OPTIMIZED CROP DISEASE SEGMENTATION AND PREDICTIVE OUTBREAK MANAGEMENT FOR PROACTIVE AGRICULTURAL SOLUTIONS

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Keywords:

Crop Disease Detection, Semantic Segmentation, Predictive Forecasting, Agricultural Intelligence Systems

Introduction:

Agriculture is the backbone of Indian livelihood, economy and rural sustainability, yet it remains vulnerable to persistent threats from crop diseases. Rust disease in sorghum, a staple crop in India, causes extensive yield loss due to its rapid spread and damaging effects on leaf physiology. Traditional manual inspection methods, which are time-consuming and subjective, have long posed challenges—often leading to delayed interventions and unnecessary pesticide usage.

To tackle this critical challenge, our project introduces a comprehensive, AI-powered solution for disease detection, assessment of disease severity, and forecasting the spread of crop disease in sorghum. By integrating SoTA frameworks such as **YOLOv8, NVIDIA's Segformer_b0** for real-time leaf disease detection and precise segmentation of infected regions.

The **N-BEATS** forecasting model is employed to predict the spread of disease by identifying patterns in historical data of environmental factors. The system enables farmers and agricultural stakeholders to act proactively rather than reactively. This approach not only facilitates early-stage detection and quantification of rust disease but also empowers precision agriculture by forecasting vulnerable regions, helps in **reduced usage of pesticide and fertilizers** and to **minimize the crop losses**. The project's relevance lies in its potential to revolutionize disease management practices in Indian agriculture, making them data-driven, scalable, and sustainable.

Objectives:

1. To develop a hybrid framework for crop disease detection and estimation of damage severity in the plant.
2. Create a forecasting framework using N-BEATS
3. Comparing various disease detection techniques (Yolov8, Yolov11 & Yolov12) and techniques for diseased area segmentation (U-Net, Residual U-Net, Multi-Residual U-Net and NVIDIA's Segformer_b0)
4. Integrate detection, segmentation, and forecasting for actionable agricultural insights.

Methodology:

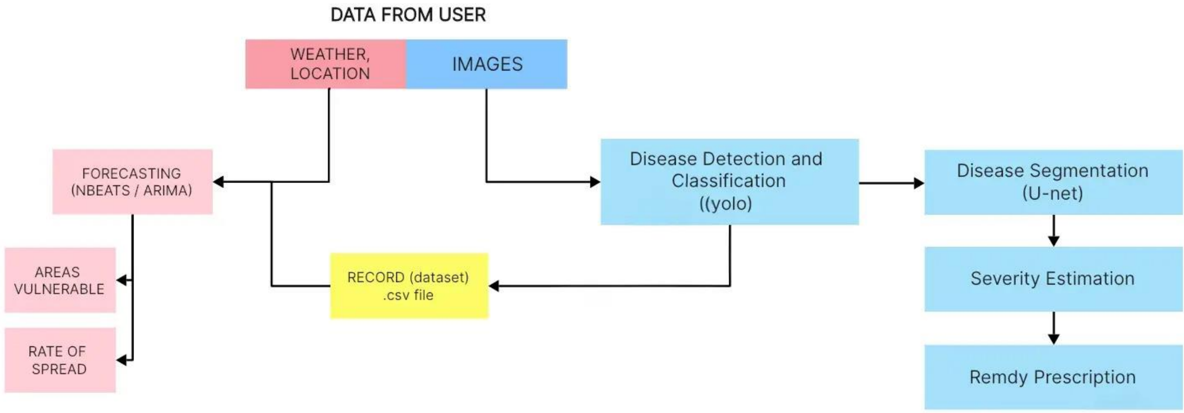

Figure 1: Proposed Architecture

The above proposed framework in the Figure 1, follows a three-stage pipeline: **Disease Detection, Segmentation** on high-resolution images of sorghum leaves having dimension of 1080 x 810 x 3 and **Forecasting** the disease spread by identifying patterns in historical data of environmental factors (weather data, historical disease occurrence record).

For disease detection, the dataset is annotated using Roboflow with bounding boxes and corresponding class labels. In addition, images are also resized to a YOLO-compatible dimension (640 x 640) and normalized for smoother model convergence. Further, the YOLO models (Yolov8, Yolov11 and Yolov12) are trained to locate the rust-affected regions in real time. These models are chosen for their effectiveness in detection even during varying lighting and background conditions.

For disease segmentation using various U-net models (U-Net, Residual U-Net, Multi-Residual U-Net), the masks are generated for the dataset using erosion and dilation techniques. The trained models resulted inaccurate segmentations. To overcome the challenge, NVIDIA's Segformer_b0 is deployed for accurate segmentation of diseased region of a leaf. The dataset is annotated using Roboflow's Segment Anything Model (SAM2) to generate masks and corresponding class label, also resized to a dimension of 512 x 512.

For disease forecasting, the N-BEATS model is used to forecast various weather factors using historical and current weather data such as humidity, rainfall, and temperature.

Finally, the detection, segmentation, and forecasting are integrated into a scalable pipeline designed for real-time analysis. This hybrid framework ensures timely identification, targeted intervention, and informed planning, promoting sustainable and efficient agricultural practices.

Results & Conclusions:

In conclusion, the project successfully achieved an end-to-end pipeline for early detection, segmentation, and forecasting of rust disease in sorghum. The **YOLOv8, YOLOv11 and YOLOv12** models demonstrated high accuracy in real-time identification of infected regions, achieving detection precision of **92%, 89% and 81%** respectively and their predictions are shown below in Figures 2, 3 & 4.

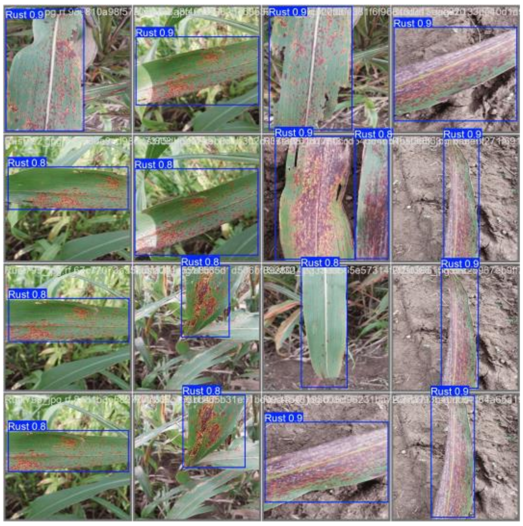

Figure 2: YOLOv8

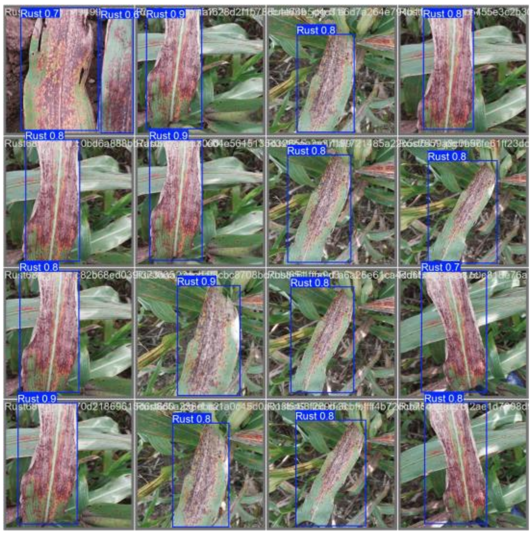

Figure 3: YOLOv11

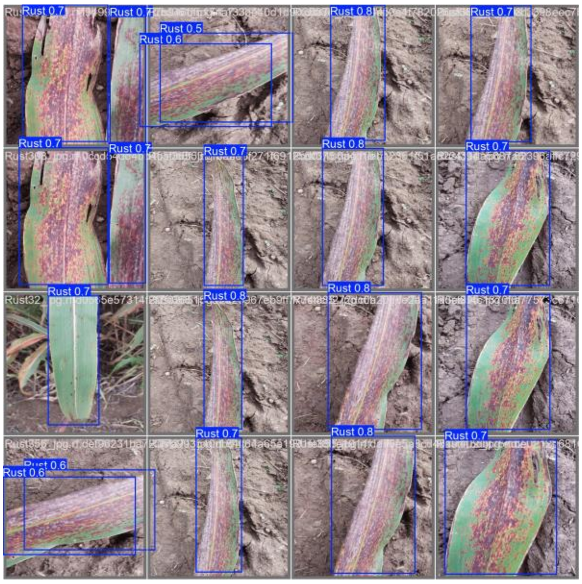

Figure 4: YOLOv12

The **U-Net, Residual U-Net and Multi-Residual U-Net** are compared with Intersection over Union (IoU) scores of **0.71, 0.74 and 0.76** respectively as shown in the Figures 5 & 6 below.

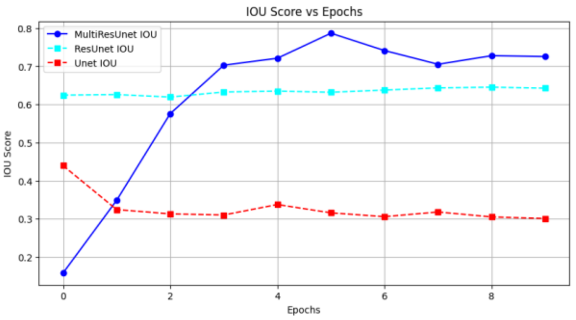

Figure 5: Comparision of various Unet models IoU Score vs Epochs

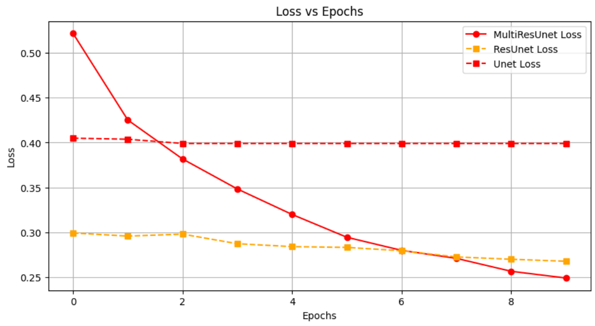

Figure 6: Comparision of various Unet models Loss vs Epochs

While **NVIDIA's Segformer_b0** achieved an IoU score of **0.82** as shown in the Figures 7 & 8 below, confirming the model's capability to distinguish disease boundaries accurately than the Unet models.

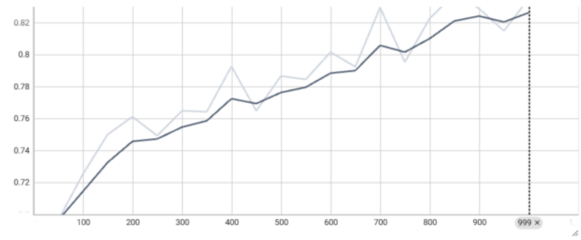

Figure 7: SegFormer_b0 IoU vs Timestamp

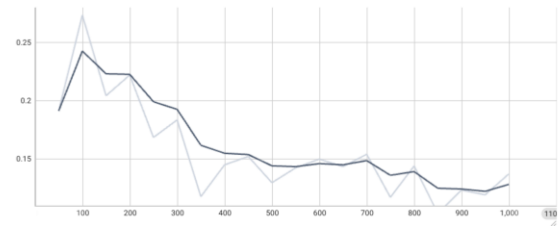

Figure 8: SegFormer_b0 Loss vs Timestamp

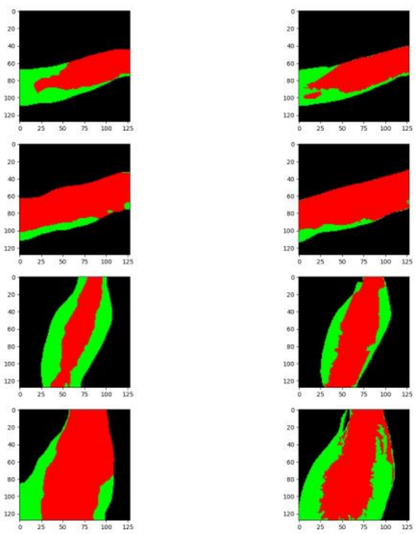

Figure 9: Segformer_b0 training results

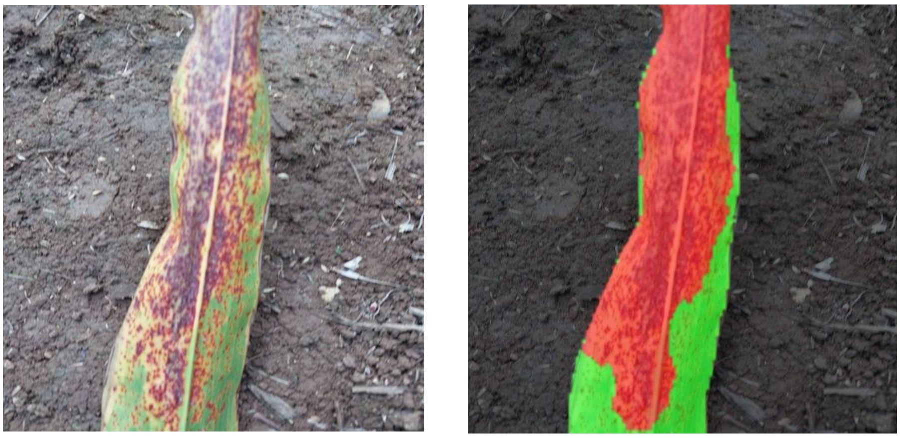

Figure 10: Segformer_b0 test Input (left) and Output (right)

Furthermore, the forecasting with **N-BEATS** model effectively utilizes various weather factors to forecast the temperature of next 5 days which is shown in the Figure 11 below.

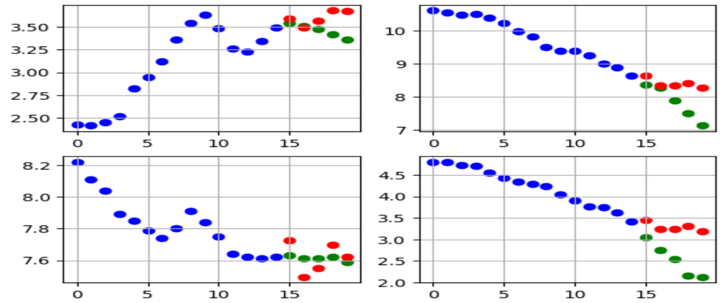

Figure 11: N-BEATS predictions (Red dots - predicted values, Green dots – actual values)

These findings validate the effectiveness of the combined approach, proving that deep learning can significantly enhance early disease detection and proactive crop management. The project demonstrates a scalable, accurate, and efficient solution with the potential to reduce economic losses and improve sustainability in agriculture.

Project Outcome & Industry Relevance:

This project delivers a high-impact, AI-driven system for early detection, segmentation, and predictive forecasting of rust disease in sorghum, enabling farmers to respond proactively and reduce crop losses. By minimizing reliance on manual inspection and excessive chemical use, it supports more sustainable and efficient farming practices.

Through the integration of **YOLOv8** for detection, **NVIDIA's Segformer_b0** for precise segmentation, and **N-BEATS** for outbreak forecasting, the system ensures real-time, data-informed decisions tailored to regional and climatic conditions. Its modular design allows easy adaptation to other crops and plant diseases, making it a versatile solution in digital agriculture.

The outcomes directly contribute to precision farming, enhancing productivity, reducing environmental harm, and aligning with global food security and sustainability goals. Its real-world relevance spans across Agritech industries, smart farming platforms, and public sector initiatives aimed at strengthening agricultural resilience.

Working Model vs. Simulation/Study:

This project is based on a physical working model and is not a theoretical study. It integrates real-time plant disease detection, segmentation, and forecasting modules, all tested using real-world sorghum disease datasets. Simulation was used only to validate model performance, but the core system is designed for practical deployment, demonstrating high readiness for use in agricultural environments.

Project Outcomes and Learnings:

Key outcomes include high-accuracy disease detection, segmentation, and outbreak forecasting for diseases found in Sorghum crop.

Lessons learned include the value of modular design, precise annotation, and potential for refinement with more environmental data and field trials, as well as the underperformance of YOLOv12, suggesting areas for improvement.

Future Scope:

1. **Enhanced Forecasting Accuracy**: Deploying a forecasting model on a historical dataset of disease occurrences across various geographical locations.
2. **Expanded Dataset Coverage**: Extend the dataset to include a wider variety of crops and diseases, making the system adaptable across diverse agricultural contexts.
3. **IoT & Drone Integration:** Integrate IoT sensors and drone technology for real-time image acquisition for disease monitoring and automated data collection at scale.

4. **Model Optimization:** Further improve YOLOv12 performance with extended training, hyperparameter tuning, and lightweight model variants for faster inference.
5. **Field Validation:** Conduct comprehensive field trials to validate system accuracy, reliability, and usability under real agricultural conditions.
6. **Decision-Support System:** Integrate the system into farm management platforms to offer actionable insights for farmers and agronomists.
7. **Scalability Across Regions:** Tailor the solution for deployment across varied geographic regions and climates to support national-level implementation.
8. **Policy & Research Collaboration:** Collaborate with agricultural research bodies and policymakers to influence sustainable farming strategies and interventions.