

Robust Denoising and DenseNet Classification Framework for Plant Disease Detection

Kevin Zhou¹ and Dimah Dera²^a

¹*Electrical and Computer Engineering, The University of Texas Rio Grande Valley, Brownsville, TX 78520 U.S.A.*

²*Chester F. Carlson Center for Imaging Science, Rochester Institute of Technology, Rochester, NY 14623 U.S.A.*
kevin.zhou01@utrgv.edu, dimah.dera@rit.edu

Keywords: Plant Disease Detection, DenseNet Image Classification, Robust Machine Learning, Denoising Neural Networks.

Abstract: Plant disease is one of many obstacles encountered in the field of agriculture. Machine learning models have been used to classify and detect diseases among plants by analyzing and extracting features from plant images. However, a common problem for many models is that they are trained on clean laboratory images and do not exemplify real conditions where noise can be present. In addition, the emergence of adversarial noise that can mislead models into wrong predictions poses a severe challenge to developing preserved models against noisy environments. In this paper, we propose an end-to-end robust plant disease detection framework that combines a DenseNet-based classification with a vigorous deep learning denoising model. We validate a variety of deep learning denoising models and adopt the Real Image Denoising network (RIDnet). The experiments have shown that the proposed denoising classification framework for plant disease detection is more robust against noisy or corrupted input images compared to a single classification model and can also successfully defend against adversarial noises in images.

1 INTRODUCTION

Plants, such as citrus fruits, provide various health benefits and are used in the production of various food products, which make them vital to the economies of many nations. Thus, it is essential to prevent significant losses in agricultural productivity to maintain a stable economy. One of the biggest causes of loss to plant production is plant diseases, which can render crop outputs to be less suitable for consumption or usage. Detection of these plant diseases is crucial to prevent significant losses in productivity (Li et al., 2020). The earlier a disease is treated in crop fields, the less damage it can cause. Removing diseased plants on assembly lines would increase the quality of sold products.

Traditional image processing methods of plant disease detection can be time-consuming, costly and need field experts. Recently, machine learning (ML) models have been used to detect and diagnose plant diseases among certain crop species automatically and accurately. In particular, deep convolution neural networks (DCNNs) have been used extensively to

identify and classify plant diseases (Nivethitha et al., 2022; Lakshmanarao et al., 2021; Shaikh and Dhole, 2017). Many of these models developed different techniques to improve the accuracy of plant disease detection and classification from plant images. However, a common problem with most of the models in the literature is that they do not fully exemplify real-life conditions. In other words, most of the state-of-the-art models have been trained on images prepared in laboratories or clean settings. In particular, recent models did not consider various sorts of noise in images, which can be generated simply through elevated light levels, heat, or the resolution of the camera sensors and can decrease the overall accuracy of a model (Boyat and Joshi, 2015). In addition to natural noise, adversarial noise also presents a challenge to obtaining a stable performance (Huq and Pervin, 2020). *Adversarial noise* is an imperceptible intentionally crafted perturbation added to input images and drives ML models to make incorrect predictions. This type of smart noise can pose an obstacle to deploying many ML-based models due to security concerns and the lack of robustness.

Previous techniques to remove noise often included filters such as median filters. However, many

^a <https://orcid.org/0000-0002-7168-5858>

filtering techniques distort image quality after reconstruction and often can not effectively remove adversarial noise where noise levels can be very small. Recently, deep learning models, including deep neural networks (DNNs), have been applied to remove distortions and noise from images effectively.

In this paper, we propose a novel DenseNet-based classification model to classify three different citrus diseases on leaves and fruits. The proposed DenseNet model is trained in two different scenarios: (1) with noise injection image augmentation and (2) without any form of image augmentation. In our experiments, we adopt and evaluate three state-of-the-art deep learning denoising models, i.e., Convolution Blind Denoising network (CBDnet) (Guo et al., 2019), Real Image Denoising network (RIDnet) (Anwar and Barnes, 2020), and Residual Encoder-Decoder network (REDnet) (Mao et al., 2016). We train these three denoising models in two different scenarios: (1) We train the models on citrus images corrupted with Gaussian and salt and pepper noise. (2) We perturbed the citrus images with two types of adversarial attacks (Fast Gradient Sign Method (FGSM) (Goodfellow et al., 2015), and Projected Gradient Descent (PGD) (Madry et al., 2019)). The three denoising models are then combined with our DenseNet classification model, which makes the model more robust and stable in predicting citrus diseases. We summarize our contributions as follows:

- Developing a novel DenseNet-based model for citrus disease classification with and without noise injection image augmentation techniques.
- Training and validating three different denoising models, i.e., CBDnet, RIDnet, and REDnet, with Gaussian, salt and pepper, and adversarial noise. Then, the denoising models are combined with the proposed DenseNet classification model.
- Evaluating and analyzing the citrus disease DenseNet classification models' performance against Gaussian, salt and pepper and adversarial noise with and without combining the denoising models. The experiments show that the denoising models contribute to increasing the robustness of the proposed DenseNet classification against various types of noise, especially FGSM and PGD adversarial noise.

The paper is structured as follows. Section 2 is the literature review. Section 3 explains the proposed denoising-classification plant disease detection framework. Section 4 presents experimental settings. Section 5 shows the experiments and simulation results. Section 6 discusses and analyzes the experimental results. Section 7 is the conclusion.

2 LITERATURE REVIEW

Shireesha *et al.* showed how a DenseNet121-based CNN model with transfer learning techniques achieved a 96% accuracy in detecting four different citrus diseases (Shireesha and Reddy, 2022), indicating the strengths of DenseNet for the classification problem of citrus disease. Sharma *et al.* combined a CNN network of three 224×224 convolution layers, three 112×112 convolution layers and 64 max-pooling layers with a long short-term memory (LSTM) network to classify citrus canker on lemons based on the stage of the disease. The model achieved an accuracy of 94.2% for the hybrid model and 98.43% for the early level of lemons citrus canker disease severity (Sharma and Kukreja, 2022). Li *et al.* made a comprehensive summary of various popular models and methods of detecting plant diseases, such as VGG-16, inception v3, GoogleNet, and hyperspectral imaging (Li et al., 2021).

While many of these models performed relatively well in classifying their respective diseases, the accuracy of these models was achieved by training them on clean images. To combat this problem, some studies have combined image-cleaning methods to remove noise from images before classification (Xu et al., 2018). Huang *et al.* introduced an asymptotic non-local mean network (ANLM) and an extreme learning machine (ELM), a learning algorithm based on a single feed-forward hidden layer optimized by linear particle swarm optimization (PSO). The ANLM model was fused with a parallel CNN (PCNN) utilizing exponential linear unit (ELU) to form a new ML model. The ANLM network was used to denoise images, while the hybrid ANLM-PCNN was used to classify images that include five types of peach diseases (Huang et al., 2020). However, the study focused on classifying peach diseases, and there was no direct measure of how much of an effect the denoising model had on the overall accuracy. Narmadha *et al.* proposed an image-processing system that consisted of image acquisition, preprocessing, feature extraction, and segmentation (Narmadha and Arulvadiu, 2017). During the segmentation part, the K-means algorithm was used to both denoise and enhance the images (Lloyd, 1982). Similarly, Deepa utilized both the median filter and K-means algorithm to clean and enhance images before classification (Deepa, 2018). Using both techniques, the quality of the image increased to 35% and allowed for better performance of the classification model.

In the past few years, more advanced denoising models based on deep learning have been proven to excel at cleaning images with noise and perturbations

compared to traditional methods, such as non-local means (NLM) and median filters (Limshuebchuey et al., 2020). Zilvan *et al.* used a denoising convolutional variational autoencoder to denoise images and classify different plant diseases through unsupervised learning. The model outperformed non-convolutional denoising variational autoencoders; however, it was only tested on salt and pepper noise (Zilvan et al., 2019). Saeed *et al.* proposed REDNet as an autoencoder denoising model with convolutional layers and skip connections. The model was able to achieve an average peak-signal-to-noise ratio (PSNR) of 33.63 dB on the Berkely Segmentation Dataset (BSD) (Martin et al., 2001). However, deep learning convolution models have shown to be better than autoencoders for denoising. Guo *et al.* introduced CBDNet, which is a convolutional denoising model with a noise estimation sub-network. The model improved the average PSNR to 38.06 dB on the Darmstadt noise dataset (DnD) (Plötz and Roth, 2017). Mao *et al.* proposed RIDNet with a modular architecture and residual structure for feature attention that achieved a better PSNR of 39.23 dB compared to CBDnet on the DnD dataset.

3 PROPOSED METHODS

We propose a hybrid model that combines two deep learning architectures, one for denoising and improving image quality and the second for disease detection and image classification. The proposed model allows the classification to operate against various unwanted image noise, increasing the robustness of a disease classification model. We evaluate three state-of-the-art deep learning denoising CNNs, i.e., CBDNet, REDNet, and RIDNet, through an extensive simulation to demonstrate which denoising model brings the most improvements to the proposed DenseNet deep learning classification models for plant disease detection. The hybrid architecture demonstrates higher robustness and superior performance under noisy conditions and adversarial attacks.

3.1 CNN-Based Image Denoising

The *Convolution Blind Denoising network (CBDnet)* (Guo et al., 2019) consists of two sub-networks. The first sub-network performs the noise estimation, and the second sub-network is used for non-blind denoising. The noise estimation sub-network creates an estimated noise map, which is used as an input to the non-blind denoising sub-network to get the final denoising results. We use the mean squared error (MSE)

loss. Given that $\hat{y}_i$ is the noisy-corrupted image and y_i is the ground truth, the loss is defined as follows:

$$Loss = \sum_{i=1}^n (y_i - \hat{y}_i)^2 + (\lambda * TV), \quad (1)$$

where λ is a hyperparameter and TV is the total variation regularize.

The *Real Image Denoising network (RIDnet)* (Anwar and Barnes, 2020) is an autoencoder-based denoising model with convolutional and deconvolutional layers. The convolutional portion acts as a feature extractor, while the deconvolutional layers, with the help of skip connections, are combined to recover the image content details. In this study, we implement the convolutional layers with zero padding to ensure that the input and output feature maps have the same dimension. The transposed convolutional layers with zero padding are used for the deconvolutional layers.

The *Residual Encoder-Decoder network (RED-net)* (Mao et al., 2016) consists of three major modules: feature extraction module, feature learning residual module, and reconstruction module. The feature extraction module is composed of one convolutional layer that extracts features of the original image. The feature learning residual module contains the enhancement attention modules (EAM) and local and short skip connections to form the residual structure. Similar to the feature extraction model, the reconstruction module consists of one convolutional layer that outputs the denoised image (Anwar and Barnes, 2020).

3.2 DenseNet Classification

We develop a novel DenseNet classification model for image classification and plant disease detection. The model is trained in separate settings with and without noise injection image augmentation techniques. The proposed model is mainly composed of dense blocks and transition layers. Every *dense block* comprises a selected number of pairs of 1×1 and a 3×3 convolution layers with the rectified linear unit (ReLU) activation function and batch normalization associated with every convolution layer. On the other hand, every *transition layer* includes 1×1 convolution layer with the ReLU activation function and batch normalization and 2×2 average pooling layer. The proposed model considers a small DenseNet architecture with 7×7 convolution layer, three dense blocks, and three transition layers, with the dense blocks consisting of 4, 6, and 8 pairs. Thus, the proposed DenseNet architecture contains 41 convolution layers and one fully connected layer (DenseNet-41). Figure 1 shows a block diagram that explains the steps of plant image

classification and disease detection. Figure 2 shows the DenseNet model architecture.

4 EXPERIMENTAL SETTINGS

4.1 Data Collection and Processing

In this paper, we assemble citrus plant images in various healthy and diseased conditions, species, and environments manually using home plants and online available plant images. We also use two publicly available datasets, i.e., the PlantVillage dataset (Hughes and Salathé, 2015) and the Colombian citrus fruits dataset (Torres, 2021). The total number of data samples is 17,306 citrus plant images. We apply multiple processing techniques, such as cropping, zooming, and many more. The collected images are based on six classes: Black Spot, Canker, Citrus Greening Leaves, Citrus Greening Fruits, Healthy Fruits, and Healthy Leaves. Then, we divide the dataset into training, validation, and test sets to train and validate the learning and robustness of the proposed models accurately. The evaluation criterion is set to have the diseased portion of the tree or fruit being clearly visible to the human eye and being the center or focus of the image. The manually collected images are sorted, labeled and assigned manually to their corresponding folder to generate training, validation and test sets of citrus images. The images are split into three sets: 66% for the training set, 16.5% for the validation set, and 17.5% for the test set.

4.2 Data Augmentation

We use image augmentation techniques to train the denoising models (CBDnet, RIDnet, and REDnet) on Gaussian and salt and pepper noise (using MATLAB). For the purpose of data augmentation, the original images are perturbed with Gaussian noise and salt and pepper noise. The salt and pepper noise corrupts 2% of pixels within the images. The standard deviation of the Gaussian noise is set to 0.1.

On the other side, we train the denoising models on two types of adversarial examples using the Fast Gradient Sign Method (FGSM) (Goodfellow et al., 2015) and the Projected Gradient Descent (PGD) (Madry et al., 2019). The severity of the adversarial noise is measured by ϵ value for both FGSM and PGD. For every image, the ϵ value is assigned randomly from the range of (0.01 – 0.1). For the PGD adversarial noise, the number of iterations is 7. In total, 17,306 augmented images are created either with Gaussian, salt and pepper, FGSM, or PGD noise.

4.3 Adversarial Noise

Adversarial noise is a specific type of noise that is injected into an image to mislead a machine-learning model into making incorrect predictions. The strength of adversarial noise is that perturbations can be small enough not to be visible to the human eye yet enough to raise the chance of incorrect classification. Adversarial noise has two types depending on the knowledge available to the adversarial network. The white-box attack is the attack generated utilizing the targeted model’s parameters. While the black-box attack is the attack generated without having access to the targeted model’s parameters. FGSM is a fast and computationally light adversarial attack that uses the signed gradients of the model to create adversarial examples. The FGSM adversarial example can be represented as:

$$\mathbf{X}^{\text{Adv}} = \mathbf{X} + \epsilon * \text{sgn}(\nabla_{\mathbf{X}} J(\theta; \mathbf{X}, \mathbf{y})), \quad (2)$$

where $\mathbf{X}^{\text{Adv}}$ is the adversarial image, $\mathbf{X}$ is the original input image, $\mathbf{y}$ is the ground truth label, J is the loss function, θ is the model parameters, and ϵ measures the severity of the attack.

PGD is a more effective but computationally heavy adversarial attack that is generated in an iterative process by computing the gradient that maximizes the loss with respect to the input image. The PGD adversarial example can be represented as:

$$\mathbf{X}_{i+1}^{\text{Adv}} = \text{Clip}_{\mathbf{X}, \epsilon} \left\{ \mathbf{X}_i + \alpha \text{sign}(\nabla_{\mathbf{X}} J(\theta; \mathbf{X}, \mathbf{y})) \right\}, \quad (3)$$

where α is a small step size. The clipping operation ensures that the adversarial examples are in the ϵ -neighborhood of the original data.

4.4 Training Settings

We train all models using the Adam optimization algorithm. All the denoising models are trained for 100 epochs. The MSE loss is used as a metric during the training of all the denoising models. For training the denoising models on adversarial noise, certain layers within the models have a larger kernel size and number of filters to increase the parameter space and boost the ability to detect pixel differences among denoising models. The proposed DenseNet plant disease classification model is trained in two different scenarios, i.e., training the model with and without noise image augmentation. The categorical cross entropy is used for the classification model in the two mentioned training scenarios.

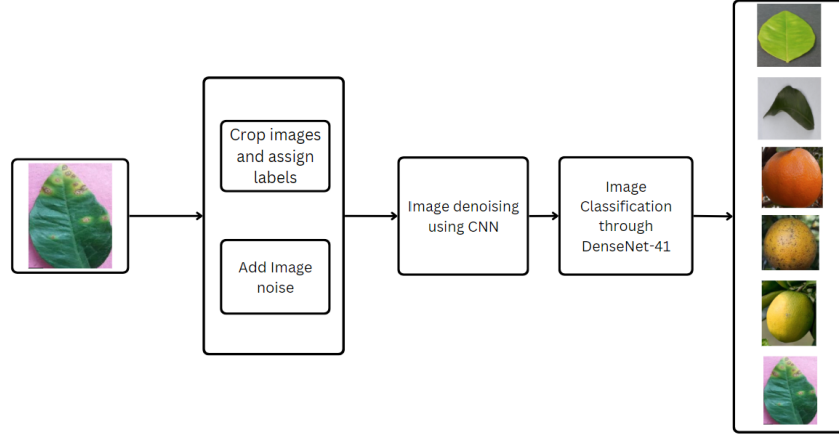


Figure 1: Block diagram that shows the steps used for the plant disease classification, including (1) image processing and noise injection augmentation, (2) image denoising using CNN, and (3) image classification using the proposed DenseNet-41.

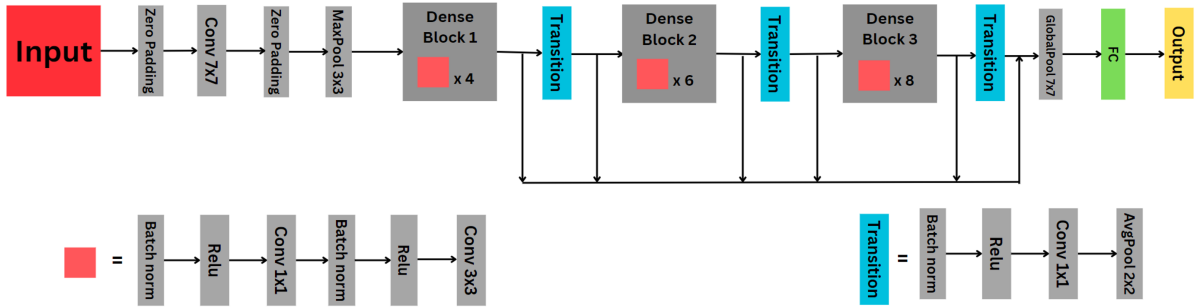


Figure 2: The proposed DenseNet architecture has three dense blocks and three transition layers. The dense blocks have 4, 6, and 8 pairs of convolution layers within each dense block. Thus, the proposed DenseNet architecture contains 41 convolution layers and one fully connected layer (DenseNet-41).

4.5 Testing Settings

4.5.1 Image Quality Metrics

We use a peak-signal-to-noise ratio (PSNR) and a structural similarity index measure (SSIM) to evaluate image quality. PSNR is calculated as follows:

$$MSE = \frac{1}{mn} \sum_{i=0}^{m-1} \sum_{j=0}^{n-1} [I(i, j) - K(i, j)]^2. \quad (4)$$

$$PSNR = 20 * \log_{10} \left(\frac{\max(I)}{\sqrt{MSE}} \right), \quad (5)$$

where $\max(I)$ is the maximum possible pixel value of an $m \times n$ image I and the noisy image K and MSE is the mean squared error. On the other hand, SSIM is calculated as follows (Wang et al., 2004):

$$SSIM(X, Y) = \frac{2(\mu_X \mu_Y + C_1)(\sigma_{XY} + C_2)}{(\mu_X^2 + \mu_Y^2 + C_1)(\sigma_X^2 + \sigma_Y^2 + C_2)}. \quad (6)$$

$$\mu_X = \frac{1}{N} \sum_{i=1}^N X_i, \text{ and } \sigma_X = \left(\frac{1}{N-1} \sum_{i=1}^N (X_i - \mu_X)^2 \right)^{\frac{1}{2}}, \quad (7)$$

where X and Y are non-negative image signals, μ and σ are the average intensity and standard deviation.

4.5.2 Test Set-Up

The experimental devices and platforms used are Ubuntu 20.04.6 with a lambda machine of NVIDIA Quadro RTX 6000. TensorFlow is the library used for building the proposed deep learning architectures. After training the denoising and classification models, the denoising models are individually combined with the DenseNet image classification model. The denoising models that are trained on Gaussian and salt and pepper noise are tested on the Gaussian and salt and pepper noise test set, and the average PSNR and structural similarity index measure (SSIM) are collected. We create an adversarial test set for the denoising models that are trained on adversarial noise with a perturbation multiplier (ϵ) value of 0. The denoising models are then paired with a DenseNet-41 to create three different denoising- classification methods: *CBDNet* and *DenseNet-41* (*CBD-DNet*), *RIDNet* and *DenseNet-41* (*RID-DNet*), and *RED-*

Table 1: PSNR and SSIM before and after applying the denoising models for Gaussian and salt and pepper noise.

	PSNR				SSIM			
	Before Denoising	RIDNet	CBDNet	REDNet	Before Denoising	RIDNet	CBDNet	REDNet
Gaussian	20.39	43.6	38.23	32.16	0.22	0.98	0.94	0.81
Salt & Pepper	21.86	34.01	34.01	31.13	0.58	0.83	0.78	0.75

Net and DenseNet-41 (RED-DNet). An independent DenseNet-41 without denoising models is also utilized. The PSNR of the denoised image, the accuracy, and the loss are collected. We conduct several experiments where the perturbation multiplier (ϵ) is increased gradually by 0.005. At the test time, we test the models on images corrupted with adversarial noise with (ϵ) value from 0 to 0.1.

5 EXPERIMENTAL RESULTS

Table 1 shows the PSNR and SSIM values before and after applying the denoising models, i.e., RIDNet, CBDNet, and REDNet. We observe from the table that the denoising models improve image quality in the denoised images with higher PSNR and SSIM as compared to noisy images before applying the denoising models. We also observe that the RIDNet model performs better than the other two denoising models with PSNR measurements of 43.6 dB and 34.01 dB and SSIM measurements of 0.98 and 0.83 for the Gaussian and salt and pepper noise, respectively.

Table 2 shows the evaluation performance of the proposed DenseNet classification model before combining it with the denoising models. The table presents the precision, recall, F1-score, and support for the model before and after applying the noise injection image augmentation techniques. We notice when noise injection image augmentation is implemented into the training of DenseNet-41, the accuracy improves by 1.1%. A reason for only a subtle increase in accuracy is that the noise levels used in the noise injection image augmentations are relatively low, meaning that the images might not significantly differ from the ground truth image, and DenseNet-41 can still recognize key patterns within the images, even with a minor noise disturbance. With higher noise levels and other image augmentation methods, such as flipping, the classification model may not easily recognize the image. Table 3 depicts the accuracy and loss values for the proposed DenseNet before and after combining it with the denoising models, where CBD-DNet means CBD combined with DenseNet and similarly for RED-DNet and RID-DNet. Figure 3 and 4 show the accuracy, loss, and PSNR values plotted versus

ϵ for the proposed DenseNet classification with and without combining the denoising models for the adversarial noise, FGSM and PGD, respectively. We observe that combining the denoising models allows for higher accuracy and lower loss, thus, higher robustness and better stability for the model behavior.

Table 2: Classification evaluation of DenseNet-41 without the denoising models.

Metrics	Disease	Ground Truth	Noise Augmentation
		Training	Training
Precision	Black Spot	0.72	0.79
	Canker	0.75	0.87
	Greening Fruit	1.00	0.97
	Healthy Fruit	1.00	1.00
	Greening Leaves	0.99	0.99
	Healthy Leaves	0.95	0.97
Recall	Black Spot	0.89	0.95
	Canker	0.39	0.48
	Greening Fruit	0.93	0.94
	Healthy Fruit	1.00	1.00
	Greening Leaves	1.00	1.00
	Healthy Leaves	1.00	1.00
F1-Score	Black Spot	0.80	0.86
	Canker	0.51	0.62
	Greening Fruit	0.97	0.96
	Healthy Fruit	1.00	1.00
	Greening Leaves	0.99	0.99
	Healthy Leaves	0.98	0.98
Support	Black Spot	250	250
	Canker	148	148
	Greening Fruit	120	120
	Healthy Fruit	1251	1251
	Greening Leaves	1114	1114
	Healthy Leaves	121	121

6 DISCUSSION AND ANALYSIS

We recognize from our extensive simulation that the denoising models improve image quality with higher PSNR and SSIM for the Gaussian and salt and pepper

Table 3: Accuracy and loss values for the proposed DenseNet classification model before and after combined with the denoising models. Two types of training are shown: One with noise injection image augmentation and one without.

Methods	Image Type	Ground Truth		Noise Augmentation	
		Training		Training	
		Accuracy	Loss	Accuracy	Loss
DenseNet-41	Gaussian	95.67	0.1235	96.77	0.0989
	Salt & Pepper	95.91	0.1186	96.94	0.0982
	Ground Truth	95.81	0.1213	96.90	0.0985
CBD-DNet	Gaussian	95.67	0.1240	96.80	0.0992
	Salt & Pepper	95.74	0.1240	96.84	0.1023
	Ground Truth	95.57	0.1250	96.77	0.1000
RED-DNet	Gaussian	95.74	0.1194	96.87	0.0994
	Salt & Pepper	95.67	0.1237	96.77	0.1010
	Ground Truth	95.64	0.1266	96.67	0.0998
RID-DNet	Gaussian	95.64	0.1270	96.67	0.1021
	Salt & Pepper	95.61	0.1242	96.74	0.0993
	Ground Truth	95.67	0.1236	96.74	0.0989

noisy images (Table 1). However, when the denoising models are combined with the proposed DenseNet classification, they don't significantly contribute to a higher performance. Table 3 shows insignificant changes in the loss and accuracy values for the proposed DenseNet-41 before and after combining the denoising models for the Gaussian and salt and pepper noise. The experiments suggest that DenseNet-41 is resistant to Gaussian and salt and pepper noise. On the other hand, the results for the adversarial noise show that the deep learning denoising CNNs act as an effective defense against adversarial noise when combined with the proposed DenseNet classification model. Figures 3 and 4 demonstrate that RID-DNet and CBD-DNet have stable accuracy and loss curves.

Overall, the best-performing denoising model is RIDnet, achieving the highest PSNR and SSIM measurements when denoising Gaussian and salt and pepper noise and the highest stable accuracy when combined with the DenseNet-41 (RID-DNet) against adversarial noise. The RID-DNet model stabilized accuracy is between 89.71% and 92.01% for PGD adversarial noise and between 92.88 and 98.83% for FGSM adversarial noise. The best-performing RID-DNet denoising model has enhancement attention modules (EAM), which are known to be effective in feature extraction and retention.

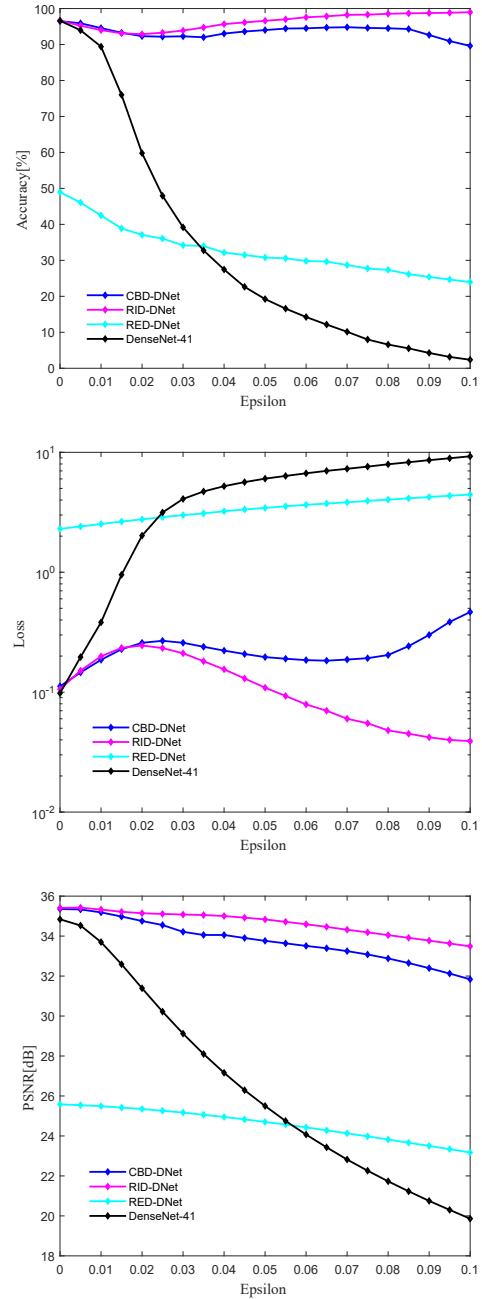


Figure 3: The test accuracy, loss and PSNR of proposed frameworks against FGSM plotted versus the severity of the adversarial noise ϵ .

7 CONCLUSION

We propose a deep learning denoising classification system to increase the robustness and efficiency of citrus disease detection against noisy and adversarial inputs. We evaluate the capabilities of three state-

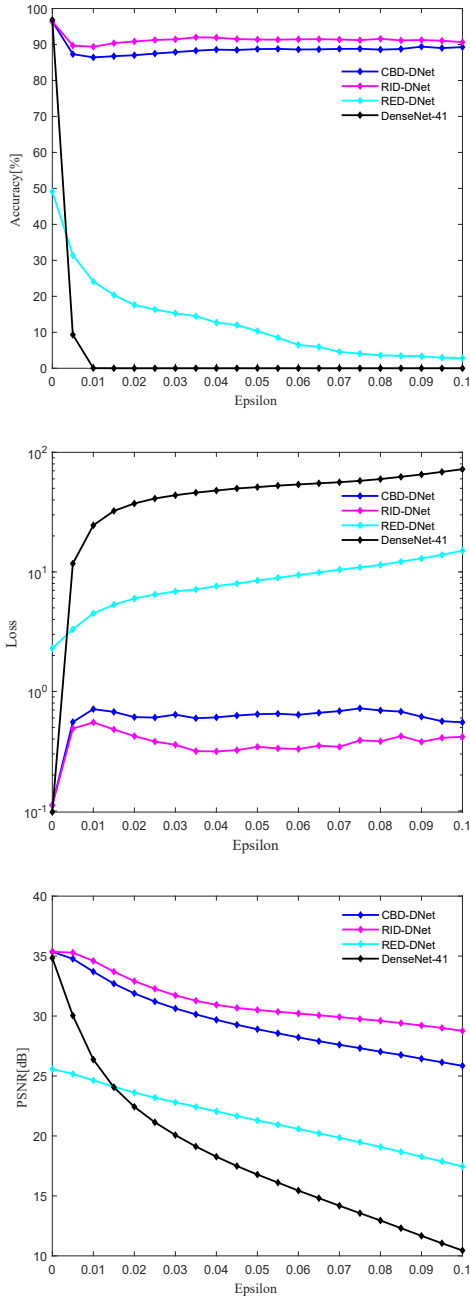


Figure 4: The test accuracy, loss and PSNR of proposed frameworks against PGD plotted versus the severity of the adversarial noise ϵ .

of-the-art denoising models before and after they are each combined with the proposed DenseNet-41 classification model. The experiments show that the combination of deep learning denoising models and the DenseNet-41 classification model is able to improve the quality of images with Gaussian and impulsive noise before classification and can successfully detect citrus diseases against white-box adversarial noises.

The proposed hybrid framework of the deep learning denoising CNN combined with the DenseNet classification model allows for cleaner images and a higher success rate against both types of adversarial noise, i.e., FGSM and PGD. By comparing the performance of the denoising models for both image quality and accuracy when combined with the DenseNet classification, the overall best denoising model is RIDnet. In the future, we aim to stretch the extent of the model by utilizing different types of image distortion and noise, such as image blurring, and use substantially stronger adversarial noise to validate the extent of the robustness of the proposed plant disease classification and detection framework.

ACKNOWLEDGMENT

This work was supported by the National Science Foundation Award CRII-2153413/2401828.

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