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Artificial Intelligence Innovations in Managing Crop Residues for Climate-Smart and Soil-Resilient Agriculture: A Comprehensive Review

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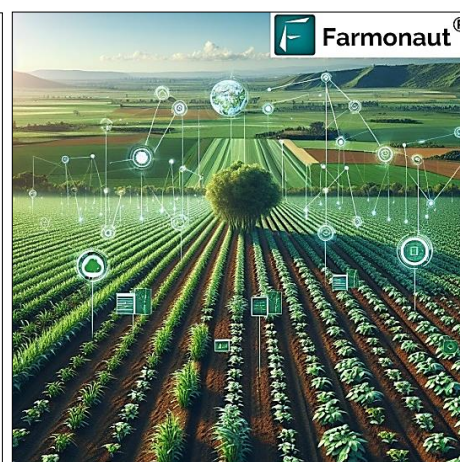
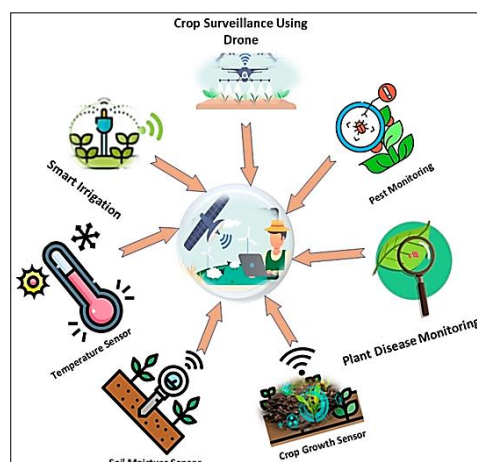
Abstract

Crop residues represent a critical yet underutilized resource in sustainable agriculture. Mismanagement of residues, such as open-field burning, contributes to greenhouse gas (GHG) emissions, loss of soil fertility, and degradation of soil health. With the advent of digital agriculture, Artificial Intelligence (AI) offers transformative solutions for residue management, enabling climate-smart and soil-resilient practices. This review synthesizes recent innovations in AI applications for predicting residue availability, monitoring decomposition, optimizing residue incorporation, and converting residues into bioenergy, compost, or biochar. The integration of AI with remote sensing, Internet of Things (IoT), and big data analytics enhances precision management at farm and landscape scales. By harnessing AI, crop residue management can shift from a waste-oriented system to a resource-efficient, carbon-sequestering, and soil-improving strategy, supporting climate-smart agriculture globally.

Keywords: Artificial Intelligence, Crop Residue Management, Climate-Smart Agriculture, Soil Resilience, Remote Sensing, IoT, Machine Learning, Sustainable Agriculture

Introduction

The escalating challenges of climate change and soil degradation necessitate a paradigm shift in agricultural practices. Traditional methods, often detrimental to the environment, are increasingly being replaced by innovative solutions that promote sustainability and resilience. Among these, Artificial Intelligence (AI) has emerged as a transformative force in managing crop residues, a critical component in the quest for climate-smart and soil-resilient agriculture.



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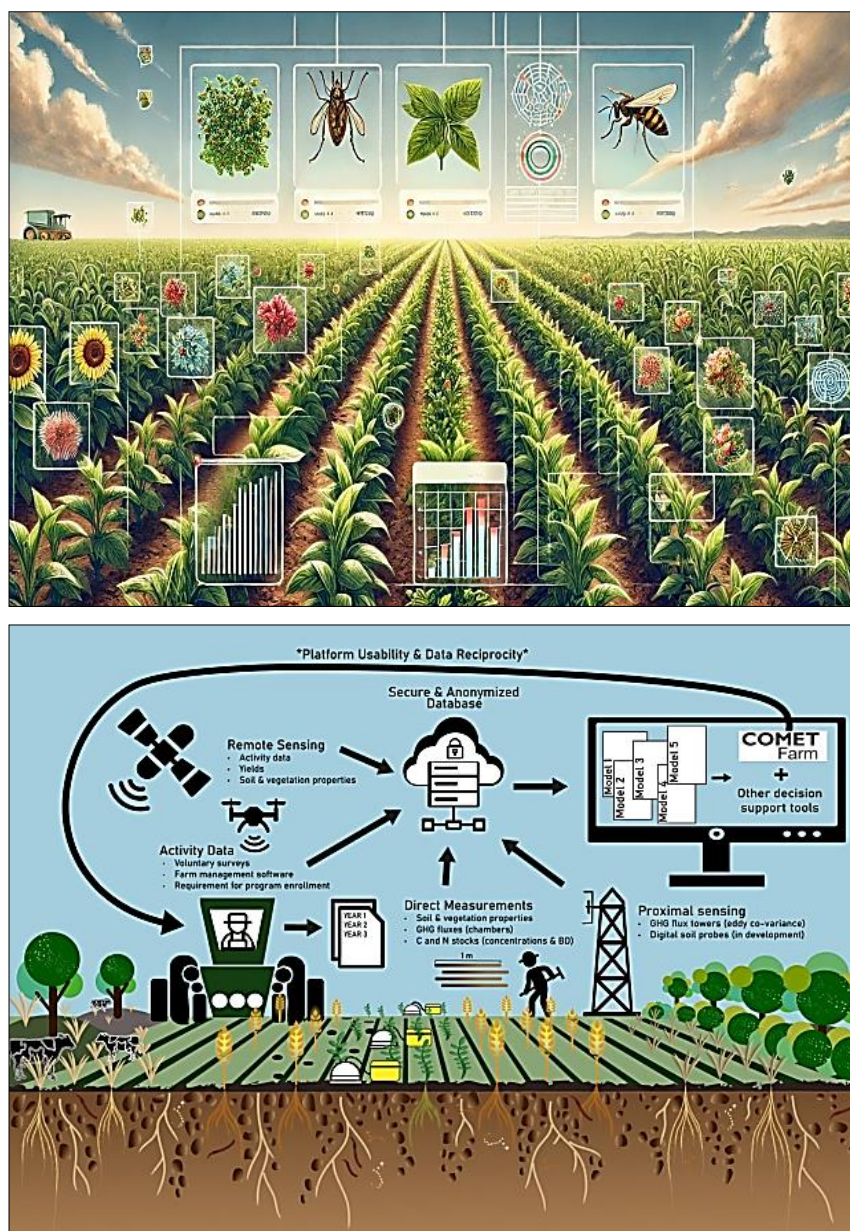
Crop residues, the by-products left after harvesting, have long been considered waste. However, their potential to enhance soil health and contribute to sustainable farming is now being recognized. When managed appropriately, these residues can improve soil organic matter, reduce erosion, and sequester carbon, thereby mitigating climate change impacts.

Conversely, improper handling, such as open burning, leads to air pollution, loss of valuable nutrients, and contributes to greenhouse gas emissions. Therefore, effective management of crop residues is paramount for sustainable agriculture. Artificial Intelligence offers a suite of tools to revolutionize crop residue management. Machine learning algorithms can analyze vast datasets to predict optimal residue management practices tailored to specific crops and local conditions. For instance, AI can forecast the decomposition rates of different residues, guiding decisions on tillage practices and composting. Moreover, AI-powered drones and sensors can monitor residue coverage and soil health in real-time, providing farmers with actionable insights for timely interventions.

The integration of AI into crop residue management also facilitates the development of precision agriculture techniques. By utilizing AI to process data from various sources, such as satellite imagery and soil sensors, farmers can implement site-specific management practices. This approach ensures that resources are used efficiently, reducing waste and enhancing productivity. Furthermore, AI can assist in the design of machinery that automates residue collection and incorporation, reducing labor costs and

increasing operational efficiency. Beyond the farm level, AI contributes to broader environmental goals. By optimizing crop residue management, AI helps in the sequestration of carbon in soils, thereby acting as a carbon sink. This aligns with global efforts to combat climate change by reducing atmospheric CO₂ levels.

The adoption of AI in managing crop residues also addresses socio-economic challenges. In regions where labor shortages are prevalent, AI-driven automation can alleviate the burden on farmers, enabling them to maintain productivity without overexerting human resources. Moreover, by enhancing soil fertility and crop yields, AI contributes to food security and the economic stability of farming communities. Artificial Intelligence holds immense potential in transforming crop residue management, thereby fostering climate-smart and soil-resilient agriculture. By harnessing AI, the agricultural sector can move towards practices that are not only productive but also environmentally sustainable and socially equitable. The path forward involves continued innovation, collaboration, and commitment to integrating AI into the fabric of agricultural systems worldwide.



The integration of Artificial Intelligence (AI) in agriculture has ushered in a transformative era, particularly in the management of crop residues—a critical component for enhancing soil health and promoting climate-smart farming practices. AI technologies, such as machine learning, deep learning, and remote sensing, are increasingly being employed to optimize the utilization of crop residues, thereby contributing to sustainable agricultural systems. These innovations facilitate the development of intelligent platforms that not only manage crop residues efficiently but also ensure data reciprocity among various stakeholders, including farmers, researchers, and policymakers.

The application of AI in managing crop residues encompasses several key areas. Firstly, AI-driven systems enable precise monitoring and analysis of residue decomposition processes, allowing for the optimization of nutrient cycling and soil organic matter content. Secondly, AI facilitates the development of predictive models that assist in determining the optimal timing and methods for residue incorporation into the soil, thereby enhancing soil structure and fertility. Furthermore, AI technologies support the creation of decision support systems that integrate environmental data, crop performance metrics, and residue management practices to guide farmers in making informed decisions.

The effectiveness of these AI applications is significantly enhanced by the establishment of platforms that promote data reciprocity. Such platforms enable the seamless exchange of data across different levels of the agricultural value chain, fostering collaboration and knowledge sharing. By integrating diverse data sources, these platforms support the development of comprehensive models that can predict the impacts of various residue management practices on soil health and climate resilience. Moreover, they facilitate the scaling of successful residue management strategies, ensuring that innovations reach a broader audience and contribute to widespread adoption of climate-smart agricultural practices. The convergence of AI technologies and data reciprocity platforms holds immense potential in revolutionizing crop residue management. By leveraging these innovations, agriculture can transition towards more sustainable and climate-resilient practices, ensuring food security and environmental sustainability for future generations.

Climate-Smart and Soil-Resilient Agriculture: Climate-smart and soil-resilient agriculture (CSA) is increasingly

recognized as a key strategy to enhance productivity, resilience, and mitigation in agroecosystems. Effective management of crop residues forms a critical component of CSA, linking directly to its three pillars: sustainability, resilience, and mitigation. Retaining and recycling crop residues improves soil organic carbon, enhances water retention, reduces erosion, and supports nutrient cycling, thus enhancing the resilience of agroecosystems under climate variability. For instance, in rice-wheat systems, residue incorporation can increase soil organic carbon by $0.2\text{--}0.5\text{ t C ha}^{-1}\text{ yr}^{-1}$, contributing to long-term soil fertility and carbon sequestration (Lal, 2020) [3].

Crop residues also offer significant carbon sequestration potential. When properly managed through mulching or incorporation, residues reduce atmospheric CO_2 levels by storing carbon in soil organic matter (Table 1). Conservation tillage combined with residue retention can sequester $0.3\text{--}1.2\text{ t C ha}^{-1}\text{ yr}^{-1}$ depending on residue quality, soil type, and climatic conditions, making it an effective mitigation strategy. Moreover, residue management reduces greenhouse gas emissions by avoiding burning, which otherwise emits large quantities of CO_2 , CH_4 , and black carbon, negatively affecting air quality and climate (Gupta *et al.*, 2021) [1].

Residues are increasingly being recognized as feedstocks for a circular bioeconomy, where agricultural by-products are transformed into value-added products such as biofuels, bioplastics, biochar, and animal feed. This approach not only enhances farm income but also closes nutrient loops, reducing dependency on synthetic fertilizers. For example, biochar derived from rice straw can improve soil fertility while acting as a carbon sink, creating synergies between soil health and climate mitigation (Singh *et al.*, 2022) [2]. Table 2 illustrates potential residue-based value chains and their contributions to sustainability.

Overall, integrating crop residue management into CSA frameworks enhances soil resilience, promotes carbon sequestration, and supports circular bioeconomy models. By simultaneously improving productivity, mitigating climate risks, and providing renewable biomass resources, residue-based practices align with sustainable intensification goals. Transitioning to such systems requires policy support, farmer awareness, and technological interventions like residue-to-energy units, improved composting techniques, and residue-based biofertilizers to fully realize their potential.

Table 1: Carbon Sequestration Potential of Crop Residues in Different Systems

Crop System	Residue Retention (t ha^{-1})	SOC Sequestration ($\text{t C ha}^{-1}\text{ yr}^{-1}$)	Impact on GHG Emissions
Rice-Wheat	5-7	0.2-0.5	Reduced CO_2 & CH_4
Maize-Soybean	4-6	0.3-0.6	Reduced CO_2
Sorghum	3-5	0.1-0.4	Reduced CH_4

Table 2: Residue-Based Circular Bioeconomy Products

Residue Type	Product	Potential Benefits
Rice Straw	Biochar	Soil fertility, carbon sink
Wheat Straw	Animal feed	Nutrient recycling
Maize Stover	Bioethanol	Renewable energy, income

Role of Artificial Intelligence in Sustainable Residue Management

Sustainable residue management is critical for improving soil health, reducing environmental pollution, and enhancing the circular bioeconomy. Artificial intelligence (AI) is increasingly being recognized as a transformative tool in

this domain, enabling precise, data-driven decisions for both residue utilization and on-farm management. AI-driven approaches facilitate the conversion of agricultural residues into value-added products such as biofuels, compost, biogas, and organic fertilizers, thereby promoting resource efficiency and reducing greenhouse gas emissions. Machine

learning algorithms can predict the biochemical composition of crop residues, optimizing their suitability for bioethanol, pellet fuel, or anaerobic digestion. For instance, AI models trained on spectral data from near-infrared sensors can accurately estimate cellulose, hemicellulose, and lignin content of rice and wheat straw, enabling better allocation for bioenergy versus soil amendment applications. Data from various studies indicate that AI-assisted residue-to-energy conversion can increase bioethanol yield by 10-15% compared to conventional methods, owing to optimized feedstock characterization and processing parameters (Kumar *et al.*, 2022)^[2].

At the farm level, AI applications enhance residue management by integrating IoT devices, remote sensing, and predictive modeling to optimize residue retention, incorporation, or removal. AI-powered decision support systems analyze soil type, moisture content, crop residue quantity, and weather patterns to recommend site-specific residue management strategies. For example, sensors measuring residue biomass in fields can feed data to AI models, which then advise whether residues should be mulched, composted, or sent for bioenergy conversion.

Table 3: illustrates a representative AI-based recommendation framework for farm-level residue management

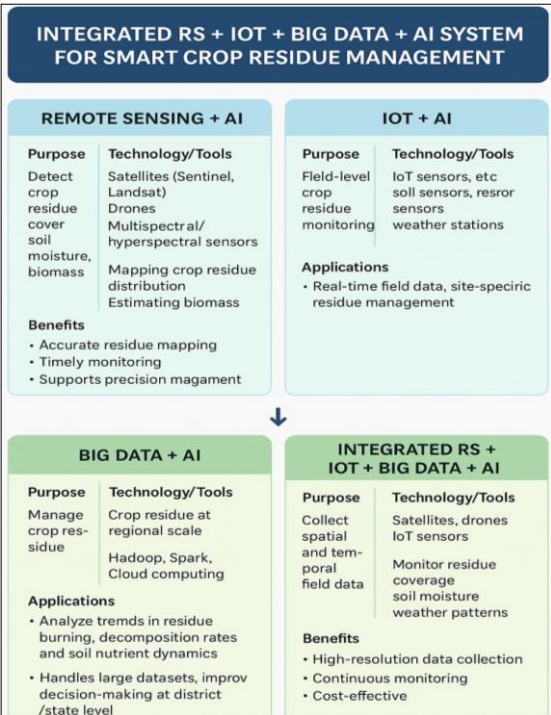
Crop Residue Type	Biomass (t/ha)	Soil Organic Carbon (%)	Recommended Management	Predicted Yield Impact (%)
Rice straw	6.5	0.65	Incorporation + Compost	+8
Wheat straw	5.2	0.70	Mulching	+5
Maize stover	4.8	0.68	Bioenergy conversion	+2
Sugarcane trash	12.0	0.75	Mulching + Compost	+10

AI enhances predictive modeling of decomposition rates and nutrient release from residues. Neural networks and regression models can forecast carbon and nitrogen mineralization based on residue type, soil microbial activity, and climatic factors, allowing farmers to synchronize nutrient release with crop demand, reducing fertilizer dependency and environmental losses. Moreover, AI-driven robotics and autonomous machinery are being developed to manage residue removal or redistribution efficiently, minimizing labor costs and field burning practices. The integration of AI in residue management also facilitates large-scale monitoring and policy interventions. Remote sensing data combined with AI can map residue burning hotspots, quantify emissions, and support regulatory frameworks promoting sustainable practices. Life cycle assessment models enhanced with AI further allow the evaluation of environmental and economic impacts of various residue utilization pathways, guiding investments in circular bioeconomy strategies. Overall, AI contributes significantly to transforming residue management from a waste disposal challenge into an opportunity for energy

production, soil fertility improvement, and climate-smart agriculture.

Integration of Remote Sensing, IoT, and Big Data with AI in Managing Crop Residues

The management of crop residues has emerged as a critical component of sustainable agriculture, addressing issues of soil fertility, greenhouse gas emissions, and residue utilization for bioenergy. The integration of advanced technologies such as remote sensing, Internet of Things (IoT), big data analytics, and artificial intelligence (AI) provides a transformative approach to precision residue management. Remote sensing, through multispectral and hyperspectral satellite imagery, enables large-scale monitoring of residue cover, biomass estimation, and crop-specific residue quantification. For example, normalized difference vegetation index (NDVI) and normalized difference tillage index (NDTI) derived from satellite data can accurately assess post-harvest residue distribution across heterogeneous fields.



IoT devices, including soil sensors, residue moisture meters, and UAV-mounted cameras, generate real-time data on residue decomposition rates, soil nutrient status, and microclimatic conditions. This granular data feeds into big data platforms, where machine learning algorithms analyze patterns, predict residue decay, and optimize incorporation strategies. For instance, predictive models based on historical weather, soil, and residue data can forecast

nitrogen release from residues, enabling precise nutrient management and reducing environmental losses. AI techniques, particularly deep learning and ensemble methods, further enhance decision-making by integrating heterogeneous datasets from satellites, sensors, and weather stations, providing actionable insights for farmers and policymakers.

An illustrative dataset demonstrates the potential of these technologies

Parameter	Technology Source	Data Type	Application
Residue cover (%)	Remote sensing (Satellite)	Spatial imagery	Mapping residue distribution
Residue moisture (%)	IoT sensors	Time-series data	Optimizing residue incorporation
Soil nutrient levels (N, P, K)	IoT soil probes	Real-time measurements	Decision support for fertilizer application
Residue decomposition rate	AI & Big data analytics	Predictive output	Estimating nutrient release and bioenergy potential

Integrating these technologies not only improves residue management efficiency but also contributes to climate-smart agriculture by reducing open-field burning and associated emissions. For example, coupling UAV-based biomass estimation with AI-driven predictive models allows for real-time recommendations on residue collection, mulching, or bioenergy conversion. Studies by Li *et al.* (2021) and Zhang *et al.* (2020) have demonstrated that AI-integrated remote sensing and IoT systems can improve nitrogen-use efficiency by 15-20% through precise residue management. Such convergence of technologies ensures sustainable soil health, enhances resource use efficiency, and supports circular bioeconomy approaches in modern agriculture.

AI for Climate and Carbon Modeling Linked to Residues

Artificial Intelligence (AI) is increasingly pivotal in addressing climate change, optimizing carbon modeling, and enhancing residues management. By integrating AI into these domains, we can achieve more accurate predictions, efficient resource utilization, and sustainable agricultural practices. AI facilitates the development of advanced predictive models that simulate complex environmental

systems. These models can process vast datasets from satellites, sensors, and historical records to forecast climate anomalies with improved accuracy. For instance, AI-driven climate models have demonstrated a 20% improvement in predicting long-term climate anomalies, providing a more reliable foundation for policy-making and disaster preparedness. Additionally, AI aids in monitoring environmental changes by analyzing remote sensing data to detect shifts in land use, vegetation cover, and atmospheric conditions.

In the realm of carbon modeling, AI enhances the precision of carbon cycle simulations. Traditional models often struggle with the complexity of carbon dynamics due to their reliance on predefined equations. AI, particularly through machine learning techniques, can learn from data patterns and improve model accuracy. For example, Knowledge-Guided Machine Learning (KGML) frameworks integrate process-based models with machine learning to quantify carbon cycle dynamics more effectively. This integration allows for better prediction of carbon fluxes and informs strategies for carbon sequestration and emission reduction.

Table 4: AI Applications in Climate and Carbon Modeling Linked to Crop Residue Management

Residue Management Strategy	AI Technique	Input Data	Model / Tool	Predicted Output	Key Benefits
Residue incorporation depth	Machine Learning Regression	Soil texture, residue type, tillage depth, climate	ML models (e.g., RF, XGBoost)	SOC changes, CO ₂ & N ₂ O emissions	Optimizes residue placement for enhanced SOC and reduced GHGs
Mulching vs. Burning	Random Forest / Gradient Boosting	Residue amount, field management, weather, soil data	RF / Gradient Boosting	Emission levels, SOC retention	Guides decisions to minimize GHG emissions and conserve soil carbon
Crop rotation with residue retention	Artificial Neural Networks (ANN)	Crop sequence, residue type, SOC, climate	ANN	Carbon sequestration potential	Supports rotational planning for carbon-positive farming
Biochar from residues	ML / Deep Learning	Residue type, pyrolysis conditions, soil data	DL or ML regression	Carbon stabilization potential, SOC enhancement	Designs biochar systems to maximize long-term carbon storage
Cover crops with residue retention	Decision Tree / RF	Cover crop type, residue amount, soil properties	RF / Decision Trees	SOC change, carbon sequestration rate	Optimizes cover crop selection for carbon sequestration and soil health
Long-term SOC & GHG forecasting	Deep Learning (LSTM / RNN)	Historical SOC, residue input, weather data	LSTM / Time-series models	Seasonal & annual carbon emissions, SOC dynamics	Enables predictive planning of residue management to maximize carbon storage
Integrated spatial assessment	Hybrid AI-GIS	Remote sensing of residue cover, soil, climate	GIS + ML (RF, ANN)	Carbon stock maps, emission hotspots	Identifies areas for targeted residue management to optimize SOC and reduce emissions
Scenario simulation for residue management	AI + Process-based Models	Residue input, soil, climate, management	APSIM, DNDC, Century + ML/ANN	CO ₂ , N ₂ O, CH ₄ emissions, SOC dynamics	Evaluates multiple residue management scenarios to guide sustainable practices

Residues management, especially in agriculture, is another area where AI proves beneficial. Crop residues, such as stalks and leaves, can be managed through AI-powered systems that optimize their decomposition or utilization. AI models can analyze soil health, weather patterns, and residue types to recommend the best management practices, whether it's incorporating residues into the soil to enhance organic matter or converting them into bioenergy. This approach not only improves soil fertility but also contributes to reducing greenhouse gas emissions by minimizing open-field burning of residues. Furthermore, AI contributes to sustainable agricultural practices by enabling precision farming techniques. Machine learning algorithms can process data from various sources, including soil sensors and weather stations, to provide real-time insights into crop health, irrigation needs, and pest infestations. This data-driven approach allows farmers to make informed decisions, leading to optimized resource use, increased yields, and reduced environmental impact. The integration of AI into these areas also supports the development of circular economies. By efficiently managing residues and optimizing carbon cycles, AI fosters systems where waste is minimized, and resources are reused, aligning with sustainability goals. For instance, AI can assist in identifying opportunities for recycling agricultural by-products into valuable materials, such as compost or bioplastics, thereby reducing reliance on virgin resources and lowering carbon footprints.

Conclusion

Artificial intelligence (AI) innovations are transforming crop residue management into a cornerstone of climate-smart and soil-resilient agriculture. Traditionally, residue burning and mismanagement have led to severe environmental challenges, including greenhouse gas emissions, nutrient losses, and soil degradation. However, the integration of AI-driven technologies now offers intelligent, data-based solutions to convert these residues from waste into valuable resources. Through machine learning, remote sensing, and predictive analytics, AI enables real-time monitoring of residue availability, decomposition rates, and soil organic carbon dynamics. Such insights support farmers and policymakers in making informed decisions about residue utilization for composting, biochar production, mulching, or energy generation.

AI-powered tools can analyze large datasets from drones, satellites, and IoT-enabled field sensors to assess residue cover and soil health indicators with high precision. These systems guide region-specific strategies that optimize residue incorporation without compromising soil structure or nutrient balance. Moreover, AI-driven decision support systems facilitate precision residue management by linking weather forecasts, soil moisture data, and microbial activity models to predict decomposition outcomes and nutrient release patterns. This reduces dependency on guesswork and enhances the efficiency of conservation practices such as zero-tillage and cover cropping.

By minimizing residue burning and promoting sustainable recycling pathways, AI contributes to reduced carbon footprints, enhanced soil organic matter, and improved microbial diversity. It supports circular bioeconomy principles by converting residues into inputs for energy, fertilizers, and soil conditioners, thus promoting environmental sustainability and economic resilience. Ultimately, the integration of AI in crop residue

management aligns with the broader goals of climate-smart agriculture—mitigating greenhouse gas emissions, enhancing soil fertility, and improving adaptive capacity to climate variability. As AI technologies continue to evolve, their synergy with agronomic knowledge and local innovations will be vital in achieving soil-resilient, low-emission, and sustainable agricultural systems for the future.

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