

Artificial Intelligence in seed science

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Abstract

The accelerating global population growth, as highlighted by the United Nations Food and Agriculture Organization (UNFAO), intensifies the demand for sustainable food production, particularly in land-constrained regions like India. Despite the historical gains of the Green Revolution, modern Indian agriculture grapples with persistent challenges such as soil degradation, plant diseases, and diminishing crop yields—plant diseases alone account for nearly 40% of losses. In this context, Artificial Intelligence (AI) presents a transformative opportunity to address these issues through precision, speed, and data-driven adaptability. This paper offers a comprehensive review of AI's applications in modern agriculture, with a focused lens on seed science and technology. Key AI components—including machine learning, neural networks, expert systems, and IoT—enable advancements in precision farming, pest control, irrigation, and predictive analytics. In seed science, AI is revolutionizing seed production, quality control, grading, germination testing, and genetic purity assessments through advanced tools like the Rice Seed Germination Evaluation System (RSGES) and image-based diagnostic platforms. Additionally, AI aids in seed marketing and demand forecasting. While the benefits are significant, challenges such as high costs, data security, and accessibility remain. Nevertheless, AI's expanding role promises to enhance agricultural efficiency, seed quality, and resilience, offering a path toward sustainable food security in a changing global climate.

Keywords: Artificial Intelligence (AI); Precision Agriculture; Machine Learning; Seed Quality Control; Germination Testing; Genetic Purity; Crop Yield; Plant Disease Detection.

1. Introduction

In the context of the global landscape, the United Nations Food and Agriculture Organization (UNFAO) has projected a population increase of 2 billion by the year 2050, accompanied by a corresponding expansion of agricultural land by approximately 4 per cent. Given that food is a fundamental necessity, agriculture remains the primary means of meeting the growing food demands of our expanding global population. According to estimates provided by ICAR, the demand for food grains is anticipated to surge from 192 million metric tons in 2000 to 345 million metric tons by the year 2030.

Bearing in mind situation of Indian agriculture, the 1960s saw the initiation of the Green Revolution, a transformative effort spearheaded by M. S. Swaminathan. During this period, High Yielding Varieties (HYV) were introduced in 1966, accompanied by intensive ploughing and increased use of chemical fertilizers and pesticides, which significantly boosted crop yields. However, like many advancements, this era brought forth its set of challenges. The extensive application of chemicals and their residual effects led to soil pollution. Moreover, the heavy ploughing with large tractors had adverse effects, including reduced air volume in the soil, decreased nutrient absorption, impaired water drainage, and depletion of essential soil nutrients. These combined factors eventually resulted in a significant drop in crop yields.

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Agriculture continues to grapple with challenges spanning from land preparation to marketing, and one particularly significant issue revolves around plant protection, given that diseases alone account for a 40 per cent crop loss. Identifying these diseases presents a formidable challenge due to the scarcity of essential expertise and infrastructure. The presence of designated diseases, physical impurities, and genetic anomalies further compounds the problem, resulting in reduced yields and even crop failures, particularly when dealing with low seedling vigour and subpar seed quality. To tackle these pressing issues, there's a compelling need for a cutting-edge solution from the new generation of technologies. This solution should be characterized by speed, precision, accuracy, and indispensability, qualities that can be effectively harnessed through the application of Artificial Intelligence (AI).

We are in the era of robotics and use of robotics in agriculture can be game changer in agriculture sector. Artificial Intelligence (AI) refers to the simulation of human intelligence in machines that are programmed to think like humans, act and mimic their actions. This term may also be applied to any machine that exhibits traits associated with a human mind such as learning and problem-solving. John McCarthy in the year 1956 coined the term Artificial Intelligence. AI is a wide-ranging branch of computer science concerned with building smart machines, capable of performing tasks that typically require human intelligence. It can solve real-world problems very easily and with accuracy. It can create personal virtual assistant, such as Cortana, Google Assistant and Siri, etc. We can build such Robots which can work in an environment where survival of humans can be at risk. AI opens a path for other new technologies, new devices and new opportunities.

AI is being intensely used in healthcare, automobiles, business, banking, e-commerce, entertainment, education, gaming, insurance, marketing and finance, manufacturing industries, social media, surveillance, space exploration and various other fields. Some best examples of AI include TESLA AI based self-driving car, first humanoid robot Sophia and first South Indian Robo Power TV news anchor Soundarya. AI is also explored in agriculture field but much of research and exploration work is yet to be done in seed science and technology.

2. Characteristics of AI

Big data: big data is simply a collection of unstructured information; AI has ability to reason and draw inference based to the situation using big data. It has Context driven awareness of the system *i.e.*, being aware and making decisions based on the specific background or situation on the way. It involves understanding the current environment, circumstances and appropriate factors before taking action or making decisions. **Learning:** AI has ability to learn based on historical pattern, expert input and feedback loop. **Reasoning:** it is capable of processing massive amounts of structured and unstructured data which can change constantly. **Problem solving:** it can analyze data and solve complex problems.

3. Understanding the Mechanics of Artificial Intelligence

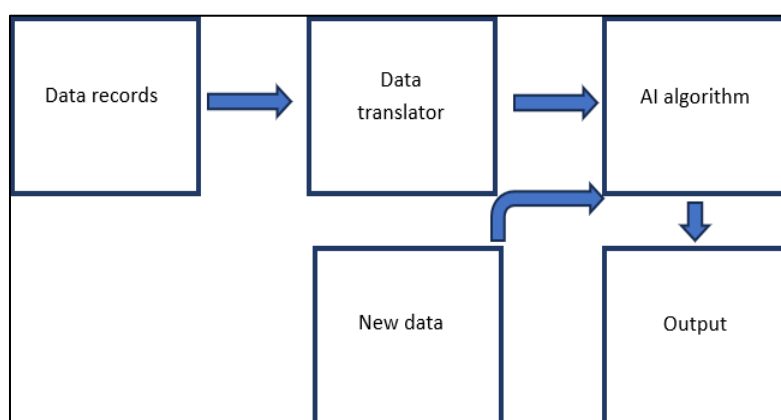


Figure 1 Inner Workings of Artificial Intelligence, design by author

The most important step in AI is algorithm. For example, whenever a nonprofessional cook wants to bake a cake, he follows sets of instructions provided in baking manual. Similarly, an algorithm is like a step-by-step recipe that tells you how to do something. It's a set of clear instructions that one can follow to solve a problem or complete a task. Just like a recipe helps you bake a cake by telling you what ingredients to use and what steps to take, an algorithm guides a computer or a person through a series of actions to achieve a specific goal. To create algorithm, set of data records are

fed, this data is first converted into the machine language. Algorithms are constructed based on data, leading to the generation of outcomes (Fig.1). The mechanics of Artificial Intelligence (AI) involve a complex interplay of algorithms, data, and computational power. Here's a simplified overview of how AI works: **Data Collection:** AI systems require a vast amount of data to learn from. This data can be structured (e.g., databases) or unstructured (e.g., text, images, audio). The quality and quantity of data are crucial for AI effectiveness. **Data Preprocessing:** Raw data often needs to be cleaned, organized, and prepared for analysis. This includes tasks like removing duplicates, handling missing values, and converting data into a suitable format. **Feature Engineering:** Features are specific data attributes that the AI model uses to make predictions or classifications. Feature engineering involves selecting, transforming, or creating relevant features from the raw data. **Algorithm Selection:** Choosing the right AI algorithm depends on the type of problem you want to solve. For instance, linear regression is used for regression problems, while deep learning is suitable for complex tasks like image recognition. **Training the Model:** This step involves feeding the prepared data into the selected AI algorithm. During training, the model learns to recognize patterns, relationships, or features in the data that are relevant to the task. **Validation and Testing:** After training, the AI model needs to be validated and tested to ensure it performs well on new, unseen data. This helps assess its generalization capabilities and identify potential overfitting (performing well on training data but poorly on new data). **Deployment:** Once the model meets the desired performance criteria, it can be deployed in real-world applications. This may involve integrating it into software systems or devices. **Inference:** Inference is the process of using the trained model to make predictions or classifications on new, incoming data. For example, a trained image recognition model can classify new images it hasn't seen before. **Feedback Loop:** AI systems often incorporate a feedback loop. This means that as the model makes predictions, it continuously learns from its mistakes and successes, improving its performance over time. **Optimization:** AI models may require periodic optimization to maintain their performance as data distributions change or new data becomes available. This might involve retraining the model with updated data. **Monitoring and Maintenance:** AI systems in production need ongoing monitoring to detect issues such as model drift (when the model's performance degrades over time) or data drift (when the input data changes significantly).

Ethical Considerations: Throughout the AI development and deployment process, ethical considerations are crucial. This involves addressing issues related to fairness, bias, transparency, and data privacy. **Scale:** Depending on the application, AI systems may need to scale horizontally (adding more machines) or vertically (upgrading hardware) to handle larger datasets or increased computational demands. **Interpretability:** Understanding why an AI model makes a specific prediction is essential, especially in critical applications like healthcare or finance. Methods for interpreting AI decisions are an active research area. **Security:** Ensuring the security of AI systems is vital. This includes protecting models from adversarial attacks and securing data used in training and inference. AI is a dynamic and evolving field, and the mechanics may vary depending on the specific AI techniques, such as machine learning, deep learning, natural language processing, or computer vision. Moreover, AI is applied across various domains, including healthcare, finance, autonomous vehicles, and more, each with its unique mechanics and challenges.

4. Domains of AI

The domain of AI machine learning is the discipline of empowering machines to tackle real-world challenges through data interpretation and analysis. Real-world challenges include climate change, health, food insecurity etc. Machine learning comprises two fundamental categories: 1) Supervised Learning:

"Train me". This technique involves instructing or educating the machine by providing it with meticulously labeled data 2) Unsupervised Learning: "I am self-sufficient in learning". It is a paradigm of training where models independently extract patterns and discern differences from unlabeled data, without receiving explicit instruction through labeled data.

Whereas deep learning is leveraging neural networks for profound insights and problem solving in high-dimensional data. Deep learning represents an advanced domain within machine learning, tailored for tackling complex problems, its applications span across diverse areas, from facebook's face verification algorithms to self-driving vehicles and virtual assistants such as google and Alexa. Deep Learning consists of Multi-Neural Network Architecture. This mainly includes networks like Artificial Neural Network (ANN), Convolutional Neural Network (CNN) and Recurrent Neural Network (RNN). In simple terms ANN is the neural network that stores data in the form of numbers. CNN is the neural network that secures data in the form of image. It is widely used in seed science *i.e.*, for image processing. And RNN is the neural network where data in the form of time and series. It is used in developing forecast model.

An expert system is a type of AI-powered computer system designed to mimic the decision-making skills of a human expert. These systems rely on if-then logic rules to solve intricate problems and don't follow the usual step-by-step programming. Expert systems find applications in fields like managing information, healthcare, and are even used in

apps like Aarogya Setu. At the end of 1970's, the expert system started to be applied in agricultural domain. An Expert System on Wheat Crop Management (Exowhem) has been developed by the Division of Computer Application, ICAR-Indian Agricultural Statistics Research Institute, New Delhi in collaboration with ICAR-IARI, New Delhi and ICAR- Indian Institute of Wheat and Barley Research, Karnal that helps in diagnosing the diseases and helps in its management. Here IF-THEN rules are employed to link symptoms with specific colors, as each disease manifests differently in the plant or its various parts. (Islam *et al.*, 2018).

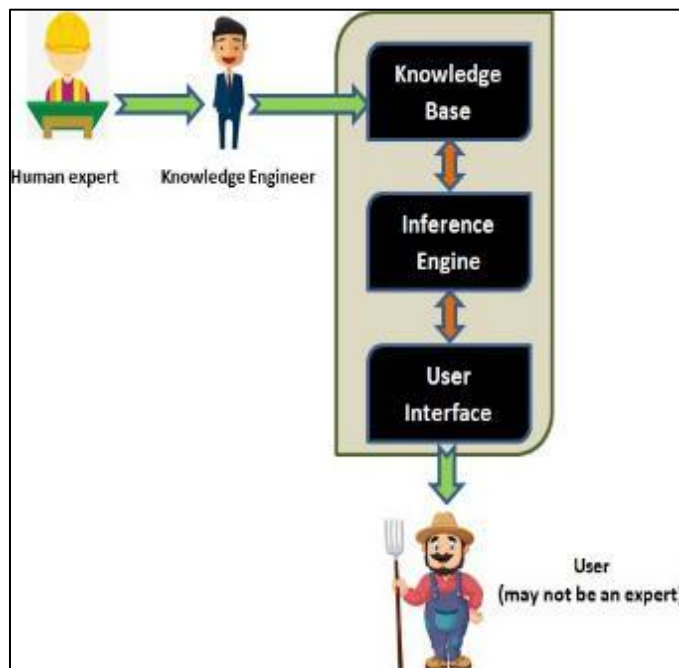


Figure 2 Main Components of an Expert System, (Mounir *et al.*, 2018)

Fuzzy logic is a computing approach based on the principles of “degrees of truth” instead of the usual modern computer logic *i.e.*, Boolean in nature. Used in the medical fields to solve complex problems that involve decision making. Generally incorporated in automatic gearboxes, degree of disease (low to severe). Internet of things (IoT) describes the network of physical objects – “things” – that are embedded with sensors, software, and other technologies for the purpose of connecting and exchanging data with other devices and systems over the Internet. IoTs in an agricultural context refers to the use of sensors, cameras and other devices to turn every element and action involved in farming into data. Large data sets on Weather, moisture, plant health, mineral status, chemical applications, pest presence can be generated. Accordingly, via software algorithms store and transfer data for development of models. Natural language processing (NLP) is a field within computer science and artificial intelligence (AI) that focuses on enabling computers to comprehend and interpret written text and spoken language, aiming to replicate human-like language understanding capabilities.

Robotics: Robotics combines AI with physical machines to create intelligent robots capable of performing tasks in the physical world. These tasks can range from manufacturing to healthcare and exploration. **Speech Recognition:** Speech recognition AI systems can convert spoken language into written text. They are used in voice assistants, transcription services, and more. **Reinforcement Learning:** Reinforcement learning is a type of machine learning where agents learn by interacting with an environment and receiving feedback in the form of rewards or penalties. It's used in areas like game playing and robotics. **Autonomous Systems:** Autonomous AI systems can make decisions and take actions without human intervention. This includes autonomous vehicles, drones, and smart home systems. **Genetic Algorithms:** Genetic algorithms use principles inspired by biological evolution to solve optimization and search problems. They are used in various fields, including optimization and machine learning. **Cognitive Computing:** Cognitive computing combines AI and cognitive science to create systems that can simulate human thought processes. These systems are designed to understand and reason about complex data. **Swarm Intelligence:** Swarm intelligence is inspired by the collective behavior of social insects like ants and bees. It's used to solve optimization and decision-making problems through the cooperation of multiple agents.

Virtual Agents: Virtual agents are AI-driven characters or entities that can interact with humans in virtual environments. They find applications in gaming, simulations, and customer service. **Emotion AI:** Emotion AI, or affective computing, focuses on recognizing and responding to human emotions. It's used in applications like sentiment analysis, mental

health monitoring, and human-computer interaction. Quantum AI: Quantum AI explores the application of quantum computing to enhance AI capabilities. Quantum computers have the potential to solve complex problems much faster than classical computers. These domains represent various facets of artificial intelligence, each with its own set of techniques, algorithms, and applications. AI researchers and practitioners often draw from multiple domains to develop comprehensive solutions for real-world problems.

Artificial Intelligence (AI) is playing a significant role in revolutionizing the agricultural industry. It offers innovative solutions to address various challenges in farming, making agriculture more efficient, sustainable, and productive. Here is some key ways AI is being used in agriculture:

Precision Agriculture: AI-driven precision agriculture uses sensors, drones, satellite imagery, and machine learning to monitor and manage crops and livestock at a granular level. Farmers can optimize planting, irrigation, fertilization, and pest control, leading to increased yields and resource efficiency. **Crop Monitoring and Management:** AI algorithms analyze data from various sources, including satellite and drone imagery, weather conditions, and soil sensors, to assess crop health and predict potential issues like disease outbreaks or nutrient deficiencies. This allows farmers to take proactive measures.

Weed and Pest Control: AI-powered robots and drones equipped with computer vision can identify and selectively target weeds and pests, reducing the need for chemical interventions. This approach minimizes environmental impact and saves costs. **Harvesting Automation:** AI-driven robotic systems are developed to harvest fruits and vegetables with precision and efficiency. These robots can recognize ripe produce, pick it gently, and sort it according to quality. **Predictive Analytics:** AI models can predict crop yields and market demand, helping farmers make informed decisions about planting and harvesting schedules. This reduces waste and improves profitability.

Livestock Monitoring: AI-powered sensors and wearables track the health and behavior of livestock. Farmers can detect diseases early, optimize feeding schedules, and improve animal welfare. **Smart Irrigation:** AI algorithms optimize irrigation by considering factors like weather, soil moisture, and crop type. This prevents overwatering and conserves water resources. **Supply Chain Optimization:** AI helps streamline the agricultural supply chain, from farm to market. It optimizes logistics, reduces spoilage, and ensures timely delivery of produce. **Farm Management Software:** AI-driven farm management platforms provide farmers with insights and recommendations for daily operations. These systems can assist in planning, budgeting, and resource allocation. **Crop Breeding:** AI accelerates crop breeding by analyzing genetic data and identifying desirable traits. This can lead to the development of crops that are more resistant to pests, diseases, and environmental stressors.

Soil Health Assessment: AI can assess soil quality and composition, allowing farmers to make data-driven decisions about soil management and nutrient supplementation. **Food Quality Inspection:** AI-powered vision systems inspect the quality and safety of agricultural products during processing and packaging. This ensures that only high-quality products reach consumers. **Market Predictions:** AI models analyze market trends and historical data to predict commodity prices. This information helps farmers make informed decisions about pricing and marketing strategies.

Rural Connectivity: AI-powered solutions are being used to improve connectivity in rural areas, enabling farmers to access information, marketplaces, and agricultural services via mobile apps and online platforms. **Climate Adaptation:** AI helps farmers adapt to changing climate conditions by providing weather forecasts, risk assessments, and recommendations for mitigating climate-related challenges.

The adoption of AI in agriculture is driven by the need to increase food production to feed a growing global population while minimizing environmental impact. AI technologies have the potential to make farming more sustainable, efficient, and resilient in the face of various challenges.

5. Applications in seed science

AI can play a crucial role in seed production, seed certification, seed processing, seed quality, seed control, seed storage and seed marketing (Fig.3). There are numerous challenges and issues in the process of seed production. Seed production is a complex process marked by various factors that can introduce uncertainty and difficulties. These factors encompass fluctuating environmental conditions in the seed production plot, challenges in determining optimal sowing timing and methods, managing seed rates, handling nutrients and irrigation, controlling weeds, identifying off-types, managing soil moisture, fine-tuning inter and intra-row spacing, and addressing pest and disease issues. These factors collectively contribute to the potential production of lower-quality seeds. Artificial intelligence (AI) has practical applications in the management of seed production. The utilization of precise sowing techniques through AI is possible

which ensures efficient seed placement, minimizes seed wastage, and allows for precise control of the seed rate (Fig.4). The AI can water plants the exact amount they need, so that crop does not suffer from drought or wastage of water (Fig.4).

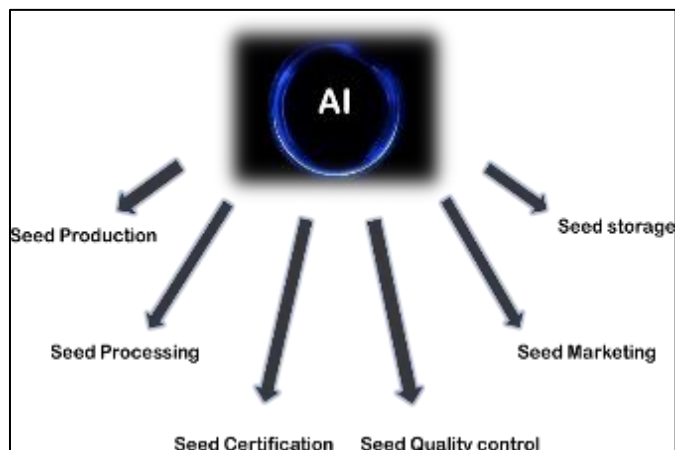


Figure 3 The figure shows the application of AI in various sectors of seed science, Design by author



Source: <https://genesis.farm.bot/v1.6/extras/reference/seeds.html>

Figure 4 Farm bot precisely planting seeds and irrigation



Figure 5 Rice seed production plot, off type detection based on anthocyanin pigmentation

AI-based farmbots have the capability to detect and eliminate weeds in their early stages within the seed production plot. This proactive weed control strategy helps preserve seed quality standards and prevents any adverse impact on the crop from weed management activities (Fig.4). Identifying off-types in seed production plants during their initial stages poses a considerable challenge, and the subsequent removal process demands skilled labour. These off-types can significantly reduce the genetic purity of crops. However, artificial intelligence (AI) has the potential to revolutionize this aspect. For instance, in a rice seed production plot, AI can effectively detect off-types by analysing the presence or absence of anthocyanin pigmentation. When AI-based robots identify off-type plants lacking pigmentation, they can systematically eliminate them, streamlining the process and preserving crop genetic purity (Fig.5).

Artificial Intelligence (AI) is making significant strides in the field of seed science, offering innovative solutions to enhance seed production, quality control, and overall agricultural productivity. Here are some key applications of AI in seed science:

Seed Sorting and Grading: AI-powered machines can accurately sort and grade seeds based on various attributes such as size, shape, colour, and quality. This ensures that only high-quality seeds are planted, leading to better crop yields.

Germination Testing: AI systems can automate the germination testing process by analyzing seedling growth patterns and providing rapid and precise results. This reduces the time and labor required for germination tests.

Artificial Intelligence (AI) can play a significant role in optimizing seed germination processes in agriculture. Germination is a critical phase in crop production, and AI can enhance germination rates, reduce resource wastage, and improve overall seedling health. Here is some ways AI is applied in seed germination:

Germination Prediction: AI models can predict seed germination rates based on various factors, including seed quality, environmental conditions, and historical data. By analyzing these variables, AI can estimate the likelihood of successful germination, allowing farmers to make informed decisions about seed planting.

Optimal Planting Time: AI algorithms can analyze weather forecasts, soil conditions, and historical climate data to determine the best time for planting seeds. This helps ensure that seeds are sown under conditions that maximize germination success.

Automated Seed Sorting: AI-powered machines can sort seeds based on their size, weight, and quality. This ensures that only high-quality seeds are planted, increasing the likelihood of successful germination.

Seed Coating Optimization: AI can optimize the application of seed coatings, including nutrients and protective compounds. By precisely controlling the coating process, AI ensures that seeds receive the necessary nutrients for germination while protecting them from diseases and pests.

Monitoring Environmental Conditions: AI-driven sensors and monitoring systems can track environmental conditions in seed germination facilities. These systems can adjust temperature, humidity, and light levels to create the ideal germination environment.

Disease Detection: AI-based image recognition can identify signs of diseases or abnormalities in germinating seeds. Early detection allows for prompt intervention to prevent the spread of diseases and improve germination rates.

Automated Irrigation: AI-controlled irrigation systems can deliver the optimal amount of water to germinating seeds based on real-time soil moisture data. This prevents over- or under-watering, which can be detrimental to germination.

Genetic Analysis: AI can analyze genetic data to identify seed varieties with superior germination characteristics. This helps breeders develop seeds with improved germination rates.

Quality Control: AI can assess seed quality by analyzing factors such as moisture content, genetic purity, and contaminants. This ensures that only high-quality seeds are used for germination.

Remote Monitoring: Drones equipped with AI technology can capture high-resolution images and data from germination fields. This allows for remote monitoring of germination progress and the early detection of issues.

Data Analysis: AI algorithms can process and analyze vast amounts of germination data, helping researchers identify patterns and factors that influence germination success. This knowledge can inform breeding and cultivation practices.

Real-time Feedback: AI systems can provide real-time feedback to farmers and seed producers during the germination process. Alerts can be issued if conditions deviate from the ideal, allowing for timely interventions.

Customized Growing Conditions: AI can recommend customized growing conditions for different seed varieties based on their specific germination requirements. This ensures that each seed type receives optimal treatment. By leveraging AI in seed germination processes, farmers and seed producers can improve the efficiency and success rates of germination, leading to higher crop yields and better resource utilization. AI's ability to analyze and adapt to changing conditions in real time makes it a valuable tool for enhancing seed germination in agriculture.

Seed Quality Assessment: AI algorithms can assess seed quality by analyzing factors like moisture content, genetic purity, and the presence of contaminants. This ensures that farmers receive seeds of the highest quality for planting. A seed quality algorithm is a computer program or mathematical model designed to assess and measure the quality of seeds. These algorithms use various data inputs and criteria to determine the overall quality of seeds, including factors such as genetic purity, moisture content, physical attributes, and the presence of contaminants. Here's a simplified outline of how a seed quality algorithm might work:

Data Collection: The algorithm begins by collecting data about the seeds under evaluation. This data can come from various sources, including physical measurements, genetic information, and visual inspection.

Genetic Purity Analysis: If the seeds are of a specific crop variety, the algorithm may analyze their genetic characteristics to ensure purity. It compares the genetic profile of each seed with the expected genetic profile for the variety in question.

Moisture Content Assessment: Seed moisture content is critical for storage and germination. The algorithm measures the moisture content of each seed, comparing it to acceptable ranges for the particular seed type.

Physical Attributes

Evaluation: The algorithm assesses the physical attributes of seeds, including size, shape, colour, and surface texture. Deviations from expected physical characteristics can indicate lower quality. **Contaminant Detection:** Visual inspection or imaging technology can be used to detect contaminants such as foreign seeds, debris, or disease symptoms. The algorithm identifies and quantifies these contaminants. **Data Integration:** The algorithm integrates data from multiple sources, assigning weights or importance to different criteria based on their significance to seed quality.

Scoring and Classification: Using the integrated data, the algorithm calculates a quality score for each seed. Seeds are then classified into different quality categories based on their scores. **Reporting:** The algorithm generates reports that provide detailed information about the quality of each seed. This may include a summary of findings, quality classifications, and any identified issues or deviations. **Decision Support:** Seed quality algorithms can provide recommendations or decision support to seed producers and farmers. For instance, they may suggest which seeds should be used for planting, which should be discarded, or whether specific treatments are needed to improve seed quality. **Continuous Improvement:** Some seed quality algorithms are designed to learn and adapt over time. They may use machine learning techniques to improve accuracy and effectiveness based on new data and feedback.

Seed quality algorithms can be implemented using various computational and analytical techniques, including machine learning, image processing, and statistical analysis. The specific design and features of a seed quality algorithm can vary depending on the goals and requirements of seed producers and the crops being cultivated. These algorithms are valuable tools in modern agriculture, helping ensure that high-quality seeds are used for planting, which ultimately contributes to better crop yields and agricultural productivity. Additionally, they aid in maintaining the genetic purity of crop varieties, which is crucial for seed certification and variety protection programs.

Disease Detection: AI-based image recognition can identify diseases and abnormalities in seeds. By analyzing seed images, AI can detect signs of fungal or bacterial infections, helping prevent the planting of infected seeds. **Predictive Modelling:** AI models can predict seed quality and germination rates based on historical data, environmental conditions, and genetic information. This helps seed producers optimize their seed production processes. **Seed Coating Optimization:** AI can optimize the application of seed coatings, including nutrients, fungicides, and insecticides. This ensures uniform and effective coating, enhancing seed protection and germination rates. **Seed Storage Management:** AI-powered sensors and monitoring systems can track environmental conditions in seed storage facilities. If conditions deviate from the ideal, AI can issue alerts to prevent seed deterioration. **Crop Forecasting:** AI can contribute to accurate crop yield forecasting by considering various factors, including seed quality and planting conditions. This information helps farmers plan their planting and marketing strategies. **Genetic Analysis:** AI-driven genetic analysis tools can accelerate the breeding of new seed varieties with desirable traits, such as resistance to pests, drought tolerance, or increased yield. **Data-driven Breeding:** AI can analyze vast amounts of genetic and environmental data to identify optimal breeding combinations. These speeds up the development of new seed varieties adapted to specific growing conditions. **Seed Inventory Management:** AI systems can track seed inventory, predict restocking needs, and ensure that the right seeds are available to farmers when needed. **Customized Seed Recommendations:** AI-powered platforms can provide farmers with personalized seed recommendations based on their location, soil type, climate, and historical performance data. **Pest and Disease Prediction:** AI models can predict pest and disease outbreaks based on environmental conditions, helping farmers take preventive measures to protect their crops. **Remote Monitoring:** AI enables remote monitoring of seed production fields. Drones equipped with AI can capture high-resolution images and data for analysis, allowing for timely interventions. **Market Analysis:** AI can analyze market trends and demand patterns for different seed varieties, helping seed producers make informed decisions about which seeds to produce and market. The integration of AI in seed science not only improves seed quality but also contributes to sustainable agriculture by reducing the use of chemicals and ensuring the optimal use of resources. As AI continues to advance, its applications in seed science are likely to expand, benefiting both seed producers and farmers worldwide.

6. Drones

Drones, officially known as unmanned aerial vehicles, represent flying robotic devices. When utilized in agriculture applications, they are commonly referred to as agricultural drones. The adoption of drones is rapidly expanding across various sectors of the economy, with the agricultural industry experiencing remarkable growth. According to reports, the agricultural drone market is projected to surge from a \$1.2 billion (USD) industry in 2019 to a staggering \$4.8 billion by 2024. Drones are poised to become increasingly prevalent on both large and small farms, serving a range of purposes from field scouting to security. These drones play a pivotal role in what's commonly known as 'precision agriculture,' where data collected from these aerial devices aids farmers in making well-informed agronomic decisions. In fact, drone technology has already become indispensable in many large-scale precision farming operations. The insights gleaned from drone surveys of fields empower farmers to meticulously plan their planting and treatments, optimizing crop yields. It's worth noting that precision farming systems have been reported to potentially boost yields by up to 5 per

cent, a significant enhancement in an industry often characterized by narrow profit margins. In this article, we will delve into the existing applications of drone technology in farming, explore emerging agricultural drone technologies, and touch upon the steps and challenges associated with the widespread integration of drones in agriculture.

Spraying drones: The use of drone technology for applying spray treatments is already well-established in South-East Asia, where South Korea, for instance, employs drones for approximately 30 per cent of their agricultural spraying needs. These drone sprayers exhibit the ability to access challenging terrain, including steep tea fields at high altitudes. Importantly, they enhance worker safety by eliminating the need for manual field navigation with backpack sprayers, which can pose health risks. Furthermore, drone sprayers excel at delivering precise, fine spray applications, allowing for targeted treatment of specific areas, thereby maximizing efficiency and reducing chemical costs. However, it's important to note that regulations surrounding drone sprayers vary significantly between countries. For example, in Canada, their use is currently not legal due to the need for further testing to assess the impact of spray drift. Some regulatory proposals advocate for the restriction of flying spray drones to trained professionals, mirroring Yamaha's approach. Yamaha, a manufacturer of spray drones, does not sell them directly but offers spray drone services complete with licensed operators. Utilizing drones for precise chemical application ensures that the correct dosages are used, leading to both the prevention of soil pollution and significant reductions in time and labour.

Crop monitoring drone: The field of drone security is rapidly expanding, offering valuable benefits not only outside agriculture but also in farm management. Drones play a pivotal role in efficiently monitoring vast farm areas, saving valuable time, and enabling more frequent oversight of hard-to-reach locations. Equipped with cameras, these drones provide continuous surveillance of farm operations, ensuring smooth running and facilitating the tracking of equipment usage. In the realm of security, drones are a cost-effective alternative to traditional security personnel for monitoring fences and perimeters, especially for high-value crops like cannabis. Additionally, drone cameras are being leveraged in innovative ways to enhance the protection of farm animals. They aid in locating missing or injured herd animals in remote grazing areas, a task that once required hours of manual searching but can now be accomplished within minutes with drones. This technology is revolutionizing the monitoring of remote areas, making farm management more efficient and effective (Fig.6).



Source: <https://www.croptacker.com/blog/drone-technology-in-agriculture.html>

Figure 6 Spraying drones and crop monitoring drone

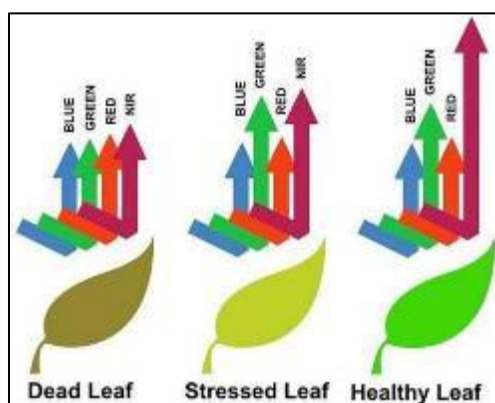
Irrigation drones: Recent research from Australia is opening up promising avenues for the application of drones in agriculture. In light of the escalating impact of climate change on drought conditions, the development of more efficient irrigation solutions is of paramount importance. Drones equipped with microwave sensing technology can obtain precise soil health data, including moisture levels, without interference from plant growth. This breakthrough allows for the optimal distribution of water across fields, promoting resource conservation and enhancing overall efficiency in irrigation practices (Fig.8).

Planting & Seeding drones: A relatively newer and less common application of drones in agriculture revolves around seed planting. Currently, automated drone seeders find primary usage in the forestry sector, but the potential for broader adoption is increasingly promising. The use of drones for planting offers several advantages, particularly in reforesting challenging and remote areas, without putting human workers at risk. Additionally, the efficiency gains are substantial, as a team of just two operators working with ten drones can plant an impressive 400,000 trees in a single day. This technology holds the promise of transforming the way we approach large-scale planting operations.

Field monitoring conditions drones: drones are increasingly employed for comprehensive field monitoring, enabling the assessment of soil health and overall field conditions. These aerial devices offer precise field mapping, including elevation data, which empowers growers to identify any anomalies within the field. Elevation information proves

valuable in determining drainage patterns and pinpointing wet or dry areas, thereby enhancing the efficiency of irrigation practices. Furthermore, certain agricultural drone retailers and service providers offer advanced sensors that can monitor nitrogen levels in the soil. This capability facilitates the precise application of fertilizers, eliminating underperforming areas and promoting long-term soil health improvements. In essence, drones are becoming invaluable tools for maintaining optimal field conditions and maximizing agricultural productivity (Fig.6).

Plant health monitoring drones: drones are proving to be highly effective tools for scouting and monitoring the health of plants. Equipped with specialized imaging technology like the Normalized Difference Vegetation Index (NDVI), they use detailed colour information to provide real-time insights into plant health. This empowers farmers to closely track crop development, enabling swift responses to any emerging issues, ultimately saving the plants from potential harm. In addition to NDVI-equipped drones, standard camera-equipped drones are also utilized for crop health monitoring. While some farmers already rely on satellite imagery for assessing crop growth, density, and coloration, accessing satellite data can be expensive and less effective in certain situations compared to the closer-range drone imaging. Drones flying in proximity to fields are less impacted by cloud cover and poor lighting conditions. While satellite imaging may offer accuracy to the meter, drone imaging provides precise image location down to the millimetre. This level of precision allows for the early detection of issues such as stand gaps after planting, enabling timely replanting as needed, and the prompt identification and treatment of diseases or pest infestations (Fig.7)



Source: <https://www.croptacker.com/blog/drone-technology-in-agriculture.html>

Figure 7 Normalized Difference Vegetation Index (NDVI)



Source: <https://www.croptacker.com/blog/drone-technology-in-agriculture.html>

Figure 8 Irrigation drones and drone pollination

Drone pollination: Emerging applications of drones in agriculture, although still in the experimental and developmental phases, hold significant promise. One of the widely discussed and sometimes sensationalized applications is the use of drones for pollination. Researchers in the Netherlands and Japan are actively working on the development of compact drones designed for pollinating plants in a non-invasive manner. The future objective is to create autonomous pollination drones capable of independently carrying out pollination tasks and monitoring crop health without the need for continuous operator intervention (Fig.8).

Several mobile applications have been developed to detect plant diseases in their early stages, and one noteworthy example is the Plantix app. The Plantix app offers coverage for 30 major crops and boasts the capability to identify over 400 plant diseases. It's available in 18 languages and has been downloaded more than 10 million times, establishing

itself as the leading agricultural app worldwide for early damage detection, pest and disease management, and enhancing crop yields for farmers. Plantix is developed through a collaborative effort involving Progressive Environmental and Agricultural Technologies, in partnership with International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Professor Jayashankar Telangana State Agricultural University (PJTSAU), the Government of Andhra Pradesh, and on-site collaboration with Food and Agriculture Organization (FAO), Centre for Agriculture and Bioscience International (CABI), International Maize and Wheat Improvement Centre (CIMMYT) and ICRISAT.

Numerous challenges exist in the realm of seed quality control, including: Identifying and categorizing seeds based on attributes like size, shape, and colour. Assessing physical purity by identifying weed seeds, other crop seeds (OCS), and inert matter. Evaluating seed quality through germination, vigour, viability, and health assessments. These issues are compounded by the time-consuming nature of these processes and their reliance on manual labour. These issues can be solved using AI. Seed Image analyser can be used to control seed quality. Image analysis refers to the process of deriving valuable insights from images. This encompasses a range of tasks, including identifying shapes, detecting edges, eliminating distortions, tallying objects and computing statistical data for tasks like texture analysis or assessing image quality. Seed image analyzer serves various purposes, including: characterizing and identifying seed varieties, sorting and grading seeds, conducting physiological assessments, such as evaluating seed vigour, viability, and germination percentage. Detecting signs of mechanical damage, insect infestations, and diseases in seeds. Seed image analyzer has been successfully used to evaluate rice germination by using digital image processing and an artificial neural networks technique. Artificial neural network (ANN): 18 features: 3 colour features, 7 morphological features (change in morphological features such as seed size, seed shape, seed area, seed perimeter, seed length, seed width, seed radicle length and roundness factor), and 8 textural features were considered to evaluate germination of rice seeds (Lurstwut *et al.*, 2017).

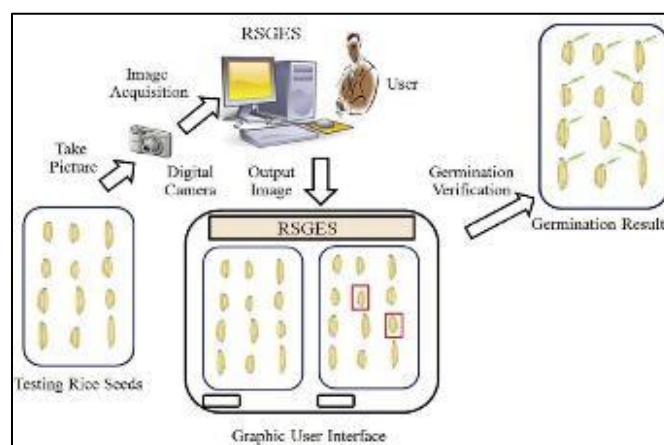


Figure 9 Rice Seed Germination Evaluation System (RSGES) conceptual diagram, (Lurstwut *et al.*, 2017)

Problems in seed marketing: Insufficient storage infrastructure, including concerns related to temperature, relative humidity, and moisture in storage facilities. The difficulty of accurately estimating seed demand. Issues related to the timely availability of seeds. Challenges with price determination, promotional activities, and sales strategies. A novel perspective on spring onion seed demand forecasting and hybrid Holt-Winters and Support Vector Machine (SVM) forecasting model was proposed by Zhu *et al.* (2019). This study provides a promising spring onion seed demand forecasting model that helps understand the seed demand and the model could potentially be applied to demand forecasting of other crop seeds to reduce total operational costs.

The advantages of AI: Precision Farming: AI enables precise monitoring and management of crops, optimizing resource utilization such as water, fertilizer, and pesticides. This leads to increased crop yields and cost savings. Crop Monitoring: AI-powered drones and satellite imagery can monitor crop health, detect diseases, and assess nutrient levels, allowing for timely intervention and improved crop management. Data-Driven Decisions: AI processes vast amounts of data from sensors, weather forecasts, and historical information to provide farmers with data-driven insights for better decision-making. Predictive Analytics: AI algorithms can predict crop yields, disease outbreaks, and weather patterns, enabling farmers to plan and adapt their strategies accordingly. Weed and Pest Control: AI-driven robots and drones can identify and eliminate weeds and pests with precision, reducing the need for chemical interventions and minimizing environmental impact. Livestock Management: AI can monitor the health and behavior of livestock, helping farmers detect diseases early and improve overall animal welfare. Supply Chain Optimization: AI can optimize the logistics and supply chain for agricultural products, reducing wastage and ensuring timely delivery to markets. Crop Sorting and

Grading: AI-powered machines can sort and grade harvested crops based on quality, size, and other attributes, improving product quality and market value. Labor Efficiency: Automation through AI reduces the need for manual labour, making agriculture more efficient and reducing labour costs. Disease Detection: AI can quickly identify and diagnose plant diseases and recommend appropriate treatments, reducing crop losses. Soil Health Assessment: AI can analyse soil data to assess soil health and recommend soil management practices to improve fertility. Climate Adaptation: AI helps farmers adapt to changing climate conditions by providing real-time weather forecasts and suggesting suitable crop varieties and planting times. Financial Management: AI-based tools can assist farmers in financial planning, budgeting, and risk management, improving overall farm profitability. Remote Monitoring: Farmers can remotely monitor their farms and equipment through AI-powered mobile apps, ensuring timely responses to issues. Research and Development: AI accelerates agricultural research by analysing large datasets and assisting in the development of new crop varieties and farming techniques. These advantages of AI in agriculture contribute to increased productivity, sustainability, and profitability while minimizing environmental impact and addressing the challenges of feeding a growing global population.

Every new technology brings with it certain drawbacks or disadvantages. As a result, some of the disadvantages include: High Initial Costs: Implementing AI technology in agriculture can be expensive, making it less accessible to small-scale farmers and developing regions. Data Privacy Concerns: The collection and sharing of extensive agricultural data for AI analysis raise concerns about data privacy and security. Lack of Skills and Training: Farmers may require training and education to effectively use AI systems, which can be a barrier in regions with limited access to technology education. Dependency on Technology: Overreliance on AI technology may reduce farmers' traditional farming skills and knowledge. Maintenance and Upkeep: AI systems require regular maintenance and updates, which can be challenging in remote areas with limited technical support. Complexity: AI systems can be complex, and farmers may find it challenging to understand and operate them effectively. Job Displacement: Automation through AI could potentially lead to job displacement in agriculture, particularly in manual labour roles. Environmental Impact: While AI can optimize resource use, it may also contribute to increased energy consumption if not designed with energy efficiency in mind. Ethical Concerns: There are ethical concerns related to AI in agriculture, including issues of transparency, bias in algorithms, and responsible AI use. Dependency on Data: AI systems heavily rely on data, and the accuracy of predictions and recommendations depends on the quality of input data. Regulatory Challenges: The regulatory framework for AI in agriculture is still evolving, which can create uncertainty and compliance challenges for farmers and technology providers. Unintended Consequences: AI decisions can have unintended consequences, and errors or biases in algorithms can lead to undesirable outcomes. Long-Term Sustainability: The long-term sustainability of AI in agriculture, including its environmental impact and economic viability, remains uncertain. It's important to recognize and address these disadvantages while leveraging the benefits of AI to ensure responsible and sustainable adoption in agriculture.

The combination of advanced computational techniques with traditional agricultural practices will unlock new opportunities for sustainable and efficient crop production. In conclusion, the integration of Artificial Intelligence (AI) in seed science represents a revolutionary leap forward in agriculture, promising to address critical challenges and unlock new opportunities in seed production, quality control, and research. As global population growth continues to strain food resources, AI offers a beacon of hope for increasing crop yields, preserving genetic diversity, and ensuring food security for future generations. AI's application in seed science is multifaceted, spanning various domains, from genetic purity analysis to seed quality assessment, disease detection, and even the optimization of planting and harvesting processes. Through machine learning, deep learning, computer vision, and data analysis, AI algorithms have the capacity to enhance nearly every aspect of seed science.

One of the most significant contributions of AI in seed science is in the domain of seed quality control. AI-driven image analysis systems can accurately and rapidly evaluate seed attributes, such as size, shape, color, and surface texture, with unprecedented precision. These systems can detect contaminants, assess genetic purity, and measure moisture content, providing invaluable insights into seed quality. The automation of these processes not only reduces human error but also accelerates the pace of seed quality assessment, facilitating quicker decisions for seed certification and distribution. Furthermore, AI has empowered seed scientists to tackle one of the most persistent challenges in agriculture: disease detection. Plant diseases pose a considerable threat to crop yields, and their early identification is paramount for effective management. AI algorithms, equipped with computer vision and machine learning, can analyze images of plants and seeds to detect signs of diseases, pests, or genetic anomalies. By identifying these issues at their incipient stages, AI systems enable timely intervention, reducing crop losses and enhancing overall agricultural productivity.

In the realm of genetic purity assessment, AI has ushered in a new era of accuracy. Through the analysis of genetic markers and DNA sequencing, AI algorithms can verify the genetic purity of seed varieties with unmatched precision. This is particularly crucial in the context of intellectual property rights and seed certification, ensuring that farmers

receive seeds of the intended variety and that breeders' rights are protected. Moreover, AI has contributed to more sustainable farming practices through precise planting and irrigation. AI-powered planting machinery can optimize seed placement, spacing, and depth, reducing waste and maximizing crop establishment. Similarly, AI-driven irrigation systems use data on soil moisture levels, weather conditions, and crop water requirements to deliver the right amount of water to plants, mitigating the risk of drought or over-irrigation. As we consider the implications of AI in seed science, it is important to acknowledge the potential challenges and ethical considerations. The adoption of AI may require investment in infrastructure, training, and technology access, posing hurdles for small-scale farmers and resource-constrained regions. Additionally, the responsible use of AI, adherence to data privacy regulations, and addressing biases in algorithms are paramount concerns. In the context of research and development, AI accelerates the breeding of new crop varieties with desired traits. By analyzing vast datasets on plant genetics, AI can predict which genetic combinations are most likely to yield superior crops. This expedites the breeding process, potentially leading to the development of drought-resistant, disease-resistant, or higher-yielding crops, essential for global food security.

Accelerated Crop Breeding: AI's ability to analyze massive datasets and simulate genetic combinations will accelerate the development of new crop varieties. Breeders can harness AI to predict which genetic traits are most likely to produce crops with desired characteristics, such as drought resistance, disease resistance, or increased nutritional value. **Pest and Disease Management:** AI will continue to improve the early detection of pests and diseases. Drones equipped with AI-powered cameras will survey fields for signs of trouble, while ground-based robots can target specific plants with precision treatments, minimizing the need for broad-spectrum pesticides. **Precision Planting and Harvesting:** AI-driven machinery will become standard in agriculture. Autonomous tractors, planters, and harvesters will optimize planting depth, spacing, and harvest timing. This precision will conserve resources and reduce labour costs. **Climate-Resilient Farming:** AI will assist farmers in adapting to changing climate conditions. Machine learning models will provide real-time climate forecasts and suggest planting and irrigation strategies to maximize yields in a given environment. **Seed Storage and Conservation:** AI-powered monitoring systems will ensure the safe storage and conservation of seed banks. These systems will track environmental conditions, detect potential threats like pests or mould, and take proactive measures to preserve genetic diversity.

Global Collaboration and Knowledge Sharing: AI will facilitate global collaboration among scientists, researchers, and farmers. AI-driven platforms will enable the sharing of agricultural data, best practices, and innovative solutions across borders, leading to more efficient and sustainable seed production. **Sustainable Agriculture:** AI will drive sustainable farming practices by optimizing resource use. Smart irrigation systems will conserve water, AI-powered machinery will reduce fuel consumption, and data-driven decision-making will minimize waste and environmental impact. **Regulatory and Ethical Considerations:** As AI becomes more deeply integrated into seed science, regulatory bodies will need to establish guidelines for responsible AI use in agriculture. Ensuring data privacy, addressing algorithmic biases, and upholding ethical standards will be critical considerations. **Accessibility for Small-Scale Farmers:** Efforts will be made to make AI technologies accessible and affordable for small-scale farmers in developing regions. Initiatives may include providing low-cost AI tools, training programs, and support networks to empower farmers with limited resources.

Lurstwut et al. (2017) worked on computer software- The Rice Seed Germination Evaluation System (RSGES). It can evaluate a rice seed image for germination prediction by using digital image processing and an artificial neural networks technique. The digital images were taken with a normal digital camera or mobile phone camera, which is very easy for farmers to process. RSGES consists of six main processing modules: 1) image acquisition, 2) image preprocessing, 3) feature extraction, 4) germination evaluation, 5) results presentation and 6) germination verification. The experiment was conducted on seed of the Thai rice species CP-111 in Bangkok and Chiang Mai, Thailand. RSGES extracted 18 features: 3 colour features, 7 morphological features and 8 textural features. The system applied artificial neural network techniques to perform germination prediction. The system precision rate was 7.66 per cent false accepted with a processing speed of 8.31 s per image.

Islam et al. (2018) conducted research on diagnosing wheat seed borne diseases using Expert System. An Expert System on Wheat Crop Management (Exowhem) has been developed by the Division of Computer Application, ICAR-IASRI, New Delhi in collaboration with ICARIARI, New Delhi and ICAR-IIWBR, Karnal that helps in diagnosing the diseases and helps in its management. The system carries information about 14 important diseases affecting wheat crop stored in its knowledge base. The system works as an information bank for wheat growing farmers that can help them in better crop management in order to enhance productivity and production of wheat in India. The system is available at the URL <http://www.iasri.res.in/wheat>.

Zhu et al. (2019) worked on Spring onion seed demand forecasting, which can help to reduce the high operational costs increased by long-period propagation and complex logistics, and has not previously been investigated yet. This paper provides a novel perspective on spring onion seed demand forecasting and proposes a

hybrid Holt-Winters and Support Vector Machine (SVM) forecasting model. This study provides a promising spring onion seed demand forecasting model that helps understand the relationships between seed demand and other dynamic factors and the model could potentially be applied to demand forecasting of other crop seeds to reduce total operational costs.

Andrew et al. (2020) worked on identification of visually similar vegetable seeds using image processing and fuzzy logic. They conducted a study comparison and identification of two vegetable seeds (pechay and cauliflower) through fuzzy logic and image processing. Images taken were processed and three morphological features were used as rules for the fuzzy inference system. The result was that the fuzzy inference system worked as expected even if there are only two true values for each characteristic. 100 per cent accuracy was obtained with pechay seeds sample, while only 65 per cent accuracy was obtained with cauliflower seeds. This gives a total of 82.5 per cent accuracy with 40 samples combined.

7. Conclusion

In conclusion, AI's role in seed science is transformative, promising to usher in a new era of precision agriculture and sustainable food production. By leveraging the power of AI, the agriculture sector can enhance seed quality, detect diseases early, optimize resource use, and accelerate crop breeding. While challenges exist, the potential benefits of AI in seed science are vast, offering a path toward meeting the food demands of a growing global population and safeguarding agricultural sustainability for generations to come. As AI continues to evolve and researchers refine its applications in seed science, the future of agriculture is brighter and more resilient than ever before.

Future aspects

The Artificial Intelligence (AI) in seed science can be used in seed production, certification, processing, quality control, seed storage and marketing. Presently AI has been exploited in the field of quality control. No research has been done in the aspects of certification, processing as well as storage.

The future of Artificial Intelligence (AI) in seed science holds immense promise, with numerous exciting aspects poised to shape the agriculture industry and seed production in the coming years. As AI technologies continue to advance and integrate into the field, we can anticipate several key developments that will revolutionize seed science and its impact on global food security, sustainability, and innovation. Enhanced Seed Quality Assurance: AI-driven seed quality assessment will become even more sophisticated. As AI algorithms evolve, they will offer greater accuracy in detecting contaminants, genetic impurities, and diseases. This will provide farmers and seed companies with an unprecedented level of confidence in seed quality, reducing crop failures and increasing overall productivity. Customized Seed Varieties: AI will play a pivotal role in personalized agriculture. Farmers will be able to access AI-powered systems that recommend specific seed varieties based on their soil type, climate conditions, and historical data. This customization will optimize yields and resource utilization while reducing environmental impact.

In summary, the future of AI in seed science is a promising one, with innovations that will significantly impact the way we produce food, conserve genetic diversity, and adapt to the challenges of a growing global population and changing climate. AI will continue to drive efficiency, sustainability, and resilience in agriculture, making it a critical tool in ensuring food security for generations to come. However, it's crucial to approach these advancements thoughtfully, addressing ethical, regulatory, and accessibility concerns to ensure that the benefits of AI in seed science are shared widely and responsibly.

Compliance with ethical standards

Disclosure of conflict of interest.

No conflict of interest to be disclosed.

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