5B). Note that the inputs use trends observed in this national-level data may vary at the state and county level data depending on the climate, seasonal length, and dominant practices.

3.4 | Water source and irrigation practices trends in US potato production

The irrigated area for potatoes experienced a sharp decline in 2012 and 2017 compared to 2001. Although 2022 showed a slight recovery relative to 2012 and 2017, it remained substantially lower than 2001 levels (Figure 6A). Groundwater was the primary source for potato irrigation, followed by off-farm and on-farm surface water. Groundwater usage decreased in 2017 compared to 2012 and 2022, while on-farm water sources increased during the same period (2012 and 2022). Conversely, off-farm water availability peaked in 2017, surpassing both 2012 and 2022 levels (Figure 6B). Pressurized irrigation was the most widely used method for potato crops, with sprinkler systems being the most common among these methods, as evidenced by 2012–2022 data (Figure 6C,D).

3.5 | GHG emission trends under US potato production

Estimates of the United States GHG emissions under potato production environmental footprint based on the CFT showed a total emission reduction of 39% when the current year under review (2022) was compared to the base year (2000) (Figure 7A). Similarly, carbon intensity was reduced by 20% during the same periods under review (Figure 7B). It was observed that GHG emissions and carbon intensity were reduced in all the potato production sectors during 2022. However, much of the total emission reduction came under fertilizer production and soil. The same observations were

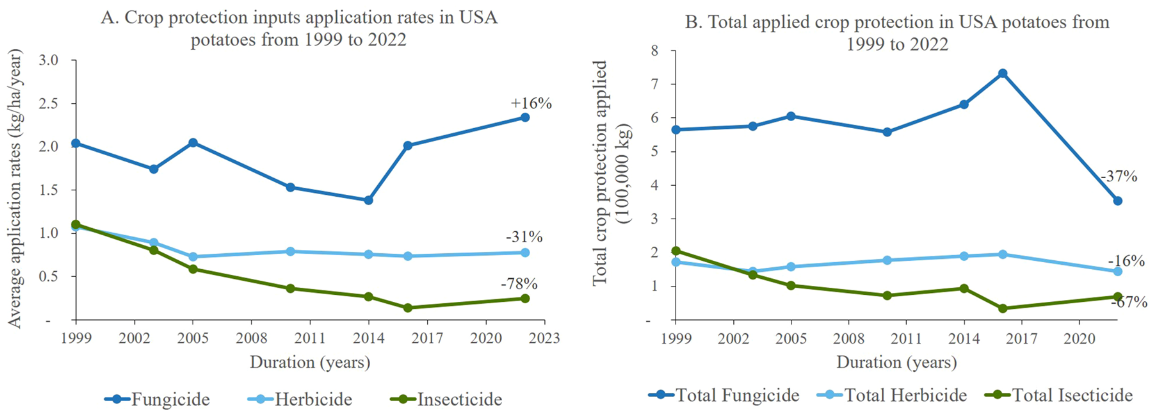

FIGURE 5 US potato production crop protection input application trends based on United States Department of Agriculture (USDA) survey data from 2000 to 2022. (A) application rate of fungicide, herbicide, and insecticide per hectare per year; (B) total applied fungicide, herbicide, and insecticide per year.

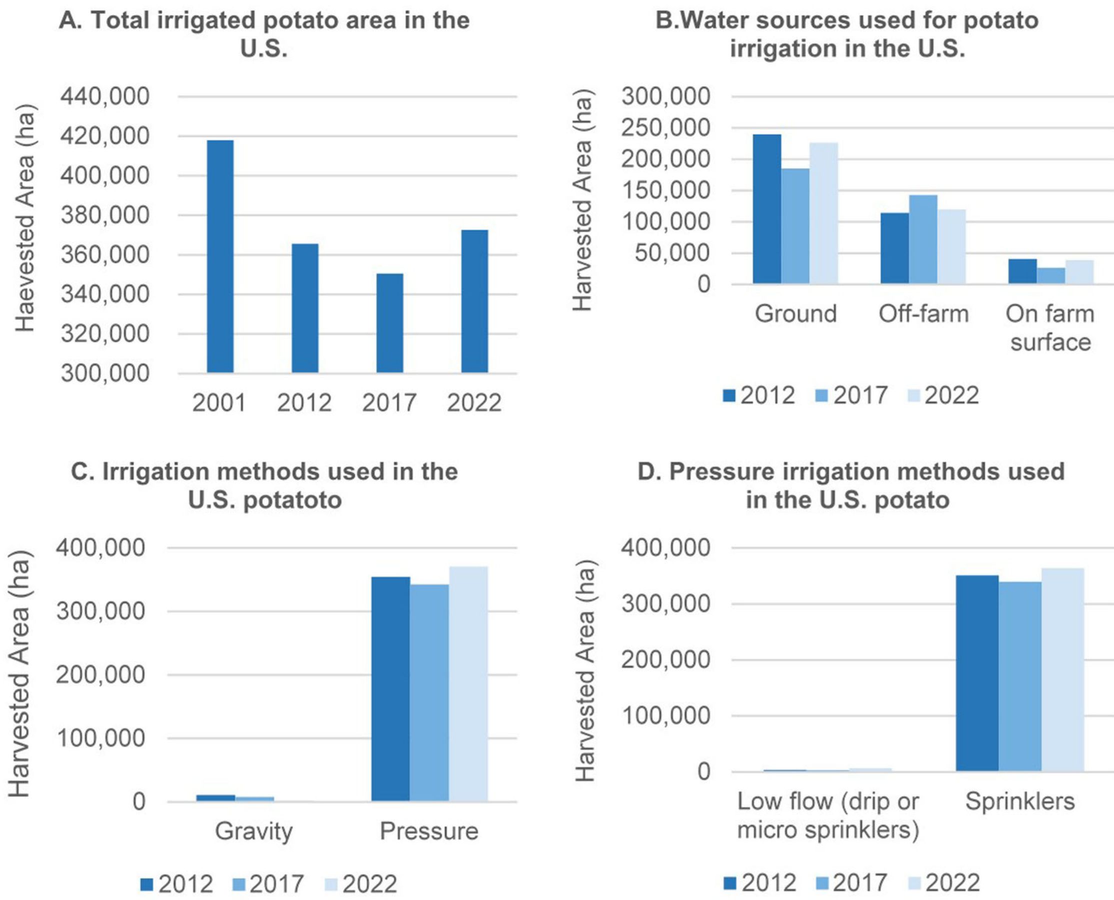

FIGURE 6 Water sources and irrigation methods used in the US potato production based on United States Department of Agriculture (USDA) census data from 2001 to 2022. (A) total irrigated potato area; (B) irrigation water sources; (C) irrigation methods; (D) pressure irrigation methods.

made for carbon intensity by yield. There was hardly any emission production under crop protection for the year under review (2022). However, there was no change in carbon intensity comparing the 2 years (2000 and 2022).

4 | DISCUSSION

The potato sector is crucial in ensuring food security in the United States and globally. The 20-year review of potato

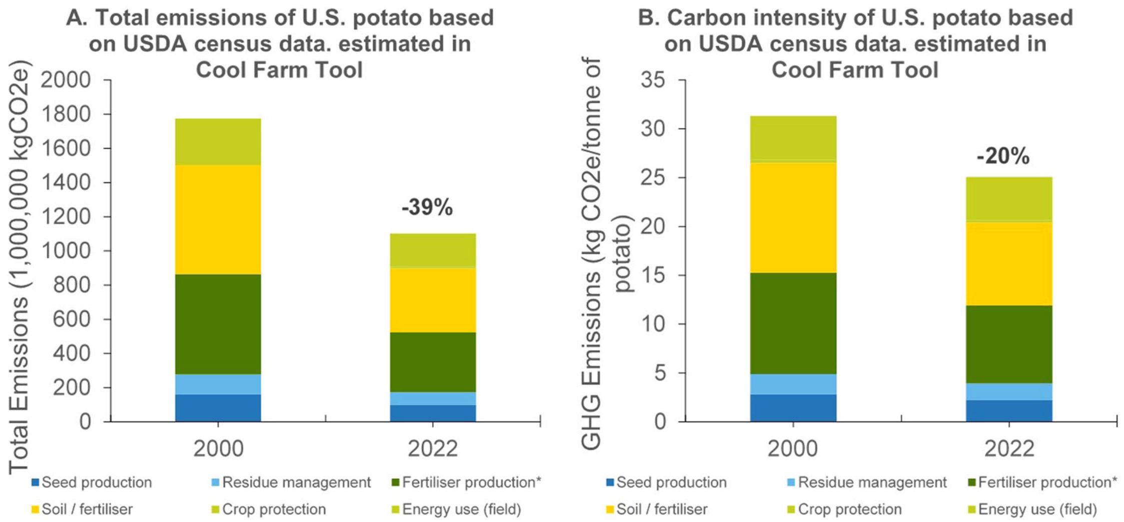

FIGURE 7 Estimates of on-farm emissions associated with US potato production based on United States Department of Agriculture (USDA) survey data from 2000 to 2022. All emission data estimates were computed in Cool Farm Tool 2.11.0. (A) total emissions from 2000 and 2022; (B) carbon intensity from 2000 and 2022. All the data for the emission estimates were based on the 1999 and 2000 data as a baseline and the 2022 most current survey data. The crop inputs data (fertilizer and crop protection) for 1999 were used as the closest proxy since 2000 potato chemical inputs data were unavailable. Other assumptions made included non-storage crops, irrigated area, and a single operation for tillage, crop protection, and fertilizer applications. Additionally, it was assumed that all nitrogen fertilizer forms were urea and ammonium nitrate produced in North America in 2014, and phosphorus and potassium world production in 2014 for both years.

production trends in the United States has provided valuable insights into total production, fertilizer use, crop protection input, and GHG emissions trends. Significant progress has been made in potato breeding and genomics, focusing on traits that enhance the crop's resilience to a changing climate. Birch et al. (2012) noted that these advancements have deepened our understanding of the key genes and mechanisms influencing potato physiology, water and nutrient use efficiency, and adaptations to biotic and abiotic stresses. These improvements have contributed to the yield increases observed in this study (Figure 1A) while reducing input requirements (Figures 4A and 5A). The productivity trends highlighted in this study, characterized by increasing yield per hectare with declining total land and input use, align with global patterns reported by Fuglie et al. (2024). This alignment underscores how agricultural productivity is driving more efficient use of natural and environmental resources in farming systems. Given that sustainable potato production remains critical for future food security and social sustainability (Devaux et al., 2020, 2021), collaboration among scientists, farmers, and stakeholders is increasingly essential to develop effective climate change mitigation and adaptation strategies (Çalışkan et al., 2023). The next section of this study examines production and sales trends, highlights key challenges, and explores the historical factors driving sustainable potato production in the United States. It also provides projections on strategies for decarbonizing the sector, positioning it as a model for the nation.

4.1 | Potato production trends and challenges in the United States

Potato yields per hectare in the United States have continued to rise despite a reduction in planted and harvested land area. According to Barrett et al. (2023), this trend aligns with a historical decline in potato production, which decreased from a peak of 1.6 million ha in 1922 to 371,000 ha in 2020. Bohl and Johnson (2010) and Barrett et al. (2023) highlighted a shift in potato production over time, in terms of growing seasons and geographical regions, moving from the eastern to the western United States. This transition led to identifying areas with more favorable environmental conditions for potato cultivation, including longer growing seasons and reduced exposure to severe weather events, which enabled higher yields per unit area. One notable advantage of the western regions was the availability of irrigation water, allowing the maintenance of soil moisture levels that support optimal potato yield and quality (Kenney, 1995; Werner, 1947).

The way potatoes are consumed has undergone significant changes since the mid-1900s (Barrett et al., 2023). Initially, potatoes were consumed almost entirely as a fresh product without processing, making production concentrated near major population centers on the East Coast (Barrett et al., 2023). Limited storage technology required harvests in both northern and southern regions to ensure consistent supply (Barrett et al., 2023). In 1960, per capita potato consumption in the United States averaged 49.1 kg (fresh weight on kilogram per person basis), with only 23% being processed forms (Barrett et al., 2023). Processed potatoes surpassed fresh ones as the primary form of consumption during the 1970s (Bohl & Johnson, 2010). By 2019, per capita consumption had risen to 54.1 kg, with processed products making up 71% of total potato consumption. In that same year, 65% of US potato production went into processing, 23% was sold fresh, and only 7% was used on-farm or lost to shrinkage and waste (Barrett et al., 2023).

A major challenge in potato production lies in achieving sustainability throughout the production process. Recently, discussions centered around sustainability have increasingly focused on soil health. A recent review highlighted several obstacles to adopting improved management practices for soil health in the northwestern United States, including the intensive tillage operations typical of potato production, limited knowledge of what constitutes healthy soils for potatoes, and the absence of standardized soil health testing methods (Barrett et al., 2023).

Another significant challenge involves the effects of climate change on potato production in the United States. Rising temperatures and increased carbon dioxide levels may have varied impacts across different regions, with colder production areas potentially benefiting from longer growing seasons and higher yield potential (Barrett et al., 2023). Zhao et al. (2022) used a model ensemble of five process-based models and one statistical model to predict the effects of climate change on fully irrigated and well-fertilized potato crops in the United States under the high-emission RCP 8.5 scenario. Their findings suggested that while increasing temperatures could reduce potato yields, this impact might be largely offset by elevated atmospheric CO_2 levels. Additionally, warming conditions could lead to an increase in new pest outbreaks in certain areas. For instance, the zebra chip disease, caused by *Candidatus Liberibacter solanacearum*, emerged in Oregon and Washington after 2011, despite the prior sporadic presence of potato psyllids, the insect vector of the disease (Crosslin et al., 2012).

4.2 | Key emissions reduction drivers in the US potato production

4.2.1 | Efficient fertilizer application rates per hectare while increasing yields

Fertilizers are a significant source of agricultural GHG emissions, stemming from their production process and field application, particularly nitrogen fertilizers (Figure 7A,B). Optimizing fertilizer use to lower application rates (Figure 4A,B) can lead to reductions in farm-level emissions, as demonstrated in this study (Figure 7A,B). This is especially effective when reducing fertilizer use does not compromise yield but instead enhances per-hectare productivity (Figure 1A). Incorporating yield into emission intensity calculations revealed a 20% reduction in GHG emissions per ton of yield, with 24% attributed to reductions in field fertilizer application and 23% from fertilizer production (Figure 7B), with nitrogen fertilizers as the primary contributor. A recent life cycle assessment of potato production by Zhang et al. (2024) showed that optimizing nitrogen application rates without overuse could yield 1.5 times the environmental benefits. It is important to note that this analysis does not include energy data from crop storage, which may result in slightly lower GHG reduction percentages than those observed in this study.

According to Jennings et al. (2020), global potato yields could increase by 10%–17% due to the benefits of climate change adaptation strategies, solidifying potatoes as a food-secure crop. In the United States, one factor linked to the yield increases observed during the study period (Figure 1A) is the rising rate of potassium fertilizer application, as supported by findings from a study on potassium application rates by Turabian et al. (2021). The consistent increase in potassium use from 2000 to 2022 may also explain the significant reductions in nitrogen application rates while maintaining higher yields. Grzebisz et al. (2020) highlighted that potassium application rates could influence the "partial factor productivity of fertilizer nitrogen" and agronomic nitrogen efficiency. This suggests that optimal potassium strategies may play a pivotal role in enhancing nitrogen productivity, enabling substantial nitrogen reductions without compromising potato yields. Grzebisz et al. (2020) further emphasized that potassium application could serve as a sustainable approach to managing nitrogen in potato production.

4.2.2 | Reduction in crop protection inputs

While crop protection inputs contribute a smaller share to overall GHG emission reductions, adopting best practices that lower their application rates still aids in reducing emissions in US potato production. Although the direct emission benefits of reduced crop protection inputs are minimal, Erekalo et al. (2024) highlighted that utilizing these inputs within a climate-smart agriculture framework through precision agriculture and integrated pest management can deliver both yield improvements and environmental benefits.

4.2.3 | The role of breeding

Birch et al. (2012) highlighted that over the past two decades, traditional breeding and advanced genomic tools have significantly enhanced our understanding of key genetic functions and mechanisms critical for improving potato development.

These advancements have led to improvements in the crop's physiology, enabling better adaptation to biotic and abiotic stresses as well as increased efficiency in resource use, such as water and nutrients. These technologies likely contributed to the observed trends of reduced fertilizer and input use in the US potato industry (Figures 4A and 5A) alongside increased yields (Figure 1A). Among the top 10 most planted varieties in 2024, about four of them (namely, Umatilla Russet, Lamoka, Caribou Russet, and Clearwater Russet) were developed within the last two decades by public breeding programs, including Cornell University, the University of Maine, and Idaho USDA-ARS. This highlights the critical role of breeding programs in driving sustained improvements in potato yield. This shows how modern tools like genomics and optimized crop nutrition can play a vital role in advancing sustainable agriculture now and in the future (Birch et al., 2012).

Zhao et al. (2022), through an ensemble model simulation of US potato production, found that rising temperatures are expected to shorten growing seasons, limiting the amount of solar radiation potatoes can utilize for photosynthesis and biomass accumulation. Their analysis also indicated that climate impacts were cultivar-specific, without fully accounting for the vast diversity of potato cultivars, which vary in development rates (ranging from very early to very late) and quality responses to elevated CO_2 levels (Loladze, 2014). The study concluded that adopting new cultivars and crop breeding strategies could serve as viable adaptation measures for future climate conditions.

4.2.4 | The role of irrigation practices

Potato is very sensitive to drought stress due to its sparse and shallow root system (Jefferies, 1993). Consequently, irrigation plays an effective role in the production of this high-yielding crop (Birch et al., 2012). In the US potato production sector, irrigation has become an integral component of the agronomic management system, and best practices are required for continued use efficiencies (Mpanga & Idowu, 2021; Mpanga et al., 2023). Irrigation in potato production significantly influences GHG emissions, primarily through energy use. The energy required for irrigation significantly impacts farm-level emissions, with the magnitude depending on the irrigation method and energy source. This review shows that the irrigated area declined sharply in 2022 compared to 2001. However, this reduction is primarily linked to the overall decrease in potato cultivation area (Figure 1A) rather than changes in irrigation practices. The decline in irrigated potato area (Figure 6A) appears to have reduced total emissions, with lower energy-related emissions observed in 2022 compared to 2000 (Figure 7A). However, due to insufficient baseline data (Figure 6B,C,D), this study could not directly link changes in irrigation practices (water sources and methods) to variations in carbon intensity.

4.3 | Toward a net-zero outlook for US potato production

The United States potato industry has made significant strides in achieving sustainability goals, including optimizing inputs (Figures 4A and 5A), increasing yields consistently over two decades (Figure 1A), and reducing emissions (Figure 7A,B). However, reaching net-zero emissions in potato production will require a multifaceted approach rather than relying on a single solution or technology. Combining innovations such as developing disease- and drought-resistant potato varieties, enhancing irrigation efficiency, adopting sound soil management practices, optimizing nutrient use, and incorporating renewable energy sources (Figure 8) can accelerate resilience and emissions reductions at scale (Reay, 2019).

A recent Breakthrough Agenda report by the Consultative Group for International Agricultural Research emphasizes that site-specific nitrogen management focusing on nitrogen use efficiency and low-emission fertilizer technology is crucial for minimizing emissions (Rusinamhodzi et al., 2024). These strategies must consider the local context, including past practices, feasibility, cost-effectiveness, and the timeline required for new technologies to become operational (Figure 8) (Basso et al., 2021). For instance, soil carbon sequestration practices like cover cropping can be implemented within 0–3 years, whereas producing greener fertilizers may take 3–15 years, and developing nitrogen-fixing microbiomes could require even longer timelines (Figure 8) (Basso et al., 2021). On the other hand, using nutrient management approaches such as low-emission technology and use efficiency could deliver a sustainable outcome compared to using only carbon sequestration practices such as cover cropping, which has limited years for claiming that benefit. Integrated approaches such as simultanously using circular and regenerative agriculture systems could be the pathway to achieving net-zero targets.

Understanding the scalability of technology limitations and associated implementation costs within a local context is crucial. For instance, while manure may be effective for decarbonizing potato production, its bulky nature and limited availability make it uneconomical to transport over long distances, posing challenges for large-scale use. In such cases, utilizing green or low-emission synthetic fertilizers may offer a more practical and scalable solution. Partnerships play a vital role in achieving these goals, as technology developers must understand the needs of farmers and raw material users, while users need to learn how to effectively utilize the technology. Collaborative approaches, as advocated by the United Nations' 17th Sustainable Development Goal, provide

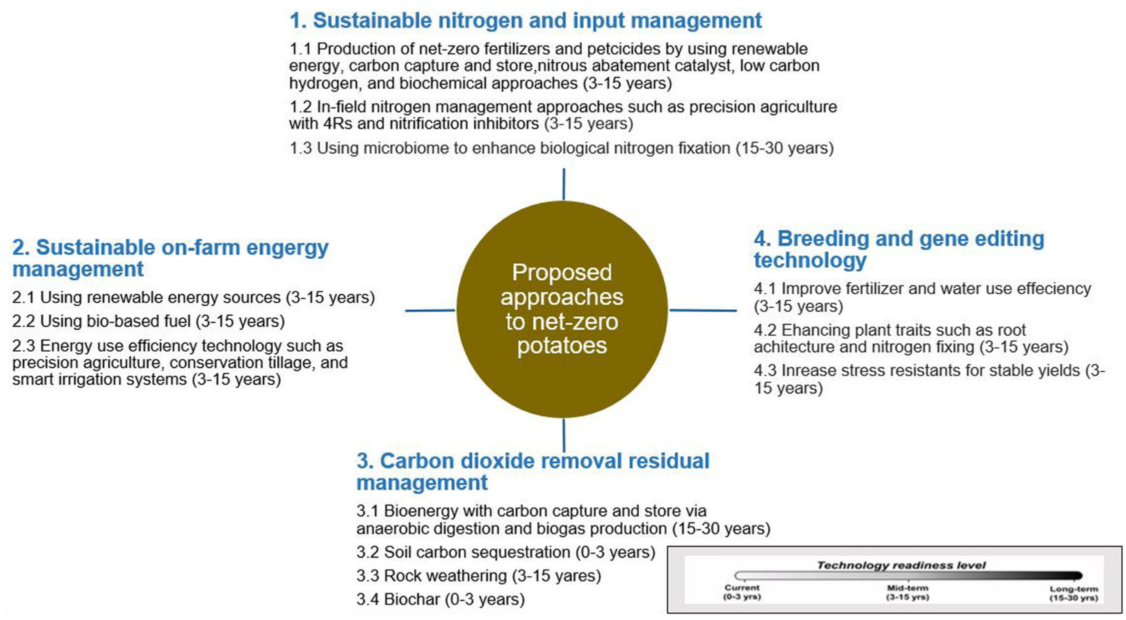

FIGURE 8 Proposed approaches and technologies for decarbonizing potato production at the farm level and a ranking on how long it takes for the technology to be ready. Adopted from Rosa and Gabrielli (2023) and technology readiness ranked based on Basso et al. (2021).

the most effective pathway for aligning these efforts (United Nations, 2024).

5 | CONCLUSION

Potato production in the United States has made remarkable progress in reducing farm input levels while consistently increasing yield per hectare over the past two decades, resulting in substantial emissions reduction benefits. This achievement comes despite a significant decline in planted and harvested potato land area, which has negatively impacted total production volumes and contributed to rising real potato prices between 2000 and 2022. To achieve net-zero emissions in potato production, our proposed integrated innovations include adopting net-zero fertilizer strategies (e.g., low-emission fertilizers), utilizing renewable energy sources, implementing carbon dioxide removal technologies, and advancing breeding techniques to enhance resource use efficiency and stress adaptation.

AUTHOR CONTRIBUTIONS

Isaac Kwadwo Mpanga: Conceptualization; data curation; formal analysis; methodology; software; writing—original draft. **Russell Tronstad**: Data curation; writing—review and editing. **Omololu John Idowu**: Methodology; writing—review and editing. **Peteh Mehdi Nkebiwe**: Conceptualization; methodology, writing—review and editing. **Eric Koomson**: Conceptualization; methodology; writing—review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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