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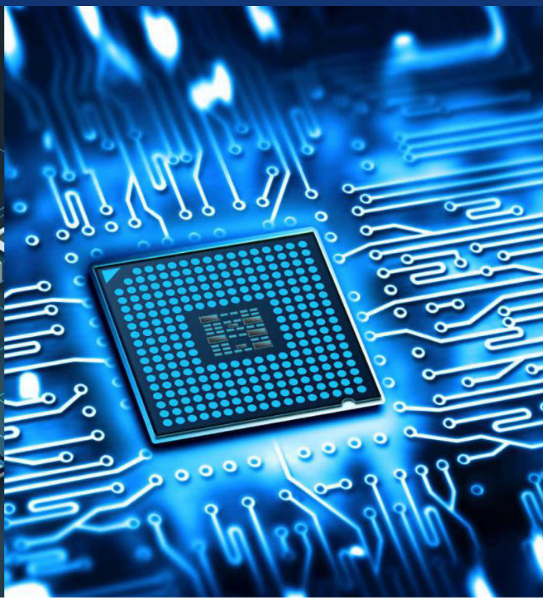

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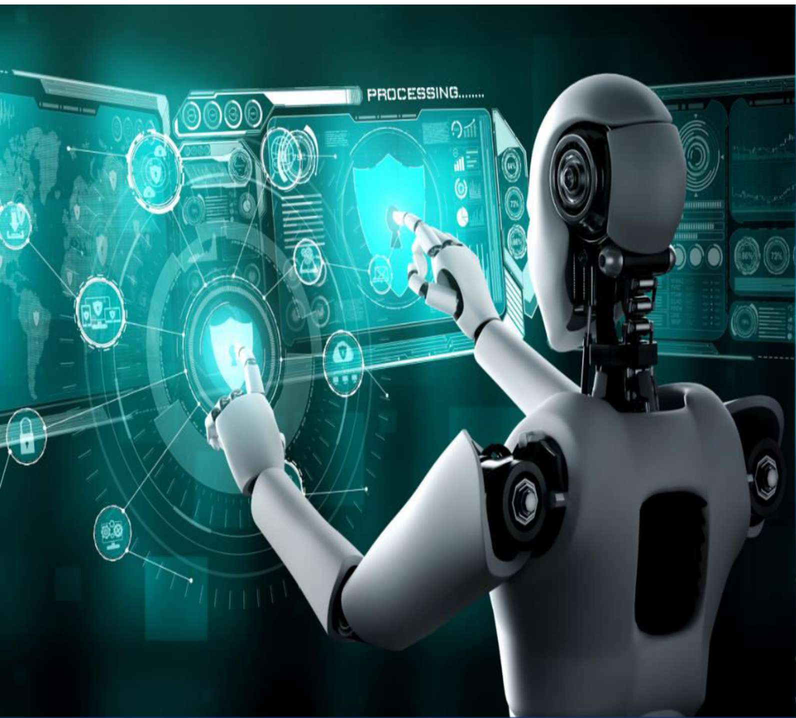

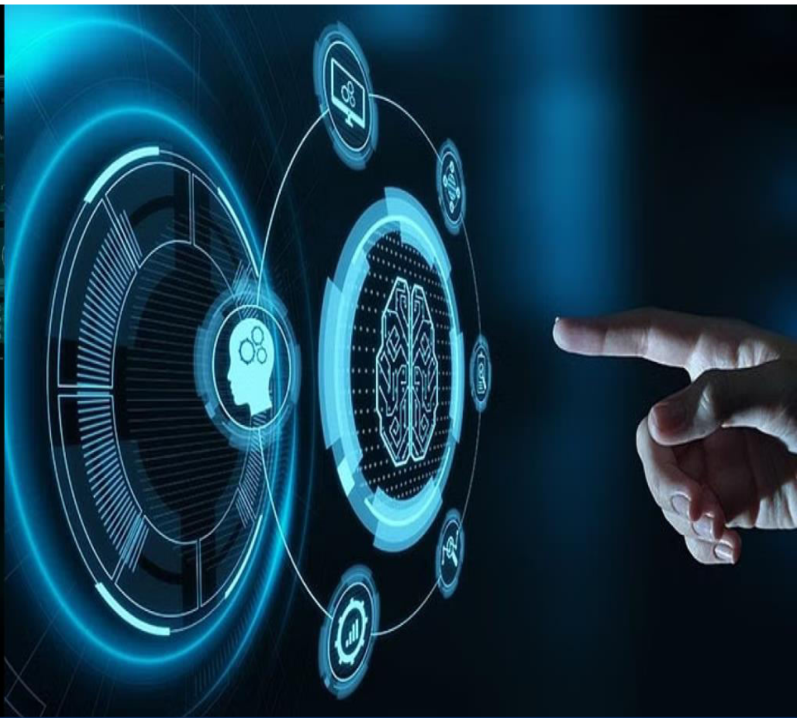

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A Review on Soyabean Seed Germination Analysis using Image Processing & Various Machine Learning Algorithms

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ABSTRACT: India is the world's fifth-largest producer of soybeans (Glycine max), one of the most commercially significant oilseed crops. Crop production and agricultural results are strongly impacted by the quality of seed germination. Maintaining seed quality and boosting agricultural productivity depend on accurate assessment of soybean seed germination. Traditional germination assessment methods are often labor-intensive, slow, and prone to subjective judgment, which limits their suitability for large-scale and high-throughput analysis. This paper proposes an automated framework for soybean seed germination assessment using image processing combined with machine learning and deep learning methods. The workflow includes image acquisition, preprocessing, segmentation, feature extraction, and classification of germinated and non-germinated seeds. Key visual descriptors such as morphological, color, and texture characteristics are derived from seed images and used to train predictive models, including Support Vector Machine (SVM), Random Forest (RF), Convolutional Neural Network (CNN), and YOLO (You Only Look Once) -based detection approaches. The proposed system is intended to enhance the accuracy, consistency, and speed of germination evaluation while reducing dependence on manual inspection. In addition, the integration of computer vision and artificial intelligence can support precision agriculture through dependable and automated seed quality monitoring. The study highlights the potential of image-driven intelligent diagnostic systems for advancing sustainable agriculture and enabling next-generation smart farming applications.

KEYWORDS: Soyabean Seed, Germination, Image Processing, Machine Learning, Convolutional Neural Network, Precision Agriculture, YOLO

I. INTRODUCTION

Mobile Soybean (Glycine max (L.) Merrill) stands as one of the most strategically important crops in global agriculture, serving as a primary source of plant-based protein, edible oil, and raw material for numerous industrial applications. Cultivated across diverse agroclimatic zones spanning North America, South America, Asia, and beyond, soybean production plays a pivotal role in ensuring food security and sustaining agricultural economies worldwide. India is the 5^{th} largest Soyabean Producer worldwide and the quality of seed germination directly influences crop productivity and agricultural outcomes**.** At the very foundation of a successful soybean crop lies one of the most critical biological processes seed germinations. The ability of a seed to sprout consistently and vigorously under field conditions not only determines the density and uniformity of the plant stand but also sets the trajectory for the entire growing season and its final yield.

Germination is the process by which a dormant (inactive) seed begins to grow into a new plant. During this process, the seed absorbs water, becomes active, and starts using its stored food. As growth continues, the root emerges first, followed by the shoot, developing into a healthy seedling that can grow on its own. For soybean seeds, germination depends on several internal and external factors. Internal factors include seed coat condition, moisture content, embryo health, and the quality of stored food reserves. External factors such as temperature, humidity, and oxygen availability also play an important role. If any of these factors are affected by mechanical damage during harvesting, fungal infection, poor storage conditions, or genetic defects, the germination rate decreases. This can lead to poor seedling growth, uneven crop establishment, and reduced crop yield, causing economic losses to farmers. Traditionally, seed germination is evaluated using the Standard Germination Test (SGT) recommended by the International Seed Testing Association (ISTA) and the Association of Official Seed Analysts (AOSA)[1]. Although this method is reliable and widely accepted, it has several limitations. The test requires trained personnel to manually examine and count germinated seeds, making it labour-intensive and time-consuming. It usually takes four to seven days to obtain the results. In addition, the evaluation may vary from one analyst to another, leading to differences in interpretation. These limitations make conventional methods less suitable for rapid, real-time, and large-scale seed quality assessment required in modern agriculture and seed certification.

To address the limitations of traditional methods, researchers have started using digital image processing and machine learning techniques for seed germination analysis. These technologies provide a faster, more accurate, and automated approach to evaluating seed quality. Image processing the computational manipulation and interpretation of digital images allows researchers to capture visual information about seeds with a level of detail and objectivity that surpasses human perception. Techniques such as colour space conversion, thresholding, morphological operations, edge detection, and texture analysis enable the extraction of quantitative features from seed images, ranging from geometric properties like area, perimeter, and aspect ratio to more sophisticated spectral and textural descriptors that correlate with seed health and germination potential. Machine learning, on the other hand, provides the algorithmic intelligence to learn patterns from these extracted features and make accurate predictions or classifications without being explicitly programmed with rigid rules. Supervised learning algorithms such as Support Vector Machines (SVM), Decision Trees, Random Forest, and k-Nearest Neighbors (k-NN) have been successfully applied to classify seeds by germination class. More recently, deep learning architectures particularly, Convolutional Neural Networks (CNNs) have demonstrated remarkable capability in learning hierarchical visual representations directly from raw image data, often eliminating the need for manual feature engineering and achieving accuracy levels that approach or surpass expert human assessors.

The combination of image processing and machine learning has created new opportunities for improving seed quality analysis. Researchers have used these technologies for different tasks, such as identifying whether a seed is viable or non-viable, monitoring different stages of seed germination, tracking seedling growth, and assessing seed quality without damaging the seeds. Advanced imaging techniques such as near-infrared (NIR), hyperspectral, and X-ray imaging have further improved the accuracy of seed analysis. These technologies provide faster, more accurate, consistent, and automated methods for germination assessment. They can be used in seed testing laboratories, automated seed sorting systems, and even portable devices for field applications. Although significant progress has been made, several challenges still remain. One of the major challenges is the lack of large and well-labelled datasets for different soybean varieties. In addition, differences in cameras, lighting conditions, and image acquisition methods can affect the performance of machine learning models. Deep learning models also require high computational power, and models trained on one soybean variety or growing condition may not perform well on others. Therefore, further research is needed to improve the accuracy, reliability, and practical use of these technologies. This review aims to provide a comprehensive overview of the existing methods, their performance, advantages, and limitations to support future research in soybean seed germination analysis.

This paper, therefore, aims to systematically review and consolidate the current state of research on soybean seed germination analysis through the lens of image processing and machine learning. It traces the evolution of techniques from classical computer vision approaches to modern deep learning frameworks, evaluates their relative strengths and weaknesses in the context of germination assessment, and identifies key directions for future research. The main goal is to provide researchers, seed technologists and agricultural engineers with a structured reference that can guide both the improvement of existing systems and the development of next-generation, intelligent germination evaluation tools.

II. LITERATURE REVIEW

Several studies have investigated the application of computer vision and deep learning techniques in agricultural quality assessment, particularly in seed classification and germination analysis. The increasing demand for high physiological seed quality and uniform crop yields has driven researchers to explore automated alternatives to conventional manual germination tests, which are time-consuming and prone to human error. YOLO (You Only Look Once), a real-time object detection algorithm, has emerged as a prominent deep learning framework due to its speed and accuracy in identifying and classifying objects within images. Recent work has demonstrated the viability of applying YOLO to classify soybean (*Glycine max*) seeds as germinated or non-germinated, achieving classification accuracy as high as

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94.58–95%, with prediction errors, measured via Mean Square Error, consistently within a narrow range of 0–0.110. The epoch value is set to 50. The model demonstrated stable learning behavior from approximately 20 training epochs, suggesting efficient model convergence with relatively modest training data. Comparative analysis between YOLO-generated results and classifications performed by human evaluators confirmed that the deep learning approach matches or surpasses traditional methods in terms of accuracy and consistency. These findings align with the broader trend in precision agriculture, where machine learning tools are increasingly being adopted to automate labor-intensive processes, reduce subjectivity, and improve throughput in seed quality laboratories. However, the literature also acknowledges areas requiring further refinement, particularly in standardizing image capture conditions and optimizing object detection pipelines to handle variability in seed appearance. Overall, the integration of YOLO into seed germination testing represents a significant step toward scalable, automated agricultural diagnostics[1].

Seed vigor and germination quality are strongly related to healthy seed characteristics. Seeds with higher vigor produced: faster germination, stronger seedlings, better root and shoot growth. The study mainly evaluated: Germination percentage, Seed vigor, Seedling growth performance The researchers found that: High-quality local cowpea (coupi bean) seeds showed better physiological performance. Vigor tests are important because some seeds may germinate normally but still produce weak plants[2]. The paper also highlights that: Seed vigor testing helps identify seeds that will perform better in field conditions. Parameters like :germination rate, seedling length, root development, and vigor index are useful for evaluating seed quality.

Recent advancements in Artificial Intelligence (AI) have significantly transformed agricultural automation, enabling smarter and more efficient farming practices. This study reviews AI-enabled applications such as irrigation management, robotic weeding, drone-based spraying, and crop monitoring. These technologies have proven instrumental in conserving vital resources, reducing dependency on manual labor, and enhancing overall crop yield and quality. By addressing critical challenges like labor shortages and food security, AI is steadily reshaping modern agriculture into a more sustainable and productive domain.[3] The study introduced a two-stage deep learning framework for corn seed classification. Mask R-CNN was employed to segment individual kernels from clustered seed images using synthetically generated training data, while a lightweight CNN (CK-CNNLW) classified the segmented kernels as healthy, defective, or impurities. The proposed method reduced manual annotation effort, achieved higher accuracy, and required substantially fewer parameters than existing approaches.[4]

The study developed a deep learning-based system for common bean disease detection using YOLOv7, YOLOv8, and YOLO-NAS models. A large, annotated dataset of leaf and pod images was used to detect five major diseases under real-field conditions. The proposed approach demonstrated high detection accuracy and was integrated into an Android application to facilitate early disease diagnosis and decision-making for farmers.[5] Common bean stands as a nutritional and economic lifeline for millions of people across Africa and Latin America, yet persistent plant diseases threaten both harvests and livelihoods. Farmers often struggle to identify these infections early many diseases look strikingly similar to the untrained eye, and by the time symptoms become obvious, significant damage may already be done. This research tackles that challenge head-on by harnessing cutting-edge YOLO deep learning architectures to detect disease quickly and it is reliable [6]. The researchers collected a large dataset containing images of five common bean diseases from farms in Africa and Colombia. To improve detection performance, they used detailed leaf annotations and data augmentation techniques. Among the three models evaluated, YOLO-NAS achieved the best performance for whole-leaf disease detection, with a mean Average Precision of 97.9% and a recall of 98.8%. In contrast, YOLOv7 and YOLOv8 showed better performance in detecting diseases on bean pods. The best-performing model was integrated into an Android application that farmers can use directly in the field. When tested on new images, the application achieved about 90% accuracy, enabling farmers to identify diseases at an early stage and take timely control measures. This approach helps reduce crop losses, improve yield, and demonstrates the practical use of artificial intelligence for disease detection in agriculture [6,7].

The YOLO family has progressed considerably, emerging as a reliable framework for real-time object detection through continuous refinements in network architecture and optimization techniques. Modern variants, including YOLOv8 and YOLO-NAS, provide an improved balance between detection accuracy and computational efficiency. Nevertheless, challenges such as identifying small-scale, partially occluded, and complex objects remain active research problems. Future enhancements are expected to integrate advanced mechanisms, including attention-based models and transformer architectures, to strengthen feature representation and detection capability. These ongoing developments highlight the continued relevance of the YOLO framework in advancing practical and high-performance

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computer vision applications[7]. YOLO Classifier is used here for corn seed germination detection. But authors have made changes in the YOLO algorithm and accordingly, the new algorithm which is the modified version of YOLO is called as CSGD-YOLO. CSGD is Corn Seed Germination Detection YOLO algorithm which is only used for detection CORN seed germination. The experimentation is done in China who is the leader in producing Corn after US & India is on rank 5. They worked on Seed quality. Compared traditional method and identified issues: 1. Manual Observation 2. Expertise 3. Time consuming 4. it gives subjective result. Researcher wanted fast, automatic and reliable system for seed germination. Previously, researchers used Sprectral Techniques (light reflection from seed) and Computer Vision &DL to detect germination from images. For this they have used models like fatser R-CNN, Mask R-CNN which were YOLO based. The seeds they have worked on were: Rice, Tomato, wildrice, corn. But they have found that it is suitable for small seeds and corn size is larger, so they have given thought to create a modified YOLO[8]. The block diagram of modified Yolo is as follows as shown in Fig. 1

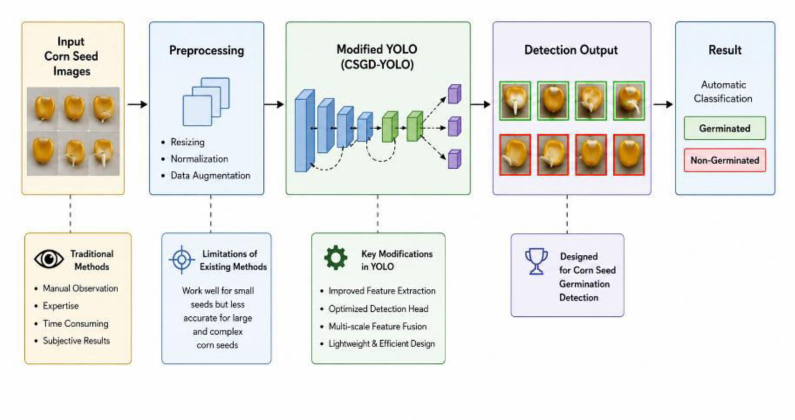

Fig 1. Block diagram of modified YOLO

Liu and Chen [9] introduced an efficient soybean seed germination identification framework by combining Partial Least Squares Regression (PLSR) with a Multilayer Perceptron (MLP) neural network. Their study demonstrated that integrating statistical regression techniques with artificial neural networks enhances the reliability and predictive performance of soybean seed viability assessment. The proposed approach utilized spectral data analysis and machine learning algorithms to estimate seed germination potential more accurately than conventional statistical methods. Experimental results indicated that the hybrid PLSR–MLP model achieved improved prediction accuracy and robustness, highlighting its suitability for intelligent seed quality evaluation. The findings emphasize the growing importance of artificial intelligence-based approaches in developing reliable and automated agricultural diagnostic systems. The authors proposed a non-destructive approach for assessing the physiological quality of soybean seeds by integrating hyperspectral imaging with machine learning techniques. Spectral reflectance data were collected from soybean leaves and seeds within the wavelength range of 350-2500 nm and used to predict important seed quality parameters, including germination, electrical conductivity, first germination count, and tetrazolium-based vigor and viability.

To evaluate the predictive capability of different algorithms, Artificial Neural Network (ANN), M5P, REPTree, Random Forest (RF), Support Vector Machine (SVM), and ZeroR were implemented and validated using stratified 10-fold cross-validation. The experimental results indicated that models trained with seed spectral data produced more accurate predictions than those using leaf reflectance. Among the evaluated algorithms, M5P, RF, and SVM consistently achieved superior performance by providing higher prediction accuracy and lower error rates. The study concluded that hyperspectral imaging combined with machine learning offers a reliable and efficient alternative to conventional laboratory-based seed quality assessment while also demonstrating the potential of leaf spectral data for early field-level prediction of soybean seed quality[10].

The authors proposed an enhanced YOLOv9-c-Ghost-Forward model for automated soybean seed defect detection using deep learning[11]. Image preprocessing techniques, including grayscale conversion, filtering, segmentation, and morphological operations, were employed to improve image quality and isolate soybean seeds from the background. The lightweight GhostConv module was integrated into the YOLOv9 architecture to improve feature extraction while reducing computational complexity. Experimental results demonstrated excellent detection performance, achieving a

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recall of 98.6% and an mAP@0.5 of 99.2%, indicating the model's effectiveness for intelligent seed quality inspection and agricultural breeding applications. Fig 2 depicts Soyabean seed detection using GhostConv Module.

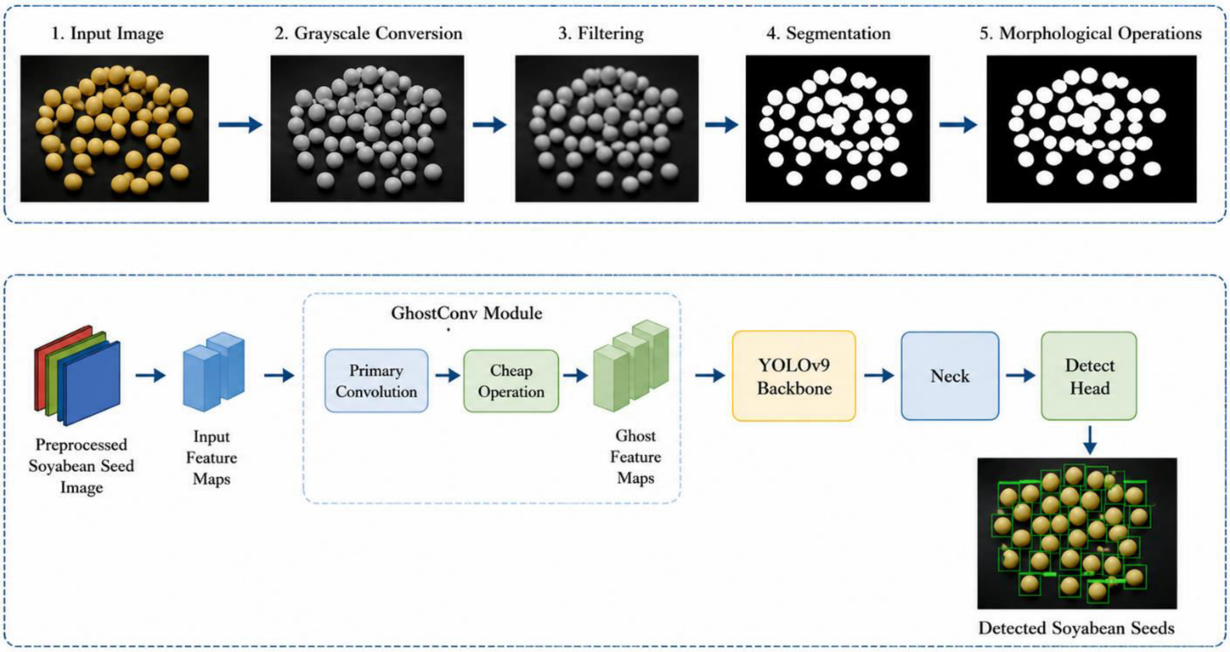

Fig 2. Soyabean seed detection using GhostConv Module

III. SYSTEM ARCHITECTURE

3.1 Factors affecting Seed germination:

Seed germination is influenced by several environmental and physiological factors that determine the ability of a seed to develop into a healthy seedling. These factors affect germination rate, seedling vigor, and overall crop establishment. Understanding their role is essential for evaluating seed quality and improving agricultural productivity.

- **Seed quality and viability**: Seed quality refers to the physical, physiological, and genetic characteristics that influence germination. Viable seeds can germinate under favorable conditions, while high-vigor seeds produce healthy and uniform seedlings. Poor-quality seeds often exhibit low germination rates and weak seedling growth.
- **Moisture availability**: Water is the primary requirement for seed germination. It initiates imbibition, activates enzymes, and supports the breakdown of stored food reserves to provide energy for embryo development. Insufficient moisture delays germination, whereas excessive moisture can reduce oxygen availability and promote seed decay.
- **Temperature**: Temperature regulates the metabolic and enzymatic activities involved in germination. Each crop has an optimum temperature range for successful germination. Temperatures below or above this range can reduce germination speed, decrease seed viability, and negatively affect seedling development.
- **Light:** Light influences germination in certain plant species by regulating physiological processes through photoreceptors. While some seeds require light for germination, others germinate better in darkness. Many cereal crops, however, are less sensitive to light conditions.
- **Oxygen availability:** Oxygen is essential for aerobic respiration, which supplies the energy required for seed germination and seedling growth. Poor soil aeration or waterlogged conditions restrict oxygen supply, resulting in slow or unsuccessful germination.
- **Storage conditions**: Proper storage conditions help preserve seed viability and vigor. Factors such as temperature, humidity, and storage duration influence seed quality. Cool and dry storage minimizes seed deterioration and improves germination performance during planting.
- **Seed dormancy and genetics:** Seed dormancy is a natural mechanism that prevents germination until suitable environmental conditions are available. Genetic factors also influence germination characteristics, seed vigor, and stress tolerance. Appropriate dormancy-breaking treatments and improved crop varieties contribute to better germination performance.

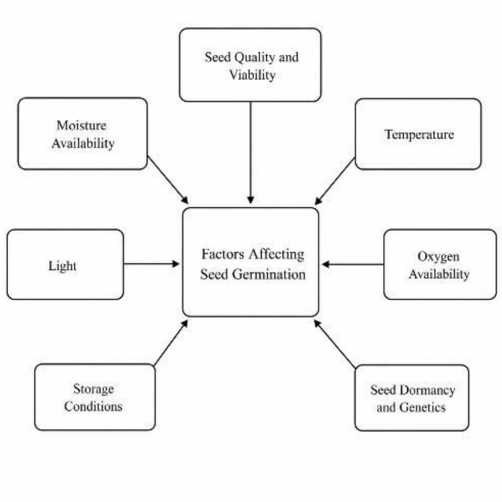

Fig: 3 Factors Affecting Seed Germination

3.2 Traditional Methods for Soybean Seed Germination Assessment

Traditional methods have been widely used to evaluate the germination and vigor of soybean seeds before sowing. The standard germination test is the most adopted method, in which soybean seeds are placed under controlled temperature and moisture conditions, and the percentage of normal seedlings is recorded after a specified period. Manual visual inspection is used to identify damaged, diseased, or immature soybean seeds based on their physical appearance. The tetrazolium (TZ) test is a rapid biochemical technique that determines seed viability by staining living tissues and is widely used in soybean seed testing laboratories. The electrical conductivity test evaluates seed vigor by measuring electrolyte leakage from soaked soybean seeds, with greater leakage indicating lower seed vigor. The accelerated ageing test is also commonly employed to predict the storage potential and field performance of soybean seeds. Although these methods are standardized and reliable, they are labour-intensive, time-consuming, and require trained personnel for accurate interpretation. Some methods, such as the tetrazolium test, are destructive and cannot be used for further planting. These limitations have led to increasing interest in computer vision and artificial intelligence-based techniques for rapid, objective, and non-destructive soybean seed germination assessment.

3.3 Image Processing and Computer Vision Image Processing and Computer Vision Techniques

Image processing and computer vision techniques have become essential tools for automated seed germination assessment because they provide rapid, objective, and non-destructive analysis. Unlike conventional manual inspection, these techniques reduce human error and improve the consistency of germination evaluation. A typical computer vision pipeline consists of image acquisition, preprocessing, segmentation, feature extraction, and classification. The process begins with image acquisition, where high-resolution images of soybean seeds are captured using digital cameras, flatbed scanners, or smartphone cameras under controlled illumination conditions. Consistent lighting and a uniform background are essential to minimize shadows and reflections that may affect subsequent analysis. After image acquisition, preprocessing is performed to improve image quality and prepare the data for further processing. Common preprocessing operations include image resizing, noise removal using filtering techniques such as median or Gaussian filters, contrast enhancement, and normalization. These operations help standardize the input images while preserving important seed characteristics.

The next stage involves image segmentation, which separates soybean seeds and emerging sprouts from the background. Segmentation techniques such as thresholding, edge detection, region-growing, watershed algorithms, and morphological operations are commonly employed to accurately identify the seed boundaries and germinated regions. Effective segmentation is crucial because it directly influences the accuracy of feature extraction. Once the seed regions are isolated, relevant visual features are extracted to characterize germination status. Commonly extracted features include geometric properties (area, perimeter, length, width, and aspect ratio), color descriptors, and texture features derived from methods such as the Gray-Level Co-occurrence Matrix (GLCM) or Local Binary Patterns (LBP). These features provide quantitative information for distinguishing germinated and non-germinated seeds.

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Finally, the extracted features are used for classification. Traditional machine learning algorithms, including Support Vector Machines (SVM), k-Nearest Neighbors (KNN), Decision Trees, Random Forests, and Artificial Neural Networks (ANN), have been widely applied for seed classification. Although these methods have demonstrated satisfactory performance, their effectiveness depends heavily on manually designed features. Consequently, recent studies increasingly employ deep learning approaches that automatically learn discriminative features directly from images, resulting in improved accuracy and robustness for seed germination detection.

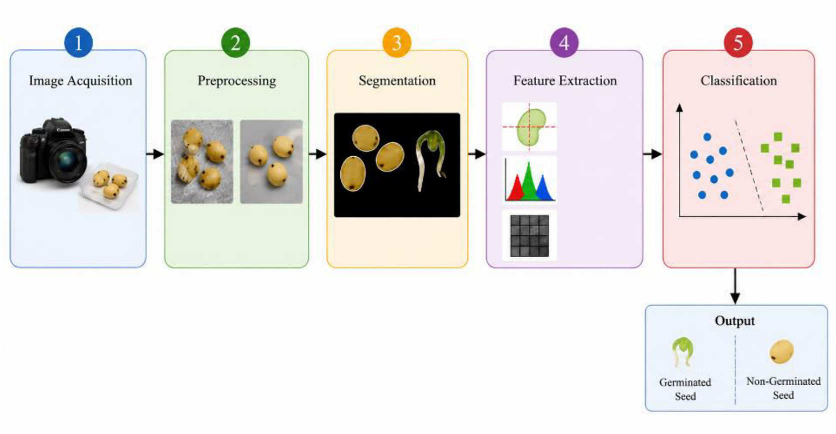

Fig. 4 Process of germination

3.4 Artificial Intelligence and Deep Learning Approaches

Artificial intelligence and deep learning have significantly advanced automated seed germination assessment by enabling accurate and efficient image analysis. Convolutional Neural Networks (CNNs) automatically learn discriminative features from seed images, eliminating the need for manual feature engineering. Object detection models such as YOLO provide real-time detection and localization of germinated seeds with high accuracy, while modified architectures, including CSGD-YOLO, further improve detection speed and precision for specific crop varieties. In addition, transfer learning and data augmentation techniques enhance model robustness, generalization, and classification performance, particularly when only limited training datasets are available.

3.5 Comparative Analysis of Existing Studies

The Table 1 depicts the comparative analysis of existing studies carried out for various seeds. The table involves the methodology used for calculating Accuracy of respective seed germination.

Table 1 Comparative Analysis of Existing Studies

Author	Seed Type	Method	Accuracy
Zanetoni et al. 2025 [1]	Soybean	Artificial Intelligence-based germinated seed identification	99.8%
Suárez et al. 2025 [4]	Corn	Few-shot learning for corn kernel classification	97.4%
Gomez et al. 2024 [5]	Common Bean	YOLO-based deep learning for disease detection	98.4%
Yan et al. 2024 [6]	Apple (Harvesting)	Improved YOLOv8s object detection	95.8% (mAP@0.5)
Terven et al. 2023 [7]	General	Review of YOLO architectures (YOLOv1–YOLOv8 & YOLO-NAS)	YOLO-NAS
Sun et al. 2025 [8]	Corn	CSGD-YOLO (Improved YOLOv8n)	99.2% (mAP@0.5)
Liu & Chen 2026 [9]	Soybean	PLSR-MLP (Partial Least Square Regression-Multi Layer Perceptron) fusion model for germination potential detection	98.7%

Oliveira et al. 2025 [10]	Soybean	Hyperspectral imaging for seed quality prediction	98.9%
Liu et al. 2025 [11]	Soybean	Improved YOLOv9 for surface defect detection	98.6%
Hegde et al. 2025 [12]	Multiple Seeds	Review of advanced seed quality assessment and germination monitoring techniques	Not Recorded

Despite significant advancements in AI-based seed germination assessment, several research gaps remain. Existing models often require large, annotated datasets and exhibit reduced performance when applied to diverse crop varieties or unseen environmental conditions. Variations in illumination, background complexity, and seed occlusion continue to affect detection accuracy. Furthermore, many deep learning models are computationally intensive, limiting their deployment on resource-constrained devices for real-time applications. Therefore, there is a need for lightweight, robust, and highly generalizable models capable of accurate germination detection under practical field conditions.

IV. CONCLUSION AND FUTURE WORK

This study presents an automated framework for soybean seed germination assessment by integrating digital image processing with machine learning and deep learning techniques. The proposed methodology offers a reliable and efficient alternative to conventional germination testing by reducing manual effort and improving evaluation consistency. Image-based feature extraction combined with intelligent classification models enables accurate identification of germinated and non-germinated seeds. The adoption of artificial intelligence in seed quality analysis can enhance productivity, support precision agriculture, and promote sustainable farming practices. Overall, the proposed framework demonstrates the potential of computer vision-based technologies; where YOLO classifier plays an important role for modern agricultural applications.

Future work can focus on expanding the dataset by including different soybean varieties and varying environmental conditions to improve model generalization. Advanced deep learning architectures, such as Vision Transformers and attention-based networks, may further enhance classification accuracy. The proposed system can also be integrated with real-time imaging devices, mobile applications, or IoT-enabled platforms for on-field seed quality monitoring. In addition, extending the framework to detect seed vigor, diseases, and multiple crop species would increase its practical applicability in smart agriculture.

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