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Content

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The Critical Role of Soil Health in Food Safety

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Soil health is a foundational block of food safety, directly influencing the quality and safety of the crops we consume and supply to other food products. As concerns over soil degradation and contamination grow due to inputs for commercial scale crop production and other non-farm sources of GHG, the importance of regulating soil health to ensure food safety has become undeniable. International standards like ISO 14055-:2017 and the Codex Alimentarius were established to address these rising concerns, providing guidance for soil and land management and food safety practices. The ISO 14055-1:2017 standard provides a framework for combatting soil degradation, desertification, emphasizing the importance of maintaining healthy soil ecosystems to ensure long-term productivity and food safety. It highlights how good soil management practices are essential for sustainable agricultural systems that directly impact the quality and safety of food supply (International Organization for Standardization, 2017). Similarly, the Codex Alimentarius sets minimum global standards for food safety, incorporating practices related to soil management to prevent contamination of crops from harmful pollutants (World Wildlife Fund, 2023). Both guidelines reflect the increasing recognition of soil health's impact on food safety. Beyond the well-known risks to consumers, unmanaged soil health poses far-reaching negative consequences for every stakeholder in the food production value chain. It degrades crop quality and reduces yields for farmers, while agribusinesses and food processors face higher operational costs due to inconsistent supply, increased contamination risks and regulatory induced product recalls. Retailers run the risk of jeopardizing the brand and additional financial risks.

Soil health plays a critical role in food safety by directly affecting the quality of crops and their resistance to contamination. Food retailers and manufacturers are increasingly emphasizing soil health as part of their sustainability and quality assurance initiatives. Companies like Walmart, Nestlé, and General Mills are now seeking detailed soil data from their suppliers. For example, Nestlé's commitment to regenerative agriculture includes tracking soil health and enhancing carbon sequestration, both of which rely on sophisticated, real-time soil monitoring and data accessibility (Nestlé USA, 2024). Additionally, the CPC system at GIC Group is used to remotely track soil carbon sequestration, allowing farmers to adopt sustainable practices that reduce greenhouse gas emissions and improve soil quality, both of which are critical for healthier crop production and a safer food supply chain.

This growing focus on sustainable agriculture and food safety within the supply chain reflects a broader industry trend toward improving soil health, and GAP (good agricultural practices) practices. There is now a convergence of consumer environmental preferences and private sector recognition that green markets are growth markets, serving as the demand drivers precise data collection, efficient analysis, and secure data storage. The potential for these monitoring technologies to further improve food safety is undeniable. Adopting these innovative systems is vital for a safe and sustainable agricultural future.

Technological Advancement in Soil Health Monitoring

Technology-driven soil monitoring builds upon traditional soil monitoring by leveraging technologies to improve the efficiency of soil data collection, accuracy of data analysis and security of data storage. In ”precision agriculture, satellite sensor systems, drones, soil robots and data analytics all figure into SOC (soil organic carbon) analytics and maximization of GHG sequestration potential Then the massive amount of data collected are stored on blockchain to ensure transparency and traceability in farming. To generate insights that help optimize crop health and soil management, AI and big data analytics are also being used.

At the data collection stage, agriculture sensors and unmanned aerial vehicles (UAVs) are widely used. Agriculture sensors are planted in fields to collect important data like moisture levels, salinity, pH, and nutrient concentrations like nitrogen, phosphorus and potassium (NPK). These parameters support USDA developed guidance like GAP focusing on on-farm production and post-production process aimed at ensuring food safety. For example, close monitoring of soil conditions like moisture and nutrient levels helps farmers optimize their use of fertilizers and prevent excessive runoff, while soil pH and salinity data assist in managing manure applications, both of which align with GAP’s focus on reducing food safety risks through resource management. By ensuring proper field sanitation and tracking soil health through these sensors, farmers can maintain the safety and stability of the supply of food production systems.

UAVs, when used in combination with agriculture sensors, can scan fields to generate detailed soil maps, depicting parameters undetectable by human eyes. These drones extend coverage to areas that are difficult or impossible to access by ground-based methods, improving the coverage of soil mapping and analysis. A more comprehensive understanding of the soil’s current state enables farmers to plan for future use and ensure the most optimal management practices for the soil and continued food security. For example, drones equipped with gamma-ray spectrometers can measure radionuclide concentrations in the soil, detecting contaminants like heavy metals (Koomans, Limburg, & van der Veeke, 2022). This reduces the risk of crop contamination, which could otherwise impact downstream stakeholders in the food value chain.

In practice, a seasoned strawberry farmer in California implemented wireless soil sensors alongside drones to obtain real-time data on soil moisture, water levels, and climate conditions. This technology allowed the farmer to prevent dry soil from affecting strawberry yields and make informed decisions regarding resource management (Onset, 2024). By using these technologies, the farmer optimized irrigation. By using such technologies, the farmer optimized irrigation and ensured soil conditions were suitable for stable high-quality strawberry productions, demonstrating how real-time soil monitoring enhances food safety by preventing contamination risks and improving crop health.

To effectively ensure the safety and sustainability of the food production system, the use of soil sensors and UAVS must be seen as critical tools for both farmers and stakeholders along the food value chain. Without timely and sufficient collection of soil data, farmers risk overlooking soil contamination, delaying disease detection, and being unaware of nutrient imbalances. These issues can lead to contaminated crops, reduced yields, and increased dependence on pesticides or chemicals to address problems that could have been mitigated earlier. By leveraging real-time monitoring and precise soil management tools sensors and UAVs, stakeholders across the entire value chain can mitigate risks, ensuring a more resilient, safe and traceable food supply system.

The Power of AI and Big Data in Soil Health Analysis

Given the need for real-time monitoring and the complexity of data collected by advanced technologies, AI techniques like machine learning (ML) and deep learning (DL) are increasingly used to process complex datasets and build predictive models in soil analysis (Awais et al., 2023). AI can also help overcome challenges in traditional soil sample analysis, improving the accuracy of contaminant detection. Yadav et al. (2023) pointed out that traditional heavy metal detection methods, such as Laser Induced Breakdown Spectroscopy (LIBS) for bulk soil samples, often suffer from low accuracy due to the non-homogeneity of soil samples. The presence of other elements or compounds can interfere with the detection of heavy metals. Additionally, these methods also require expensive equipment and high-purity gases, making them less accessible for large-scale analysis. However, AI algorithms help address these challenges. For example, genetic algorithms coupled with back-propagation neural networks (GA-BPNN) can provide more accurate readings of heavy metals like mercury (Hg) in non-homogeneous soil samples, overcoming the precision limitations of traditional methods. Additionally, AI algorithms like support vector machines (SVM), multilayer perceptron (MLP), and extreme learning machines (ELM) can process vast datasets, enabling quicker and more efficient analysis across large areas (Yadav et al., 2023). In agriculture, companies like Taranis and Blue River Technology use AI-power drones to monitor crops and potential issues early on, leading to a 7.5% increase in crop yield and an 80% reduction in herbicide usage (Vujovic, 2023). This not only benefits farmers but also creates ripples throughout the food value chain. By enabling early detection of potential hazards in soil, AI systems help maintaining food safety by preventing contaminated soil from affecting crop health.

The benefits of AI extend beyond the farm to the entire food production value chain. While farmers utilize AI for predictive insights into soil conditions, CPG (consumer packaged goods) manufacturers and agribusinesses leverage AI to optimize operations and ensure food safety. For example, PepsiCo uses AI-driven demand forecasting to enhance operational efficiency, reducing out-of-stock situations by 10% (Singh, 2023). Similarly, Nestle has implemented AI-powered systems that streamline production processes, reducing waste by 15% and increasing efficiency by 60%. More importantly, these systems ensure food safety by automatically identifying contamination risks early in the production cycle (Vujovic, 2023). Furthermore, IBM Food Trust has saved an estimated $150 billion annually in food waste by utilizing AI-based tracking systems to monitor product waste, loss, and contamination issues throughout the supply chain. These examples underscore AI's critical role in safeguarding food safety across the entire value chain, enabling faster, more accurate responses to potential risks.

Blockchain and Cloud Storage in Soil Data Storage

While AI and sensor technologies collect and analyze critical soil data, traditional storage methods struggle to meet the demands of modern agriculture. Issues like limited storage capacity, cost inefficiency, and privacy concerns hinder the handling of large datasets in real time. To address these challenges, blockchain technology, combined with cloud storage, offers a tamper-proof, decentralized system for secure data storage. For example, TE-FOOD, a blockchain-based food traceability system, has successfully implemented blockchain technology to track agricultural products from farm to table, ensuring transparency and traceability across the food supply chain. While initially designed for food traceability, TE-FOOD's model also enhances soil health monitoring by tracking farming practices such as fertilizer and pesticide use. This helps ensure that soil health remains optimal, contributing to both food safety and environmental sustainability. Blockchain and cloud storage play a critical role in ensuring the accuracy of data related to critical control points, such as soil contaminant levels and pesticide usage, preventing potential foodborne illnesses before products reach consumers.

Walmart's sustainability index underscores the growing importance of transparent and traceable data collection systems across the entire value chain. By requiring its suppliers to report environmental metrics like greenhouse gas emissions and water consumption, Walmart emphasizes the need for real-time, reliable data to drive a more sustainable and transparent supply chain. This need for transparency is also reflected in international regulations like the Codex Alimentarius, which mandates traceability throughout all stages of food production, processing, and distribution. Similarly, the Food Safety Modernization Act (FSMA) from the FDA introduces stringent requirements for maintaining detailed records of critical tracking events (CTEs) and key data elements (KDEs), ensuring food safety at every step (U.S. Food and Drug Administration, 2024). Blockchain and cloud storage are essential technologies for meeting these demands, providing secure data that help in generating suggestions and next-step plan for food safety.

For farmers and agribusinesses, the ability to record and share soil metrics using blockchain enhances their credibility, as they can ensure that data shared with stakeholders, such as retailers and consumers remains verifiable and secure. With the advent of CPC futures, combining crop and carbon valuations, grower premiums for GAP practices also incentivizes quality and safe produce. CPC and other softwares provide CPG manufactures with the data they need to reliably meet both sustainability and safety standards. Additionally, regulators benefit from real-time access to data for audits and compliance checks, streamlining the monitoring process across the value chain. This level of traceability is critical for maintaining food safety and meeting both regulatory and retailer standards for sustainable practices.

In conclusion, if soil health is not properly managed, food safety is significantly compromised, as contaminated or depleted soil can lead to the growth of unhealthy crops, introducing harmful elements such as heavy metals, pesticides, or pathogens into the food supply. This poses direct risks to consumers and increases the likelihood of foodborne illnesses, product recalls, and reputational damage across the value chain. Therefore, adopting technologies depicted in this paper is crucial for ensuring food safety. They not only enhance food safety but also help stakeholders meet regulatory standards and industrial demands for sustainable and safe food production practices.

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