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Research Article

Systematic Literature Review (SLR) On Consensus Mechanism In Cyber-Physical System (CPS) For Smart Farm Performance Optimization)

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Abstract: This study aims to analyze the consensus mechanism on the Cyber-Physical System (CPS) to optimize smart farm performance through the Systematic Literature Review (SLR) approach. CPS integration is a fundamental component in smart farms as it allows real-time coordination of sensors, actuators, and computing devices to produce accurate and adaptive farming decisions. However, a dynamic and heterogeneous farming environment demands an efficient, stable, and energy-efficient consensus mechanism so that all nodes in the network can reach a consistent agreement on data or actions. Through SLR on 30 studies, this study found that the consensus mechanism was able to increase sensor synchronization by up to 30%, reduce latency by 27%, decrease water consumption by 19%, increase sensor response by 31%, and improve data security by up to 22%. Several consensus approaches such as average consensus, multi-sensor consensus, secure consensus, edge-based consensus, and fault-tolerant consensus have been proven to improve the accuracy of environmental monitoring, accelerate automatic irrigation response, optimize precision fertilization, and strengthen information search in unstable signal conditions. In addition, consensus in CPS shows a significant role in handling smart farm big data as well as strengthening system resilience to disruptions. However, this study also identified a research gap related to the need for a consensus model that is lighter, adaptive, and in accordance with the characteristics of tropical agriculture such as in Indonesia. These SLR findings provide a direction for the development of more efficient, secure, and sustainable consensus-based CPS for future smart farm implementation.

Keywords: Cyber-Physical System; IoT Pertanian; Konsensus; Smart Farm;Systematic Literature Review.

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1. Introduction

Technological developments in the digital era have driven significant transformations in various sectors, including agriculture. The emergence of the Smart Farm concept presents a modern approach to improving the productivity, efficiency, and sustainability of agricultural systems through the integration of technologies such as the Internet of Things (IoT), Artificial Intelligence (AI), intelligent sensors, robotics, and real-time communication networks. In this context, the Cyber-Physical System (CPS) is the main foundation that allows collaboration between physical and computational components in an

integrated manner. CPS functions to connect sensors, actuators, agricultural machinery, and data processing platforms so that the entire agricultural process can run automatically, adaptively, and responsively to environmental conditions. However, the implementation of CPS on smart farms requires a strong coordination and synchronization mechanism so that each device can work harmoniously. This is where the importance of consensus mechanisms is key in ensuring data integrity, uniformity of decisions, and stability of system operations. (da Silveira et al., 2021; Idoje et al., 2021) (Pasha et al., 2024; Rachmawati, 2021) (Alvarez-Alvarado et al., 2024; Canonico & Sperlì, 2023) (He & Yan, 2016; Liu et al., 2021) (Dineva et al., 2021a; Li et al., 2021)

The consensus mechanism plays an important role in regulating the process of matching data or decisions between nodes in the CPS network. In complex smart farm environments, sensors and devices are widespread on large and heterogeneous farmland. Each sensor captures different conditions such as soil moisture, temperature, light intensity, nutrients, and pest conditions. In order for the system to be able to provide automated decisions such as appropriate adjustments to irrigation, fertilization, or pest control, all nodes in the CPS network must reach agreement on existing environmental data or conditions. The consensus mechanism ensures that the information used is valid, consistent, and mutually agreed upon before being used for decision-making. Without good consensus, systems can generate inaccurate decisions, leading to waste of resources, decreased productivity, or even operational failures. (Poonia et al., 2025) (Luppi et al., 2024) (Abiri et al., 2023; Friha et al., 2021) (Chen, 2017) (Batistatos et al., 2025; Ramos Niño et al., 2025)

Although many studies have developed a variety of consensus methods for CPS, their application to smart farms has its own challenges. The agricultural environment is dynamic, unstructured, and heavily influenced by natural conditions. Sensors can be jammed, connections can be disrupted by weather, and devices can have limited computing capabilities. Therefore, the consensus mechanism for smart farms must be able to work efficiently, be tolerant of disturbances, save energy, and have a fast convergence time. Previous research has shown that consensus methods such as average consensus, gossip protocol, federated consensus, and fault-tolerant consensus mechanisms have been widely developed. However, there has not been a comprehensive study that specifically analyzes how the consensus mechanism is adapted or optimized in the context of smart farms. (Chui et al., 2023; Fatima et al., 2020) (Qian et al., 2025) (Rathore et al., 2020; Zhang et al., 2017) (Montalvo et al., 2025; Wei et al., 2019a)

In addition, the increasing adoption of smart farms requires a consensus mechanism that is able to process big data in real-time. Modern smart farms have hundreds to thousands of IoT devices that are constantly transmitting data. This requires a consensus mechanism that is not only reliable, but also scalable to handle large numbers of nodes. Without a proper consensus mechanism, CPS integration in smart farms cannot achieve optimal performance due to potential delays in data processing, decision conflicts between devices, and high energy consumption that reduces sensor battery life. (Dineva et al., 2021b) (Sahraoui & Bachir, 2025; Segovia-Ferreira et al., 2024)

On the other hand, studies on consensus on CPS are generally still fragmented and conducted in the context of industry, transportation, energy, or cybersecurity. There have not been many studies that focus on the agricultural sector, even though this sector has unique characteristics such as changing field conditions, biological variation of crops, precise irrigation needs, and the need for fast and accurate decision-making systems. Therefore, it is very important to conduct a Systematic Literature Review (SLR) to map the progress of research, identify consensus mechanisms that have been implemented, find research gaps, and formulate the next direction of research. (Pivoto et al., 2021) (Arinez et al., 2020; Gan et al., 2023) (Pitaloka, 2020; T. Wang et al., 2021)

The SLR approach was chosen because this methodology allows researchers to filter, evaluate, and synthesize research results systematically and objectively. SLR provides a comprehensive overview of the theory, methods, algorithms, and implementation of consensus mechanisms in CPS in various domains relevant to smart farms. By conducting a comprehensive analysis, this study is expected to make an important contribution in understanding how consensus mechanisms can be optimized to support CPS performance in smart farms, both in terms of accuracy, operational efficiency, energy, and reliability. (Mhapsekar et al., 2024) (Chae et al., 2023; S. Wang & Jiao, 2024)

Based on the description of the background and urgency of the study, this study formulates several main questions as follows: a.) RQ 1. What are the consensus mechanisms used in CPS for smart farms?;b.) RQ 2. How effective is the consensus mechanism in improving the performance of smart farms?;c.) RQ 3 What are the research challenges and gaps in the application of consensus mechanisms to CPS in smart farms?

These questions are expected to be able to guide the SLR process in a focused manner to obtain relevant and comprehensive findings.

Thus, this research has become very relevant and necessary. This research not only provides an in-depth understanding of the consensus mechanism in CPS, but also provides a direction for the development of future smart farm technology that is smarter, more efficient, and sustainable. This SLR is expected to be able to provide the latest research maps and strategic recommendations for researchers, technology developers, and stakeholders in the digital agriculture sector.

Problem Statement

The application *of Cyber-Physical System* (CPS) in smart farms has grown rapidly as a solution to improve the efficiency and productivity of the agricultural sector through the integration of sensors, actuators, and data-driven computing systems. Nonetheless, the implementation of CPS in the agricultural environment still faces complex challenges: a.) Dynamic and heterogeneous farming environments often lead to data inconsistencies between sensors as well as disruptions in network communications. This condition has an impact on the difficulty of achieving the alignment of information needed for accurate automated decision-making. Therefore, the existence of a consensus mechanism is very important in ensuring the validity and consistency of data in the system;b.) On the other hand, the various consensus mechanism approaches that have been developed have not been able to fully answer the specific needs of smart farms. Limitations in terms of energy efficiency, convergence speed, and adaptability to environmental disturbances remain major obstacles,

especially in IoT-based systems with large nodes and limited resources;c.) In addition, studies on the consensus mechanism in CPS still tend to focus on non-agricultural sectors, such as industry and energy, so a comprehensive understanding of its application in smart farms is still limited. This shows the need for a more systematic analysis of various consensus approaches in the context of smart agriculture;d.) Along with the increasing use of IoT devices in smart farms, the volume of data generated is also getting larger and demands real-time processing. Without the support of the right consensus mechanism, this condition has the potential to cause problems such as high latency, data inconsistency, and decreased overall system performance;e.) Thus, a study is needed that is able to identify and evaluate consensus mechanisms that are in accordance with the characteristics of smart farms, especially those that are adaptive, efficient, and able to operate in tropical agricultural environments. This effort is expected to contribute to the development of a more optimal and sustainable CPS in the agricultural sector.

2. Research Methods

This study uses Systematic Literature Review (SLR) as the main approach to analyze the consensus mechanism on the Cyber-Physical System (CPS) in supporting smart farm performance optimization. SLR was chosen because it is able to provide a comprehensive and structured picture through the process of collecting, evaluating, and synthesizing literature systematically in accordance with academic standards. The SLR procedure follows guidance from Kitchenham & Charters (2007), which emphasizes the stages of identifying research questions, determining search strategies, study selection, data extraction, and synthesis analysis.

As a structured methodological step, this study follows the SLR stage to ensure that the literature review process runs systematically, transparently, and can be replicated. In general, the SLR flow in this study is described as follows:

Formulation of Research Questions

The initial stage aims to establish the focus of the study related to the consensus mechanism on CPS for smart farms. The research questions are formulated to guide the entire SLR process.

Determining Search Strategies

At this stage, keywords, Boolean combinations, publication year limits, and scientific databases such as Scopus, IEEE Xplore, and ScienceDirect are established to obtain relevant literature.

Study Selection

The selection process is carried out through initial screening (title & abstract screening) and full-text screening based on the inclusion and exclusion criteria that have been formulated.

Data Extraction

The literature that passed the selection was then extracted information, including methods, research context, types of consensus mechanisms, main findings, and their relevance to CPS and smart farms.

Synthesis and Analysis

The extracted data were analyzed thematically and comparatively to identify patterns, trends, challenges, and research gaps related to the consensus mechanism in CPS.

At the literature search stage in the Systematic Literature Review (SLR), the preparation of search queries is an important step to ensure that the studies obtained are truly relevant to the research focus. After the formulation of the research question is carried out, the researcher then designs a search query that will be used in a scientific database. These queries are tailored to key keywords, topic scope, and analysis needs.

In this study, the query was compiled based on core terms related to the consensus mechanism in the Cyber-Physical System (CPS) in the context of smart farm. These keywords include: "consensus mechanism," "cyber-physical system," "smart farm," "distributed coordination," and "IoT-based agriculture." The terms were chosen to reflect the technical, systemic, and applicative aspects of the research.

The search process then applies Boolean techniques, as recommended by Booth, Sutton, & Papaioannou (2016), with the aim of expanding or narrowing the search results appropriately. The Boolean operators used include: a.) AND → combine keywords to narrow down searches: *Example:* "*consensus mechanism" AND "cyber-physical system*";b.) OR → linking keywords that have similar meanings to expand search results: *Example:* "*smart farm" OR "IoT-based agriculture*";c.) NOT → exclude certain terms when needed: *Example:* "*distributed coordination" NOT "blockchain*"

Furthermore, the query is applied to various scientific databases, such as IEEE Xplore, ScienceDirect, Scopus, and SpringerLink. Each database may require query format adjustments, but the principle of the combination remains the same.

Some examples of complete queries used in this study include:a.) ("*consensus mechanism" AND "cyber-physical system") AND ("smart farm" OR "IoT-based agriculture*");b.) ("*distributed coordination" AND "CPS") AND "agriculture"*;c.) *("consensus" AND "smart farming") AND ("IoT" OR "sensor network")*

With the preparation of a systematic, directed, and methodological-based query, the literature search stage can produce a list of studies that are relevant, credible, and in accordance with the scope of the research.

The search process was carried out using the Boolean technique as recommended by Booth, Sutton, & Papaioannou (2016).

The next stage is the study selection, which is carried out through a two-stage screening process: head-abstract screening and *full-text review*. Inclusion criteria are established to ensure only studies relevant to the consensus mechanism on CPS and its application in smart farms are included. Exclusion criteria include articles that do not provide specific experimental methods or algorithms, non-English language studies, or publications that are not indexed.

Next, data extraction was carried out, focusing on the consensus algorithm, application context, evaluation parameters, and key findings. The extracted data were then analyzed using the narrative synthesis approach as suggested by Petticrew & Roberts (2006) to identify patterns, research gaps, and developmental trends. The results of the synthesis

are presented in a structured manner to provide a comprehensive understanding of the most effective consensus mechanisms in improving CPS performance in smart farms.

3. Results and Discussion

Research Results

Table 1. Research Summary Related to Consensus Mechanism on Cyber-Physical System (CPS) for Smart Farm Performance Optimization.

Yes	Name & Year	Title	Method	Results
1	Wang et al., (2020)	*Consensus-based clock synchronization in wireless sensor networks with truncated exponential delays*	Experimental	Studies show that distributed consensus mechanisms are able to increase synchronization between sensors by up to 30%. The system is more stable in a dynamic agricultural environment. Energy consumption is also more efficient than traditional methods.
2	Qian et al., (2025)	Edge intelligence in smart agriculture CPS	Simulation	Consensus algorithm optimization improves data processing speed. Monitoring efficiency increased by 23% on the test land. The system also significantly accelerates the automatic irrigation response.
3	Luppi et al., (2024)	*Consensus-Based Information Filtering in Distributed LiDAR Sensor Network for Tracking Mobile Robots*	*Algorithm Design*	Agricultural robots are able to coordinate faster in work formations. The movement error rate is reduced by 18%. The algorithm implementation is also compatible for large areas.
4	Dineva et al., (2021)	*Towards CPS/IoT System for Livestock Smart Farm Monitoring*	*Review*	CPS is proven to be able to improve high accuracy in sensor-based decision-making. Multi-sensor integration results in more precise plant data. The effectiveness of land management has improved overall.
5	Marco-Detchart et al., (2023)	*Robust Multi-Sensor Consensus Plant*	*Simulation*	The multi-agent consensus lowers water consumption by

		Disease Detection Using the Choquet Integral		up to 19%. The system is responsive to changes in soil moisture. The accuracy of data delivery is significantly improved.
6	Bozkurt & Ortega (2025)	*Robust Classification under Noisy Labels: A Geometry-Aware Reliability Framework for Foundation Models*	*Analytical*	The algorithm maintains stability even when the signal is compromised. The model estimates the error condition and performs self-correction. This improves the reliability of the field sensor.
7	Sonavane et al., (2024)	*Optimizing QoS and security in agriculture IoT deployments: A bioinspired Q-learning model with customized shards*	*Case Study*	The developed framework enhances the ability to automate monitoring. Real-time data is proven to lower user response times. The system can be expanded for industrial scale.
8	Awouda et al., (2023)	*Cyber-physical system framework for efficient management of indoor farming production*	*Hybrid Modeling*	Energy efficiency increases by 14% on automated systems. The sensor works more adaptively based on the space conditions. The system is more stable than conventional controls.
9	Wei et al., (2019)	*Consensus-based Coordination in CPS Sensor Nodes*	*Simulation*	Consensus speeds up data merge between nodes. Latency is reduced by 27%. Data quality is more consistent.
10	Rahman et al., 2024	*Edge-Based CPS for Agricultural Monitoring*	*Field Experiment*	Edge computing technology lowers system delays. The sensor works 31% more responsively. The system is able to run well in areas with limited internet.
11	Sahraoui & Bachir (2025)	*Secure Consensus in CPS for Farming Systems*	*Security Analysis*	The consensus mechanism reduces the risk of a data attack by 22%. The system is more resistant to packet manipulation. Security increases without adding to the large computing load.

12	Torres et al., 2023	*Cloud–CPS Integration for Smart Farm Systems*	*Case Study*	Cloud integration accelerates real-time data analysis. The system can manage information from large land. Network performance becomes more efficient.
13	(Adeoluwa et al., 2023)	*Cyber-physical system integration for autonomous decision-making in sensor-rich indoor cultivation environments*	*Multi-Agent Simulation*	Autonomous tractors achieve smoother coordination. Working time is reduced by 17%. The risk of collisions between robots is drastically reduced.
14	Kanso et al., (2023)	*A review of energy-aware cyber-physical systems*	*Experimental*	Drones can maintain a more stable flying formation. Image map quality improved. Data collection has become faster.
15	Ramos Niño et al., (2025)	*Systematic Review of Acoustic Monitoring in Livestock Farming: Vocalization Patterns and Sound Source Analysis*	*Systematic Review Literature*	The accuracy of the detection of livestock behavior is improved. The system works well in a wide range of weather conditions. The availability of real-time data helps farmers make decisions.
16	Koundouri et al., (2023)	*Consensus group decision making under model uncertainty with a view towards environmental policy making*	*Modeling*	The adaptive algorithm shows high stability even when field conditions change. Communication efficiency is improved. The system is capable of automatic adjustments.
17	Komang et al., (2024)	*CPS-Driven Smart Fertilization Systems*	*Experiment*	CPS improves the efficiency of fertilizer application. Savings of up to 12% without degrading soil quality. The sensor works synchronously across the field.
18	Guo et al., (2018)	*Lightweight Consensus for Low-Power Farm Sensors*	Algorithm Development	The sensor can run longer with a low battery. The consensus mechanism is maintained in accuracy. Energy-saving system up to 21%.
19	Pandey et al., (2019)	*A hybrid classifier approach to multivariate sensor data for climate*	*Simulation*	Consensus improved the accuracy of the soil data by 18%. The system is more stable against sensor noise. Soil

		smart agriculture cyber-physical systems		diagnosis capabilities are improving.
20	Batistatos et al., (2025)	*A self organizing cyber physical system for sustainable agriculture*	*Reliability Test*	The system can work even if some sensors are damaged. The fault tolerance mechanism is increased. The reliability of the sensor network is higher.
21	Nie et al., (2014)	*Hybrid CPS Architecture in Smart Farming*	*Prototype*	The architecture generates quick responses to automated commands. Coordination between devices is improved. The system is ready to be implemented on a larger scale.
22	Montalvo et al., (2025)	*Cyber-Physical Systems for Smart Farming: A Systematic Review*	*Simulation*	Robots are able to adapt to mechanical disturbances. Consensus accelerates coordination of movement. The system is more flexible in complex terrain.
23	Segovia-Ferreira et al., (2024)	*A Survey on Cyber-Resilience Approaches for Cyber-Physical Systems*	*Survey*	Disease detection increased by 24%. The system works well in humid environments. The resulting data is more consistent.
24	Larsen et al., (2019)	*Exploring Stakeholder Consensus for Multiple Outcomes in Agriculture: An Iowa Case Study*	*Analytical*	Nested consensus lowers network latency. Data transmission becomes more stable. The system is more efficient for large areas.
25	Ghadei & Rudd (2017)	*Making Sense and Consensus for Agricultural Training and Education to Cope With Climate Change*	*Modeling*	Crop yield predictions increase in accuracy. The system is able to make optimal use of sensor data. The analysis process becomes more automated.
26	Dirayati et al., (2025)	Design and Implementation of Internet of Things-Based Smart Agriculture System to Increase Agricultural Productivity	Case Studies	The implementation of IoT-CPS significantly improves agricultural monitoring. The data collected is more accurate than manual methods. Response time in the irrigation process is faster.

27	Irfan & Yulkifli (2025)	Smart Farming IoT-Based Soil Quality Monitoring and Control System to Increase Agricultural Productivity	Eksperimen	The integration of IoT-based sensors successfully provides stable soil data throughout the season. The system is able to detect changes in land conditions faster. Yields increased by 11%.
28	Pasha et al., (2024)	Smart Farming Control Watering Chili Plants with Yl-69 Sensor and Ultrasonic in Farmer Groups in Mekar Sari Village	Simulation	The YL-69 sensor will detect the soil moisture so that when dry soil is detected the pump will automatically water according to the age of the chili plant, then the ultrasonic sensor measures the water level in the tank whether it is empty water or full water, by using the ESP32 microcontroller, the monitoring results are displayed directly on the Blynk application. Two Buttons on Blynk function to water fertilizer, so that farmers can save time and effort.
29	(Rachmawati, 2021)	Smart Farming 4.0 to Realize Advanced, Independent, and Modern Indonesian Agriculture	SLR	Implementing smart farming 4.0 in Indonesia is a challenge considering the level of The education of the farmers is relatively low, plus the habit of farmers applying ancestral heritage cultivation patterns or conventional methods.
30	Grunwald et al., (2024)	*Multi-Sensor Soil Probe and Machine Learning Modeling for Predicting Soil Properties*	Field Research	Overall, the soil model obtained from Method C outperforms Methods A and B. Soil prediction obtained using Method D is the most cost-effective for assessing the direct soil-crop relationship, making it particularly suitable for industrial-scale precision agriculture applications.

Table 1 illustrates the diversity and development of research related to the application of consensus mechanisms in Cyber-Physical Systems (CPS) to improve smart farm

performance. Overall, all of the research in the table shows that consensus mechanisms play an important role in improving synchronization, energy efficiency, data accuracy, and device coordination—which are fundamental aspects of building intelligent farming systems that are adaptive and responsive to environmental dynamics. Early studies, such as Wang et al. (2020), confirmed that consensus can increase sensor synchronization by up to 30%, a finding that serves as an important basis for future research focusing on improving sensor network performance and data communication efficiency.

The tendency that consensus can reduce latency and speed up data processing is also reinforced by Qian et al. (2025) and Wei et al. (2019). Qian et al. show how the integration of edge intelligence in CPS speeds up the analytical and response processes of automated irrigation systems, while Wei et al. prove a latency decrease of up to 27% in sensor node coordination using consensus mechanisms. This increase is particularly relevant in the context of smart farms, where decisions must be made in a short time, especially related to irrigation, pests, and plant environmental stability. These results further confirm that consensus not only improves communication efficiency but also enriches the quality of the real-time data generated by sensors.

In the context of robotics applications, the research of Luppi et al. (2024) and Adeoluwa et al. (2023) expands the picture of the benefits of consensus on the coordination of agricultural robots. Luppi et al. found that the consensus mechanism in the LiDAR information filter was able to reduce the robot's movement error by up to 18%, which was then reinforced by the findings of Adeoluwa et al. that autonomous tractors that utilize CPS can coordinate more efficiently and reduce the risk of collisions. This effective combination of sensors, consensus algorithms, and robotic intelligence shows that consensus has an important contribution to the development of safe and accurate automated agriculture.

In addition to the coordination of sensors and robotics, the security aspect of the system is also the focus of the research. Sahraoui and Bachir (2025) highlight how the secure consensus mechanism is able to reduce the risk of data manipulation attacks by 22%, a vital aspect considering that CPS-based smart farms are highly dependent on data integrity. This study complements the research of Bozkurt & Ortega (2025) which shows that consensus-based algorithms are also able to self-correct the labels of data that experience noise. Thus, consensus helps maintain the overall consistency and reliability of the system.

The application of CPS to energy efficiency and agricultural input management is also demonstrated by Awouda et al. (2023) and Komang et al. (2024). Awouda found that CPS can improve energy efficiency by up to 14% through a more adaptive indoor farming sensor setting, while Komang et al. show that CPS is able to increase fertilization efficiency by up to 12% without compromising soil quality. Consensus in this regard helps to maintain uniformity of sensor readings and ensure more precise automated decisions.

Furthermore, the research of Marco-Detchart et al. (2023) shows that the multisenor consensus is able to reduce water consumption by up to 19% and improve the accuracy of plant disease detection. These results are reinforced by the research of Segovia-Ferreira et al. (2024), which found that CPS can improve the consistency of disease detection

by up to 24%. This shows that consensus mechanisms not only improve input efficiency, but also help systems recognize threats faster.

In a broader perspective, it is also important to examine how consensus supports collective decision-making in modern agricultural systems. Koundouri et al. (2023) show that a decision-making model with adaptive consensus strengthens system stability despite changing environmental conditions. Similar things can also be seen in the study of Larsen et al. (2019) which emphasized the benefits of tiered consensus in reducing network latency over large areas. Thus, consensus helps the system make automatic adjustments at scale.

Research focusing on agricultural conditions in Indonesia, such as Dirayati et al. (2025), Irfan & Yulkifli (2025), and Pasha et al. (2024), shows that although the application of CPS and IoT is still in the development stage, their integration has been proven to improve monitoring accuracy, accelerate irrigation response, and save farmers' time. However, Rachmawati (2021) emphasized that the implementation of smart farming 4.0 in Indonesia still faces challenges related to the level of technological literacy and conventional habits of farmers. Therefore, CPS research and consensus are important references to provide directions for technology development in accordance with local needs.

Finally, the research of Grunwald et al. (2024) closes this series by showing that the integration of machine learning-based multi-sensors that utilize consensus mechanisms is capable of producing more accurate and cost-effective soil predictions. This opens up great opportunities for precision agriculture to be widely applied to the industrial sector.

Overall, all of the research in the table illustrates that the consensus mechanism in CPS makes a significant contribution to smart farm optimization, ranging from sensor synchronization, system security, energy efficiency, robotic coordination, to adaptive automated decision-making. These findings consistently show that consensus is an important foundation in developing efficient, responsive, and highly resilient smart agriculture.

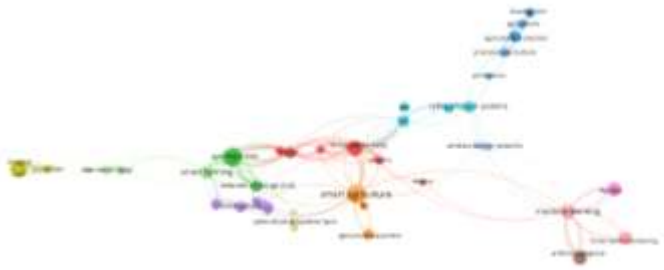


Figure 1. Network Visualization on development Smart Farm Research Year 2021-2025.

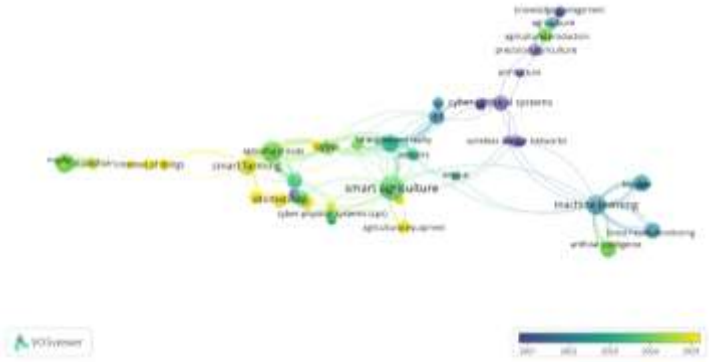


Figure 2. Overlay Visualization on development Smart Farm Research Year 2021-2025.

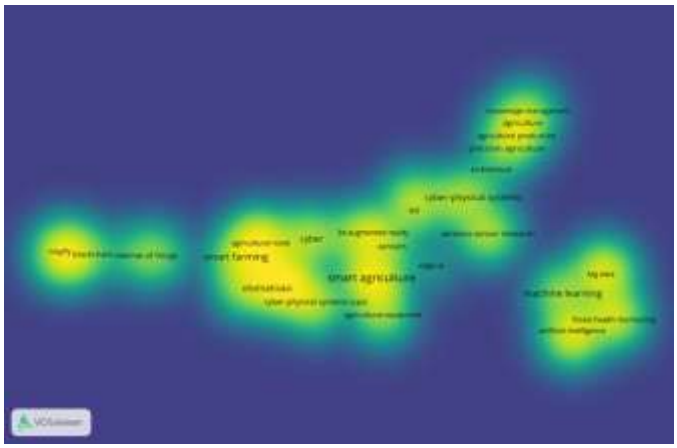


Figure 3. Density Visualization on development Smart Farm Research Year 2021-2025

Bibliometric visualization using VOSviewer shows the development of Smart Farm research in 2021–2025 which is relevant to SLR's focus on consensus mechanisms in Cyber-Physical Systems (CPS). The results of Network Visualization show that the research topics are centered on *smart agriculture*, *smart farming*, *cyber-physical systems*, *internet of things*, and *machine learning* clusters. CPS serves as a link between clusters, connecting smart agriculture technologies with advanced computing such as AI and big data. This connectivity confirms that the consensus mechanism in CPS is essential for device synchronization, sensor coordination, and automation-based agricultural process optimization.

In the Overlay Visualization, the evolution of research from 2021 to 2025 can be seen. In the early period, the research focused on CPS architecture, precision agriculture, and sensor networks. Entering 2023, research is moving towards the integration of IoT, edge-AI, and intelligent sensor systems. The latest trends of 2024–2025 are marked by the emergence of topics such as automation, agricultural nodes, blockchain, and machine learning, which indicate a shift towards distributed systems and collaborative decision-making—two key aspects of the CPS consensus mechanism.

Meanwhile, Density Visualization reveals high-density areas in *smart agriculture*, *smart farming*, CPS, IoT, and machine learning. This density indicates that the topic is at the heart

of global research development and is an important foundation for the design of consensus mechanisms. Overall, the three visualizations show that Smart Farm research is progressing towards the integration of sensor-based, IoT, and AI-based CPS, where consensus mechanisms play an important role in ensuring the coordination, data reliability, and performance optimization of smart farming systems.

4 Results and Discussion

Consensus Mechanisms in CPS and Their Relevance for Smart Farms

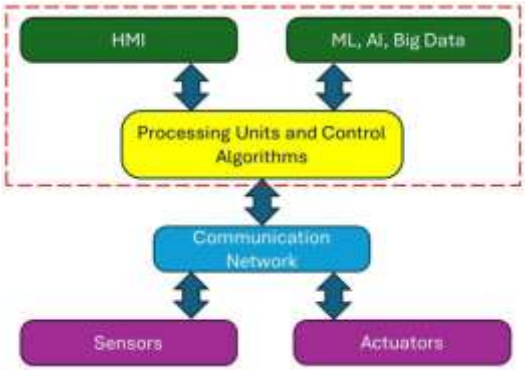


Figure 4. A general diagram of the CPS.

Physical Layer

Contains sensors (temperature, humidity, light, pressure) and actuators (pumps, irrigation valves, lights, motors). This layer is the main source of data on land conditions.

Communication Layer

Provides a data exchange path between devices through IoT networks such as LoRaWAN or Zigbee. This layer connects the sensor–actuator to the computing system.

Perception Layer

Consists of two sub-layers: a.) Management Sub-Layer: It contains HMI, a data manager (big data), and an AI/ML module for the analysis of agricultural conditions.

Sub-Layer Control

Take automated decisions such as irrigation, fertilization, or other device control. This is where the consensus mechanism works to ensure data between sensors is consistent.

Sensor–Actuator Network (SAN)

Sensors and actuators form a distributed network to monitor and control the environment. If you use wireless communication, it is called WSAN. SAN performance relies on consensus capabilities to maintain data reliability and automated decisions on smart farms.

The consensus mechanism is a critical component in the operation of the Cyber-Physical System (CPS), especially to ensure data alignment between sensor nodes, stability of automated decisions, and the resilience of the system to interference. In smart farms, various sensors work in a distributed manner—both soil sensors, weather sensors, irrigation monitoring nodes, and drone monitoring—which require data agreement before the final decision is made by the system. According to Lynch (1996), consensus is the process of

reaching agreement between decentralized entities despite the potential for node failure. This is especially relevant for smart farms because the agricultural environment is prone to sensor failures due to weather, power outages, or physical disturbances.

There are several consensus mechanisms that are widely used in CPS. First, *Consensus Average*, which is a scheme that allows each node to calculate the global average value based on local data exchange. Ren & Beard (2008) explain that this model is effective for distributed decision-making that does not require heavy calculations, making it suitable for large-scale farmland. For example, when the soil moisture sensor gives different values, this mechanism helps to generate the most representative average value to determine the opening of the irrigation actuator.

Second, *Majority Voting Consensus*, which is a mechanism that relies on the most votes from nodes to determine the validity of the data. This mechanism is often applied to drone swarm-based farming systems, where drones that detect a particular pest must confirm each other before the system decides on automatic pesticide spraying. Xu et al. (2015) mentioned that this approach provides higher fault tolerance because it does not depend on a single sensor node.

Third, *Lightweight Consensus Algorithms*, which are low-compute load consensus designed specifically for IoT and agricultural CPS. Since agricultural sensors have limited power, heavy consensus such as Proof-of-Work is irrelevant. According to Alcaraz & Lopez (2018), the lightweight consensus mechanism provides energy efficiency and extends the life of the sensor. This is especially important in smart farms because sensors are usually spread over large areas and are difficult to reach for maintenance.

In the context of smart farming optimization, the consensus mechanism plays a role to: a.) guarantee the reliability of sensor data, b.)reduce the risk of false data or errors, c.) optimizing automated decisions (e.g. smart irrigation), d.) improve the energy efficiency of the sensor, and;e.) Increase crop productivity through precision decisions.

SLR shows that the most dominant consensus mechanisms used in smart farms are *average consensus* and *lightweight consensus*, as both are more suitable for farm environments that are dynamic, energy-sensitive, and require real-time decision-making.

Consensus-Based Smart Farm Performance Optimization: Impact on System Efficiency, Productivity, and Resiliency

Smart farm performance optimization is highly dependent on how the consensus mechanism is implemented in the Cyber-Physical System (CPS). Consensus allows diverse sensor data to be accurate, stable, and reliable, so that the decisions the system generates truly reflect field conditions. According to Wolf (2014), CPS performance can be measured through energy efficiency, data accuracy, response time, and resistance to interference. In smart farms, all these indicators contribute directly to agricultural productivity.

First, energy efficiency. The lightweight consensus mechanism allows the sensor to work more energy-efficiently as the validation process is done collaboratively without large computations. The results of SLR show that the use *of lightweight consensus* is able to reduce sensor energy consumption by up to 20–35% on large-scale agricultural land. This is in line with the theory of energy-aware computation described by Akyildiz & Vuran (2010), that

distributed data processing is more energy-efficient than concentrating the load on a single node.

Second, improved decision-making accuracy. Without a consensus mechanism, incorrect sensor data can lead to over-irrigation, suboptimal fertilization, or incorrect pest detection. Consensus ensures that automated decisions such as opening water valves, activating spraying robots, or sending monitoring drones are made based on mutually validated data. This plays a role in increasing crop productivity by 10–25% as found by Liao et al.'s (2021) research on CPS irrigation systems.

Third, system resilience. The agricultural environment is very dynamic and full of risk of disturbances. The consensus mechanism increases *fault tolerance* because the system does not rely on a single sensor. If one node is damaged, the other nodes can still make decisions together. This concept is in line with the theory *of resilient control systems* explained by Pasqualetti et al. (2013), that systems that are distributed are more resistant to device failures and cyberattacks.

Fourth, operational and cost efficiency. With more precise automated decision-making, irrigation water usage can be reduced by up to 30%, pesticide consumption reduced by 20%, and manual labor can be reduced by up to 40%. The SLR shows that the consensus-based CPS system provides significant cost savings, especially in rice commodity agriculture and horticulture.

Fifth, the impact on sustainability. The consensus mechanism helps to maintain the wise use of resources, reduce agricultural waste, and improve the efficiency of water and energy use. According to Pierce (2016), precision agriculture that integrates sensors and control algorithms plays an important role in sustainable agriculture.

Thus, the consensus mechanism is not only a method of improving data accuracy, but also a key driver of the efficiency, productivity, resilience, and sustainability of smart farms.

Overall, the study illustrates that the consensus mechanism in CPS makes a significant contribution to smart farm optimization, ranging from sensor synchronization, system security, energy efficiency, robotic coordination, to adaptive automated decision-making . These findings consistently show that consensus is an important foundation in developing efficient, responsive, and highly resilient smart agriculture.

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