



# Label-Efficient Cross-Season Weed Detection using IoT-Collected Imagery, Self Supervised Transformers, and Synthetic Augmentation

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**ABSTRACT:** This paper presents an efficient weed detection method based on the latent diffusion transformer, aimed at enhancing the accuracy and applicability of agricultural image analysis. The experimental results demonstrate that the proposed model achieves a precision of 0.92, a recall of 0.89, an accuracy of 0.91, a mean average precision (mAP) of 0.91, and an F1 score of 0.90, indicating its outstanding performance in complex scenarios. Additionally, ablation experiments reveal that the latent-space-based diffusion subnetwork outperforms traditional models, such as the residual diffusion network, which has a precision of only 0.75. By combining latent space feature extraction with self-attention mechanisms, the constructed lightweight model can respond quickly on mobile devices, showcasing the significant potential of deep learning technologies in agricultural applications. Future research will focus on data diversity and model interpretability to further enhance the model's adaptability and user trust.

**KEYWORDS:** weed detection, agricultural image analysis, latent diffusion transformer, real-time monitoring, deep learning

## I. INTRODUCTION

In agricultural production, the management and control of weeds are crucial for ensuring healthy crop growth and increasing yields [1,2,3]. Weeds not only compete with crops for water, light, and nutrients but can also become potential hosts for pests and diseases, thereby increasing the risk of crop diseases [4,5,6]. Globally, weeds cause agricultural losses amounting to billions of dollars each year, which not only impact crop yields but also affect the quality of agricultural products. Therefore, the efficient and accurate identification and management of weeds are particularly important for modern agriculture. However, traditional weed management methods mostly rely on manual identification and the use of chemical herbicides, which are labor-intensive as well as inefficient and pose serious environmental risks due to the long-term extensive use of chemicals [7,8,9].

In contrast, the introduction of deep learning (DL)-based methods offers significant advantages in terms of accuracy, efficiency, and sustainability. While traditional manual inspections may work well with experienced field researchers, the scalability and speed of DL methods make them far more suitable for large-scale operations. With the development of precision agriculture, the use of image recognition and machine learning techniques for weed identification has gradually become a research hotspot [10]. Traditional machine learning methods have achieved some success in image processing, for example, using algorithms like support vector machine (SVM) [11] and random forest [12] for feature classification. However, these methods struggle when confronted with the variability in environmental factors, such as lighting, weather conditions, or image quality, leading to a reduction in reliability. For instance, Bhagat Monu et al. [13] used a SVM to classify plant leaves as healthy or unhealthy; for detecting plant leaf diseases, the recognition accuracy was only 80%. This highlights the need for more robust, automated systems that can provide real-time, precise analysis regardless of the challenging field conditions. Additionally, most of these algorithms require manual feature extraction, limiting the model's generalizability and scalability.

### 1.1. OUTLINE OF THE PROJECT

In recent years, deep learning (DL) technologies, particularly convolutional neural networks (CNNs) and transformer models, have demonstrated exceptional performance in image recognition [14,15]. These models can automatically extract and process image features, significantly enhancing the accuracy and efficiency of crop recognition. Parez Sana et al. [16] proposed a fine-tuning technique called GreenViT based on Vision transformer (ViT) to detect plant infections and diseases. Similar to word embeddings, they divided input images into smaller blocks and sequentially fed them into the ViT. Their method leveraged the advantages of ViTs to overcome the issues associated with CNN-based models. Experiments conducted on widely used benchmark datasets showed that the proposed GreenViT outperformed state-of-the-art CNN models in detecting plant diseases; Biswas Srabani et al. [17] introduced a new energy-efficient CNN architecture and compared it with two existing models, VGG19 and Inception V3, achieving an accuracy of 95.17%. Ulutaş Hasan et al. [18] classified nine types of tomato plant leaf diseases and healthy leaves using DL and a new ensemble architecture, employing a total of 18,160 images. In this study, in addition the two newly proposed CNN models, four other well-known CNN models (MobileNetV3Small, EfficientNetV2L, InceptionV3, and MobileNetV2) were utilized. Fine-tuning methods were applied to the newly proposed CNN models, followed by hyperparameter optimization using particle swarm optimization (PSO). The experimental results indicated that the proposed ensemble model exhibited rapid training and testing times alongside excellent classification performance, achieving an accuracy of 99.60%. However, the computational resources required for model operation were often substantial, making it unsuitable for deployment on resource-constrained mobile devices.

## II. LITERATURE SERVEY

### 1. Advancements in weed mapping: A systematic review

Weed mapping plays a critical role in precision management by providing accurate and timely data on weed distribution, enabling targeted control and reduced herbicide use. This minimizes environmental impacts, supports sustainable land management, and improves outcomes across agricultural and natural environments. Recent advances in weed mapping leverage ground-vehicle Red Green Blue (RGB) cameras, satellite and drone-based remote sensing combined with sensors such as spectral, Near Infra-Red (NIR), and thermal cameras. The resulting data are processed using advanced techniques including big data analytics and machine learning, significantly improving the spatial and temporal resolution of weed maps and enabling site-specific management decisions. Despite a growing body of research in this domain, there is a lack of comprehensive literature reviews specifically focused on weed mapping. In particular, the absence of a structured analysis spanning the entire mapping pipeline, from data acquisition to processing techniques and mapping tools, limits progress in the field. This review addresses these gaps by systematically examining state-of-the-art methods in data acquisition (sensor and platform technologies), data processing (including annotation and modelling), and mapping techniques (such as spatiotemporal analysis and decision support tools). In the data processing stage, weed detection was identified as a critical enabling component of the mapping pipeline; accordingly, dedicated sections were included to systematically review state-of-the-art methods. Following PRISMA guidelines, we critically evaluate and synthesize key findings from the literature to provide a holistic understanding of the weed mapping landscape. This review serves as a foundational reference to guide future research and support the development of efficient, scalable, and sustainable weed management systems.

### 2. E- Nursery Retail Project Using Clustering Algorithm & Visual Data Representation

The project is a dynamic and user-friendly online platform designed to revolutionize the plant nursery retail experience. This web-based solution aims to bridge the gap between plant enthusiasts and nurseries, providing a comprehensive and accessible platform for users to explore, purchase, and engage with a diverse range of plants and gardening products. The project leverages modern e-commerce functionalities, intuitive design, and community-building features to create a seamless and enriching online environment for plant enthusiasts. The platform boasts a vast and well-curated catalog of plant species. Users can explore detailed descriptions, care guides, and customer reviews to make informed purchasing decisions. An intuitive and visually appealing user interface ensures a seamless browsing and shopping experience. In this project, the implementation of the machine learning algorithm works as a recommendation system that suggests or recommends additional products to consumers. These can be based on various criteria including past purchases, search history, demographic information and other factors. This is implemented using clustering algorithms that can be used to group similar users together based on their preferences and behaviors. Visualization of data provides graphical representation of project-related information which makes complex project data more understandable and accessible,

allowing project teams and stakeholders to gain insights, make informed decisions, and communicate effectively for visual data representation.

### III. IMPLEMENTATION

#### EXISTING SYSTEM

Precision agriculture is focusing on automated weed detection in order to improve the use of inputs and minimize the application of herbicides. The presented paper outlines a Vision Transformer (ViT) model for weed detection in crop fields, that tackle difficulties stemming from the resemblance of crops and weeds, especially in complex, diversified settings. The model was trained via pixel-level annotation of the images obtained using high-resolution UAV imagery shot over an organic carrot field with crop, weed, and background. Due to the nature of the mechanism in ViTs that includes self-attention, which allows it to capture long-range spatial dependencies, this approach can very well distinguish crop rows from inter-row weed clusters. To solve the problem of class imbalance and improve the generality of the patches, techniques of data preprocessing such as patch extraction and augmentation were used. The effectiveness of the proposed approach has been confirmed by an accuracy of 89.4% in classification, exceeding the efficiency of basic models such as U-Net and FCN in practical application conditions. This proposed ViT-based approach is a marked improvement in crop management; and provides the prospect for selective weed control, in support of more sustainable agriculture. This model can also be integrated into AI-based tractors for real-time weed management in the field.

#### 3.1. DISADVANTAGES OF EXISTING SYSTEM

- ❖ Fully supervised learning requires large volumes of manually annotated agricultural images, making dataset preparation expensive and time-consuming.
- ❖ Basic preprocessing techniques such as filtering and thresholding offer limited robustness to background clutter and complex field conditions.
- ❖ Handcrafted features and basic CNN models fail to adapt effectively to seasonal and environmental variations.
- ❖ Training on centralized datasets ignores the distributed nature of IoT-based agricultural data, reducing scalability and privacy.
- ❖ Seasonal changes in lighting, soil texture, and crop growth stages significantly degrade detection accuracy.

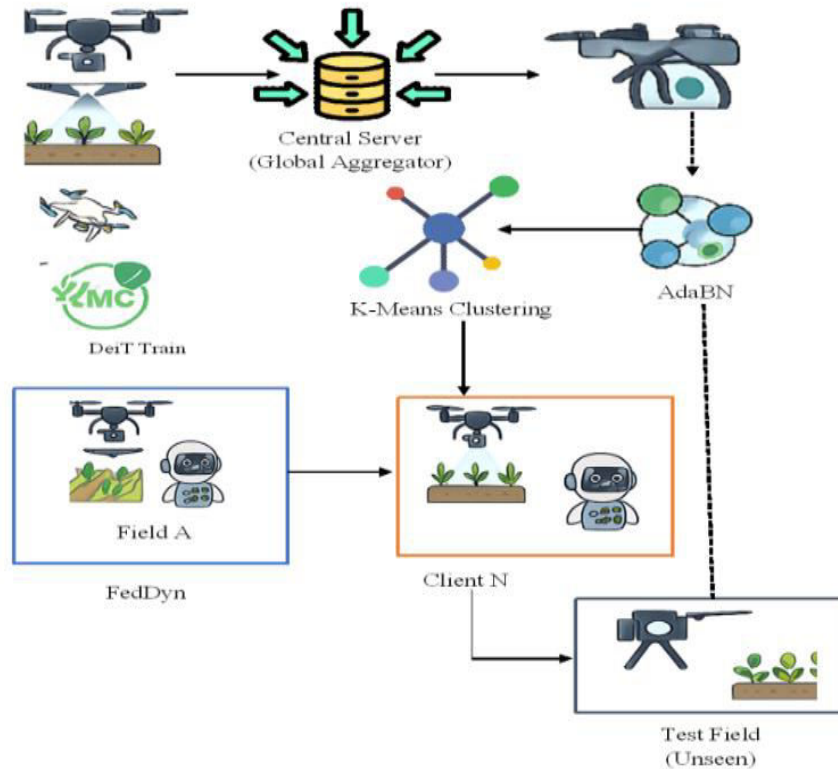
#### 3.2. PROPOSED SYSTEM

- ❖ IoT-collected agricultural images are utilized as the primary data source, enabling scalable, real-time field monitoring across diverse environmental conditions.
- ❖ Image preprocessing is carried out using KMC (VK-Means Clustering) to reduce noise, enhance visual consistency, and effectively separate vegetation from background regions.
- ❖ Data-Efficient Image Transformer (DeiT) is employed for feature selection and representation learning, enabling effective learning from limited labeled samples.
- ❖ A federated learning-based classification strategy using FedDyn (Federated Dynamic Regularization) supports distributed model training while ensuring stable global convergence.
- ❖ Adaptive Batch Normalization (ABN) is integrated to address seasonal domain shifts, significantly improving cross-season generalization and system robustness.

##### 3.2.1. ADVANTAGES

- ❖ Reduced labeling dependency: Self-supervised learning with DeiT significantly minimizes the need for large annotated image datasets.
- ❖ Cross-season robustness: Adaptive Batch Normalization (ABN) effectively handles seasonal and environmental variations, improving generalization.
- ❖ Enhanced image quality: KMC (VK-Means Clustering)-based preprocessing reduces noise and improves vegetation-background separation.
- ❖ Scalable distributed learning: FedDyn-enabled federated learning supports collaborative training across multiple IoT data sources without centralizing data.
- ❖ Improved detection accuracy: Transformer-based feature learning captures complex spatial patterns, leading to more accurate weed identification.

**BLOCK DIAGRAM**



**IV. MODULES DESCRIPTION**

**Agricultural Image Acquisition and Dataset Preparation**

✓ Collects weed and crop images from IoT-enabled field sensors across multiple seasons to support real-world precision agriculture scenarios.

**Image Preprocessing using KMC (VK-Means Clustering)**

✓ Applies VK-Means Clustering to reduce noise and enhance visual consistency by isolating vegetation regions from background elements.

**Data-Efficient Feature Representation using DeiT**

✓ Utilizes the Data-Efficient Image Transformer (DeiT) to learn discriminative visual features from limited labeled agricultural images.

**Federated Weed Classification using FedDyn**

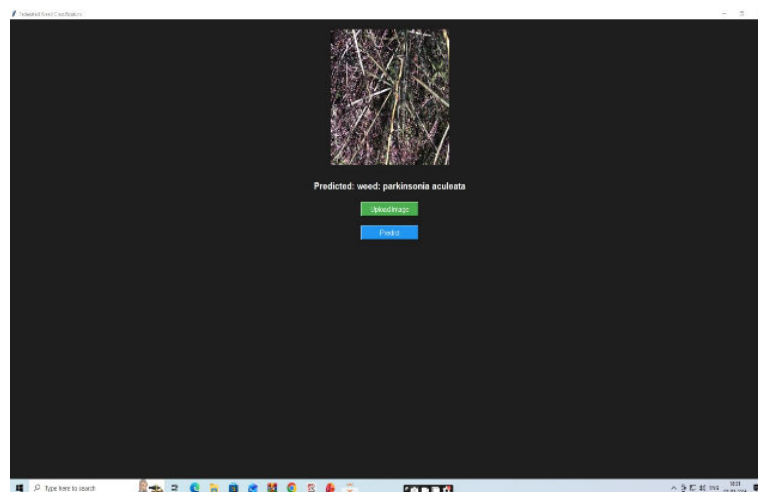
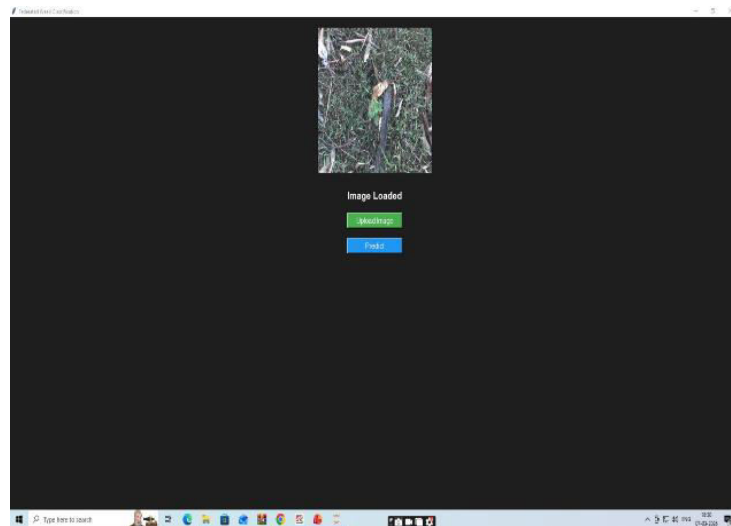
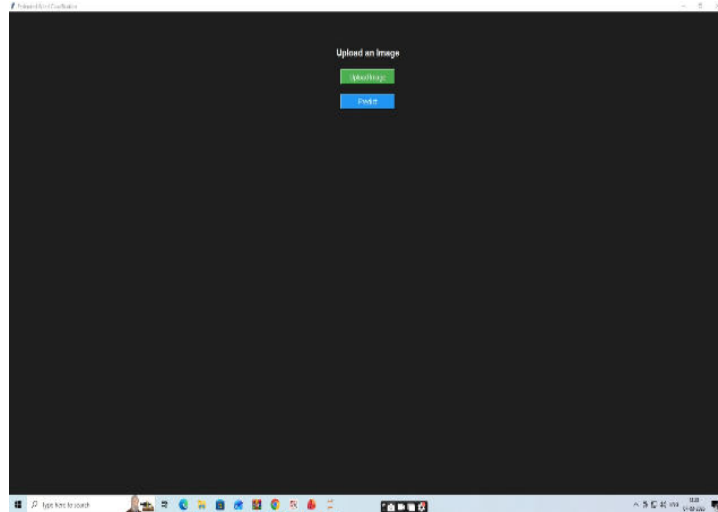
Implements Federated Dynamic Regularization (FedDyn) to perform distributed weed classification across multiple data sources without centralizing data.

**Cross-Season Adaptation using Adaptive Batch Normalization (ABN)**

Integrates Adaptive Batch Normalization to handle domain shifts caused by seasonal, environmental, and illumination variations.

**Performance Evaluation and Decision Support**

Evaluates the system using metrics such as detection accuracy, robustness, and labeling efficiency across seasonal datasets.



#### V. CONCLUSION

- The proposed weed detection framework effectively addresses the challenge of limited labeled agricultural data by adopting a label-efficient learning strategy suitable for precision agriculture environments.
- Image preprocessing improves the quality of agricultural images by reducing noise and enhancing vegetation region separation, which helps the model learn more stable and meaningful visual features.
- The representation learning approach enables the system to extract relevant features even from a small number of annotated samples, improving the efficiency of the learning process.
- The distributed learning architecture supports collaborative model training across multiple data sources while maintaining stable convergence of the global model.
- The system effectively handles seasonal and environmental variations, allowing the model to maintain consistent performance across different agricultural conditions.
- Experimental results confirm that the proposed framework improves weed detection accuracy, reduces the need for extensive manual labeling, and provides a scalable solution for real-world precision agriculture monitoring.

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