

Application of Supply Chain Analytics in Agriculture: A Road to Sustainability

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Received Aug 06, 2025, **Revised:** Aug 10, 2025, **Accepted:** Aug 15, 2025, **Published Online:** Aug 30, 2025

Reviewers: Anonymous Peer Review

Citation: Kumar, S. (2025). Application of Supply Chain Analytics in Agriculture: A Road to Sustainability. *International Journal of Supply Chain Management*, 14(4), 16-26, <https://doi.org/10.59160/ijscm.v14i4.6335>

Abstract— Every aspect of modern human living has now become significantly dependent on the use of data and analytics to reach optimum utility levels. Agriculture, modernized and mechanized over the ages, now makes judicious use of data analytics, particularly on aspects of agricultural supply chain, to improve efficiency. This article focuses on the merits of using supply chain analytics in agriculture. Global agricultural information can be organized and made universally accessible and useful. This article brings out how and why enormous volumes of data should be harnessed to effectively enhance agri SC in a sustainable manner, and benefit not just the customers but also the environment. This article establishes the rationale behind applying SC Analytics (SCA) in Agriculture and prepares the floor for further research on how volumes of agricultural data can be used effectively by corporate giants to implement Blockchain and AI technologies in agri SC.

Keywords—Supply Chain, SC, Agriculture, Agricultural Supply Chain, ASC, Data, Data Analytics, Supply Chain Analytics, SCA, Artificial Intelligence, AI, Machine Learning, ML.

1. Introduction

The world around us is progressing in terms of knowledge and technology. Progression in pharma and healthcare sciences now keep more people healthy and increase their longevity. This together with lower infant mortality rates have led to a steady rise in the aggregate world population. However, bigger population but inadequate food supply growth, especially agricultural produce, has led to a significantly large section of the population remaining under-fed or unfed. Today's young population of the most populated nations like India and China would eventually age and there would be

more mouths to feed than hands to produce. The ever-dynamic geopolitical environment has now become all the more volatile, disrupting the global agriculture supply chain (ASC). It has, therefore, become essential that ASC be effectively managed to maintain its smooth functioning and to ensure food safety and security. This calls for application of ultra-modern technologies which demands data analysis. Agri data besides being unstructured and unorganized, is inadequate and has low accessibility making it unsuitable for use in studies. This article focuses on the need to organize this data and on the virtues of applying supply chain analytics (SCA) to bring in a sustainable solution to food safety and security.

2. Literature Review

2.2 Agricultural (Agri) Product Supply Chain (SC)

SC is the lifeline for any product [1], involving a series of activities from procurement of inputs to the delivery of finished products to the final consumers. ASC, also referred to as the agri-food supply chain or agricultural value chain (AVC), denotes a complex network of interrelated activities, institutions, resources, including human, that are involved in completing this journey of farm products from the producers to the final consumers. This comprehensive process includes stages such as production (input suppliers and farmers), processing (the processors), storage, transportation, and distribution (distributors and retailers), playing a crucial role in income generation, guaranteeing food security, and in creation and provision of jobs or employment opportunities [2].

The United Nations Food and Agriculture Organization (UNFAO) aptly describes the food SC as a network consisting of all stakeholders

participating in the synchronized activities of production and value-addition that is necessary for production of food products [3]. Significant complexity, therefore, is ingrained in the management of ASC, and it affects food safety and quality, the sustainability of the entire process, and its economic viability [2]. Consequently, risks such

as market volatility, sustainability anxieties and infrastructural limitations are inherent in the very nature of agriculture, particularly in the developing and the less developed countries where the scope of mechanizing the whole process is small [4], despite agribusiness being a key driver of economic growth in these regions [5].



Figure 1 Agriculture Supply Chain [6]

The food SC encompasses both agricultural upstream and downstream sectors and spans across the entire value chain from the supply of agricultural inputs (for instance seeds, feeds, fertilizers, equipment and / or medicines) to cultivation and production, post-harvest handling, processing of the farm products to produce the final product, their transportation to the warehouses, cold storages etc.; and finally marketing, distribution, and retailing of the final products [3].

In case of AVC and marketing, the initial stages of production are referred to as upstream and focusses on the procurement and storage of raw

materials required for production. Downstream, on the other end, deals with such activities as processing, packaging, and distribution to consumers and refers to the processes that take place following the production phase [7]. It is the stage in which products are made and delivered.

In the case of wheat, for instance, the upstream activities would involve the production and supply of wheat seeds, fertilizers, and several other inputs that go into the production process, as well as the farming practices and procedures that are employed for growing the wheat. Grinding the wheat into flour in mills, baking bread, packaging the bread and distributing it to consumers are the activities involved in the downstream part of the AVC.

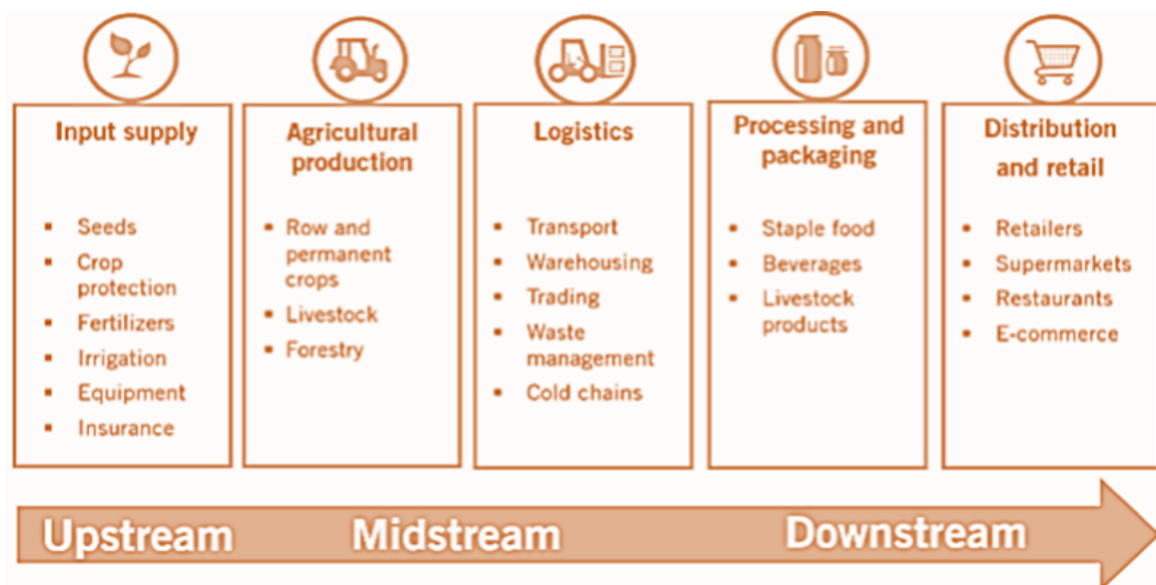


Figure 2: Agricultural Value Chain [8]

The recent decades have seen the food supply chain growing rapidly. Present-day consumers now expect fresh foods, even exotic ones, on their plates, all year round. Most fruits and vegetables are available throughout the year. Seasonal is just a notion. Even imported food products are now available easily. This has resulted in the supply chain being extended geographically and across larger number of parties, which, besides elongating the supply chain has magnified its complexity to an unprecedented level [9].

2.3 The Need for Managing ASC

The world population is increasing by leaps and bounds and with it the demand for food. The global food supply is affected by weather, internal environment of a country and geopolitical conditions it has therefore become imperative to manage the agricultural supply chain to ensure that there exists a sustainable food supply chain. Such a supply chain is believed to be sustainable at 3 levels

- Economic - is expected to be profitable across all the stages involved in the supply chain,
- Social - has wide-reaching benefits for society (both globally and locally),
- Environmental – is either positive or neutral in terms of impact on the natural environment (environmental sustainability).

Some key concepts central to the 2030 Sustainable Development Goals are sustainability in production and consumption. They serve as the foundation for achievement of food security – a key to eradicating hunger. However, according to the UNFAO the extent of deviation from this track has

been perturbing. The organization has also sounded concerns that the ASC is now in position to turn into a substantial contributor to global warming, adding a fair share to the emission of greenhouse gases. Furthermore, both the COVID-19 pandemic and the Russia-Ukraine war have aggravated and magnified the problem further as millions more plunged into hunger. For the achievement of the Sustainable Development Goals and ensuring a sustainable future, it has therefore become imperative that the gap between the envisioned goals and the current reality be rectified and a permanent solution be found to the problem [10]. This article evaluates the existing and the possible and foreseeable challenges in the agri-food supply chain, and focuses on the application of SCA in furthering sustainable production and consumption.

Studies reveal that over the last decade or so, the most important change in AVC has been the increased need for food quality/safety to meet increasingly stringent domestic and international standards and for traceability or the ability to track the passage of food through the various stages of its agricultural value chain [8]. The development and enhancement of the agri goods supply system, which entails the journey of the agricultural products from the producers to consumers, is a pressing issue, as products travel around the world and have to conform to strict quality standards, both home and abroad, to be able to feature as safe to consume. This can be achieved through the efficient application of supply chain management, which is a complex system that guarantees the turnover of agricultural products on the market [11]. A system that has higher efficiency and effectiveness is most likely to be beneficial to not just the producers but to the consumers as well as it

will help to reduce waste, lower prices, and ensure a better reliable flow of goods.

2.4 Problems in Managing ASC – Changing Dynamics

Contemporary development and progression of agricultural business across the globe is focused on a flexible network management system that brings together and fosters synchronization and collaboration amongst information, innovations, and intellectual property [11]. At the heart of this lies the efficient collection, storage, organization and processing of relevant data that is capable of not only generating valuable insights but of supporting crucial decision-making.

There are certain difficulties in managing the ASC which include, but are not limited to the following:

- **Weather Dependence** — Agriculture by its very nature is heavily dependent on natural forces for a fruitful harvest. Climate variability and weather conditions like rainfall, temperature, etc. have a significant impact on ASC as they have determining influences on such attributes as crop quality and yields. Climate change has already started affecting and is leading to unpredictable weather patterns, that affect both crop yields and availability [12]. The unpredictability of the forces of nature makes it extremely difficult to align demand and supply [2]. Uncertainties generally disrupt SCs, leading to food shortages and higher prices making it essential to adopt agricultural practices that are more resilient [13].

- **Perishability** — A large number of agricultural products are perishable. They have limited shelf lives and can get spoiled very soon which means they require proper storage, timely processing and quick transport in order to avoid spoilage. This adds complexity to logistics and inventory management [2]. The situation becomes particularly challenging at the time of striving to coordinate transportation, storage, and distribution especially during peak harvesting seasons [4].

- **Variability in Quality** — There is significant lack of standardization in Agri products. It is nearly impossible to find agricultural products that are exactly alike in size, taste, etc., making standardization and quality control extremely difficult [2]. Weather sold at home or in the domestic market, every product, irrespective of its nature, must adhere to some specific quality standards defined for the product category. Consistency in maintaining product quality and persistent adherence to global standards is usually

challenging, especially in areas that see diversity in agricultural practices. Difference in quality requirements across markets has the potential to lead to rejected shipments and consequent substantial financial losses [4].

- **Inadequate Infrastructure and Labor issues** — In several regions across the world, lack of requisite storage facilities, power infrastructure, improper road conditions and inadequate transportation facilities are the biggest factors hindering the efficient physical movement of agricultural products. Under developed markets and limited access to markets also result in delays. The outcomes of all these adversities is wastage and higher costs [4]. Another key problem is frequent labor shortages due to seasonal nature of demand, increased urbanization, aging workforce, and skills gaps caused by rapid advancement in agro technologies [2].

- **Fragmented in Nature** – In general agricultural supply chains would involve a number of intermediaries, from producers who are generally farmers and processors to distributors and retailers. The higher the number of intermediaries involved, the higher is the fragmentation and the higher is the scope for inefficiencies, lower is the transparency, and tracking the products becomes more and more difficult [4].

- **Lack of Digitization and Limited Accessibility** – When it comes to analyzing global agri information it is very difficult to get structured relevant data as much of the data is undocumented since it comes from the unorganized sector. Low penetration of technology, low or no education, lack of skills at data gathering and storage makes the data unusable even when it is relevant [14]. Both digitization and digitalization are huge issues. Complexity and fragmentation of agricultural data, absence of standardization on all platforms, restricted accessibility and problems of rural connectivity, together with data privacy and ownership concerns hinder the full potential of digital agriculture.

- **Market Access and Trade Barriers** – The world being a global village, countries source all kinds of consumption products from overseas. Agricultural products are no exception. Hence their supply chains are also spread across the world. Trade barriers, tariffs and quantitative regulations are some of the factors creating difficulties in agricultural trade across borders. These barriers are capable of impeding and significantly delaying the movement of goods resulting in escalation of costs for both exporters and importers [4].

- **Sustainability** — It is a key aspect of 2030 Sustainable Development Goals. It requires sourcing agricultural products that are organic,

environmentally friendly, or ethically sourced. This adds a further layer of complexity to sourcing of various agri products, their traceability, storage, processing, packaging, and transportation of the final product [2].

The above-mentioned points can act as major stumbling blocks when it comes to production efficiency, profit, and customer satisfaction. However, both strategical and technological solutions are available to address them. Smart Agriculture is now a reality

3. Smart Agriculture (SA) – The Impending Transition

Technology related to every aspect of modern life and its advancement are always data driven. SA is no exception. It uses of data analysis, sophisticated technology, and automation for enhancing different aspects of farming, including livestock management, crop monitoring, and precision farming. Smart Agriculture incorporates such sophisticated technologies as Internet of Things (IoT), use of sensors, drones and satellite imagery; artificial intelligence (AI) and machine learning (ML), as well as data analytics for the optimization of farming operations [15].

According to TraceX Technologies, an India-based Agri Food and a Climate Tech company, the global smart agriculture market was estimated to be approximately USD 6.455 billion in 2018 which was expected to grow at a CAGR of 13.09% to reach USD 19.625 bn by 2027 [13] and growth at 11.3% CAGR was expected during 2023-2033 with the market crossing \$60 billion in 2033 [15]. According to Grand View Research, in 2024 the global smart agriculture market size was estimated at USD 25.36 billion in 2024 [16].

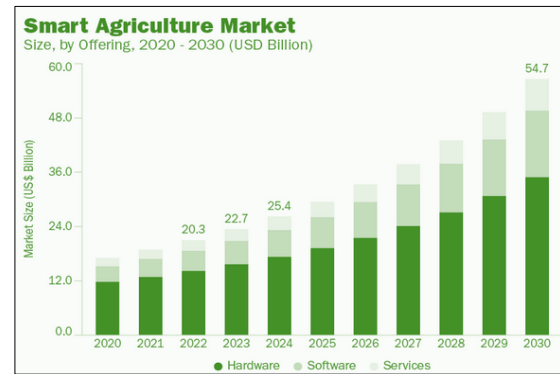
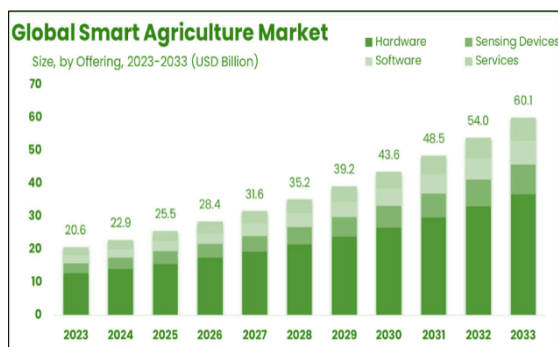


Figure 2: Smart Agriculture Market Size Projections [13, 15, 16]

Global population is projected to touch 10 billion by 2050 [17], offering a number of critical challenges that can impede matching the world's burgeoning food demands. Obviously, the farmers are expected to encounter increasing pressures to produce increasingly larger volumes food on arable land whose size is getting increasingly restricted due to increased urbanization and higher industrialization, which in turn will make innovation and sustainable practices imperative for maximizing crop yields [18].

Scaling up crop production and farming activities significantly, is now essential to meet rapidly growing food demand from the exploding population. Agriculture companies will eventually have to increase their presence in fulfilling these demands. The Asia Pacific has remained in the forefront of the agriculture markets, in terms of the size, followed by North America. [13].

Every aspect of agricultural activities and the related SC generates a lot of data every day. Automation, mechanization, digital transformation, application of new and innovative technology will demand the analysis of a massive volume of data if these changes have to be implemented effectively to enhance productivity and make agricultural supply chain more sustainable.

3.2 Blockchain

Blockchain has rapidly developed into a crucial technology in several applications of precision agriculture. Lately, the development of blockchain-based IoT systems in precision agriculture is emerging as key thoughts in technological advancement in the supply chain management (SCM) space due to the requirement to develop smart peer-to-peer (P2P) systems that can verify, secure, monitor, and analyze agricultural data.

Blockchain has a crucial role to play in replacing conventional methods of storage, organization and sharing or distribution of agricultural data in decentralized manner which ensures that the data is undisputable, has better reliability and is more transparent [19].

ASC has a multilayered structure and involves a large number of stakeholders thereby complicating and increasing the difficulties associated with the management of critical factors including origin of the product, production phases, product pricing, and its quality standards. Such challenges frequently bring about inefficiencies, miscommunication, making the supply chain weak

and susceptible to fraud, which in turn undermines consumers' trust and compromises food safety. Blockchain technology provides a groundbreaking approach towards solving the SCM problems by offering a tracking mechanism across agri-food supply chain stakeholders that is safe, secure, efficient, as also transparent. The technology supports real-time monitoring of food products, better safety measures, maintains and supports the quality standards, and creates and fosters trust among the stakeholders [20].

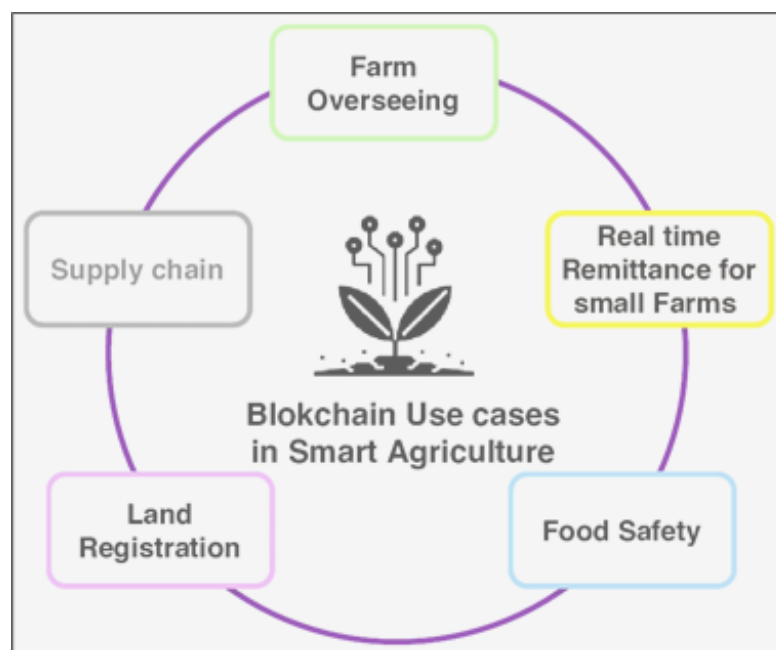


Figure 4 Application of Block Technology in Smart Agriculture [19].

Combining Internet of Things (IoT) and the blockchain in precision farming, will help us move from just “smart farms to the internet of smart farms” and be instrumental in adding more control in supply-chains networks [19]. Blockchain technology when integrated with IoT offers a novel technology which can be applied for the mitigation of important challenges that exist in precision agriculture. [21]

3.3 Need for Data

Maximization of value from ASC demands a number of efficient decision-makings [22]. The decisions are not mutually exclusive and generally intertwined.

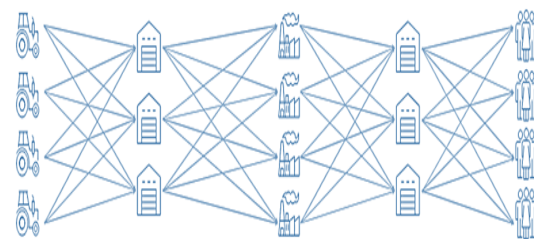


Figure 3 Intertwined Nature of Complex ASC Decision Making [22]

4. Applying Data Analytics

Modern decision-making is data driven. The use of structured relevant data in decision making increases the efficiency of the decision. A good quality data results in good and timely decisions.

The data becomes particularly useful for corporates who are in the agricultural space. Crop producers, farmers, fertilizer manufacturers, seed producers, agri logistics businesses are all benefitted through the use of data analytics as better accessibility and data quality helps and promotes agricultural research – they key to food safety, security and sustainability.

4.2 Organizing Global Agricultural Information

Due to the presence of significantly large number of small and medium-sized enterprises (SMEs) in production and marketing of agricultural produce around the world, the use of flexible management methods alongside digitalization have become absolute necessities for the management of supply chain in agricultural business requires [23].

Herein lies the need to improve the quality of agricultural data, by addressing the existing issues that relate to errors occurring during quantification, lower relevance or coverage, since they meaningfully restrict the data credibility thus adversely impacting agricultural research. Time and again inconsistent attention has been provided to data quality issues. Evidently higher industry has been dedicated towards using ex-post adjustments on the basis of econometric solutions rather than capitalizing on superior ex-ante options or alternatives at the design stage [24].

Organizing agricultural data benefits a plethora of stakeholders through enhanced access to information, promotion of global collaboration, thrust on innovation, increased research visibility, and empowerment of professionals and farmers with the newest agricultural knowledge. Data structuring and presentation is undertaken by such organizations as The Food and Agriculture Organization of the United Nations (FAO) to enhance the visibility of and provide global access to critical agricultural knowledge produced through an increasing number of global agricultural research.

The structured data can be utilized by both businesses and individual farmers for various purposes. For businesses like fertilizer and chemicals manufacturers, seed manufacturers, etc. predicting crop cycles and demand forecasting can be extremely useful. Even farm mechanization requires analysis of structured data to gauge the possibility and the extent of mechanization.

4.3 Applications of SCA in Agriculture

Using SCA it is possible to significantly improve the management of global agricultural information,

through the process optimization, efficiency enhancement, and waste reduction. An organization can leverage data-driven insights for better demand forecasting, more efficient inventory management, besides ensuring delivery of the right agricultural products from the farm to the right consumers and on time thus leading to higher profitability for farmers, lower food wastage, and better food security at the international level.

Companies across industries agree that value-creation is possible through the application of digital and analytics technologies to novel business models and innovative product offerings. Today, agri players, across the value chain, are realizing that modern SC technologies can be pivotal to optimization of the brutally complex ASC [22].

In agriculture, the application of SCA entails engagement of sophisticated data analysis, generally powered by artificial intelligence (AI) and machine learning (ML) or similar technologies, for farm-to-fork processes optimization, efficiency enhancement, better productivity, sustainability, and higher food safety. Analytics helps to transforms gigantic volumes of relevant agricultural data into acumens that can be acted upon, thus making data-driven decisions possible throughout the whole ASC, starting with crop management and ending with distribution and consumption.

4.3.1 Use of Digital Twins

Following the examples set by companies in other industries, leading agriculture players are building digital twins of their physical supply chains utilizing the data flood that they are capturing. The virtual replicas help companies run simulations and optimizations, that can result in substantial savings on cost associated with moving the crops through the system [22]. Digital Twin technology provides higher transparency and traceability to an ASC [25]. Creation of physical supply chain digital twins permits virtual simulations to explore potential scenarios and make informed decisions in real-time which facilitates optimizations.

Agri industries are cornerstones of global sustenance, but face complex challenges extending from resource scarcity to climate changes. Farming facilitates that integrate these sophisticated modern technologies improve managerial decision-making leading to better yield. To usher in effective changes, smart farming could be introduced in combination with drones, wireless sensor networks, AI, robotics, robotic agricultural bots, cloud computing, expert systems and the Internet of Things (IoT) [26]. Following explain the potential that application of modern SCA holds.

4.3.2 Precision Farming and Resource Optimization

Precision agriculture optimizes crop yields and resource management. Applying sophisticated technology and analytics to factors such as soil conditions, weather patterns, and crop growth, allows extraction of useful information for making informed decisions on planting seeds, irrigation, fertilization, and pest control. The farmers can modify their practices to maximize efficiency and minimize waste. Using analytics based on real-time data drawn from sensors and field imagery can optimize fertilizer usage, irrigation and pest management, through higher yields and lower waste. [27].

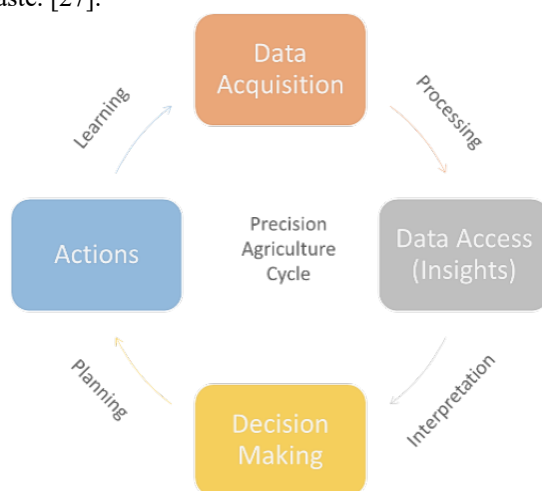


Figure 6: The Cycle of Precision Agriculture

4.3.3 Crop Yield Prediction and Efficient Use of Fertilizers

Data analytics is pivotal in predicting crop yields and optimizing fertilizer usage, resulting in better efficient and more sustainable agricultural practices. Crop yield prediction weighs data pulled from various sources, including weather patterns (humidity, rainfall, temperature), soil properties (texture, pH, nutrient levels), historical yield data, as also satellite imagery [28]. Such broad-based data analysis provides valuable insights that allow farmers make informed decisions, thus maximizing yields and minimizing wastage. Predictive modeling enables more accurate yield forecasts thus aiding planning and resource allocation.

Smart Agriculture Yield and Fertilizer Optimization System (SAYFOS), is an innovative approach designed to tackle the challenges of precisely forecasting crop yields that can cause environmental harm along with lower agricultural efficiency. By integrating advanced data analytics, IoT technologies, and ML algorithms, SAYFOS allows real-time supervision and management of

soil conditions and crop health. Valuable data from weather forecasts, soil sensors, and satellite imagery is analyzed for precise crop yield prediction and optimization of fertilizer application rates. SAYFOS increases crop productivity by 0.25% while reducing water consumption by 0.33% with fertilizer efficiency enhanced by 0.25% over traditional practices [29].

4.3.4 Supply Chain Optimization

Analytics facilitate effective inventory management, optimization of logistics, and well-organized distribution networks, enabling efficient and timely delivery of fresh produce to markets. Modern SCM spreads much wider than simply distribution of finished goods to desired markets. Data analytics empowers modern agriculturalists with useful insights to forecast market conditions to adjust production, anticipate consumer behavior, identify emerging market trends, enhance product traceability, factor-in inflation, streamline logistics and transportation, better inventory management, build stronger relationships with suppliers and buyers and adjust with other variables which help in planning the complete process even before commencement of sowing. Predictive farm management can help optimize logistics, minimize losses, and improve return on investment [30]. These improvements help reduced post-harvest losses, heighten product quality, enhance customer satisfaction, build and foster, competitive advantage thus enhancing sustainability [31].

4.4 Key Benefits:

4.4.1 Predictive Maintenance (PdM)

PdM uses sensors, AI and ML allows real-time scrutiny of equipment and environmental conditions in, allowing for early detection of potential failures and optimization of farm operations. Analyzing equipment data can predict potential failures, allowing for proactive maintenance and minimizing downtime.

4.4.2 Enhance Productivity

Agricultural data organization improves accessibility that facilitate informed decisions by stakeholders towards increasing agricultural productivity [32]. Timely detection of inefficiencies and bottlenecks help in adopting effective remedial measures which increases productivity, lowers wastage besides ensuring that farmers receive fair prices compensation while consumers can access affordable and safe food [7]. SCA also helps reduce food waste throughout the

supply by optimizing logistics.

4.4.3 Traceability and Food Safety

A thorough comprehension of upstream and downstream sectors is pivotal to AVC optimization and ensures food security. Applying technology solutions like blockchain combined with analytics, enhances transparency and traceability throughout the supply chain. Maintaining clear and permanent product journey records, improves food safety, lowers fraud, and builds consumer trust. This can help improve collaboration among stakeholders and reduce fraud [4].

4.4.4 Efficiency, Standardization and Sustainable Supply Chain Management

Planning and forecasting helps to optimize transportation schedules ensuring minimum SC disruptions. Infrastructure development is crucial. Public and private players can use agricultural data for jointly or singly improving ASC by developing better transportation networks, establishing cold storage facilities, and enhancing access to remote markets. Utilizing ASC data to establish industry-wide quality standards and adhering to them ensure product consistency. This improves consumer confidence and enhances user experience.

Applying data analytics help streamline processes and reduce waste through demand forecasting thus enabling more competent resource management thus promoting environmental and social sustainability. Numerous modern farms, globally, have already benefitted from integration of data analytics and operations.

80 Acres Farms, a leader in vertical farming, employs data analytics for monitoring and optimizing almost all aspect of their indoor farming environment. Using real-time data, every variable, from light levels to nutrient delivery, is cautiously controlled and judiciously adjusted to ensure higher yields and effective resource use [31]. The cloud-based farm management platform, John Deere's Operations Center, offers detailed insights to farmers on their field operations. It provides analysis of data collected from farm equipment, which aids farmers in crucial decision-making decisions regarding efficiency enhancement, cost rationalization, and augment sustainability [31]

5. Emerging Challenges

With higher adoption of analytics in agriculture, such challenges as data quality concerns, lack of connectivity, and higher operational expenses are emerging. Technology adoption is a costly affair. Where the products travel overseas the data also

becomes costly and changes in regulatory environments pose significant threat. Collaboration and cooperation between governments and international organizations can simplify trade procedures while reducing restrictions. But these are highly volatile.

6. Conclusion

Globally agricultural sector is transitioning rapidly, due to interdependent factors like demographic transitions, climate change, and lopsided economic growth. Despite technological innovations making essential enhancements in accessibility, suitability and overall data quality, several technical and institutional challenges remain. Enticing new data sources tend to divert attention away from consolidating critical foundational data that will address policy issues, validate and standardize novel data collection modes. Transformation within agricultural data systems is required to navigate this transition in methodology. Modern agriculture cannot thrive well without agri tech application and for that the utility of structured and clean data can't be overlooked.

This article establishes the virtue of applying SC analytics in facilitating the transaction and prepares the floor for discussion on how these data can be used by corporate giants to effectively implement technologies like AI and Blockchain in agro industries. The emerging trends in robotics, ML and the IoT indicate impending future application of AI in agriculture. AI adoption infers all-round benefits including increased efficiency, lower environmental impact and better crop quality. Additionally, the budding agri-tech sector can potentially create jobs and stimulate economic growth.

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