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Design and Development of a Portable NDVI-Based System for Pesticide Residue Detection on Fruits

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ABSTRACT

Food, clothing, and shelter are the basic needs of every human being, and among these, food plays the most important role in sustaining life. In a country like India, which has a large and continuously growing population along with rich agricultural diversity, the demand for food is increasing every year. Due to the decrease in cultivable land and the pressure to improve crop yield, farmers widely use pesticides to protect crops from pests and diseases. Although pesticides help in increasing production, their excessive or improper application often leaves harmful chemical residues on fruits and vegetables. These residues can affect human health if consumed over a long period.

Considering this issue, the present work aims to design and develop a portable device for detecting pesticide residues on agricultural produce. The proposed system is based on the Normalized Difference Vegetation Index (NDVI) technique. It uses an infrared (IR) sensor and a photodiode to capture reflectance data, which is processed by an ATmega8 microcontroller. The calculated NDVI value is then displayed on a screen for the user. The device is compact, affordable, and easy to operate, making it suitable for everyday use. It provides a quick and non-destructive method for preliminary screening of fruits and vegetables, thereby contributing to improved food safety and public awareness.

Keywords:- Pesticide Residue Detection, Normalized Difference Vegetation Index (NDVI), Infrared (IR) Sensor, Atmega8 Microcontroller, Non-Destructive Testing

1. INTRODUCTION

India is one of the leading producers of fruits and vegetables worldwide and plays a significant role in global agricultural output. With a rapidly increasing population and decreasing cultivable land, agricultural productivity must be enhanced to meet food demands. To achieve higher yields and protect crops from pests and diseases, farmers extensively use pesticides and agrochemicals. While these chemicals improve production efficiency, their excessive or improper application leads to pesticide residues remaining on fruits and vegetables after harvesting.

The presence of pesticide residues in food commodities has become a major public health concern. When residue levels exceed the prescribed **Maximum Residue Limit (MRL)**, continuous consumption may result in adverse health effects such as neurological disorders, hormonal imbalance, reproductive complications, and even carcinogenic risks. Children and pregnant women are particularly vulnerable to pesticide exposure. Therefore, ensuring food safety through effective detection of pesticide residues is of critical importance.

Pesticides are chemical or biological agents used to prevent, destroy, or control pests that interfere with agricultural production, storage, and distribution. They are broadly classified into chemical pesticides (such as insecticides, herbicides, fungicides, rodenticides, and nematicides) and biopesticides derived from natural sources. Among chemical pesticides, organophosphates, organochlorines, and carbamates are widely used due to their high effectiveness. However, these compounds may persist in the environment and accumulate in food products.

Various laboratory-based analytical techniques are currently employed for pesticide residue detection. These include spectrophotometry, gas chromatography (GC), liquid chromatography (LC), gas chromatography–mass spectrometry (GC–MS), electroanalytical methods, capillary electrophoresis, enzyme-linked immunosorbent assay (ELISA), and biosensor-based approaches. Although these techniques provide high accuracy and sensitivity, they involve expensive instrumentation, complex sample preparation, skilled operation, and significant analysis time. Moreover, they are generally confined to laboratory environments and are not suitable for rapid on-field testing.

To overcome these limitations, there is a need for a portable, cost-effective, and user-friendly detection system that enables rapid and non-destructive analysis of pesticide residues on fruits and vegetables. In this work, a microcontroller-based detection system is proposed using the Normalized Difference Vegetation Index (NDVI) principle. The system utilizes an infrared (IR) sensor, photodiode, Atmega8 microcontroller, and LCD display unit.

The proposed device operates by measuring the reflected red and infrared light from the surface of agricultural produce. The NDVI value is computed from the ratio of reflected wavelengths, and deviations from reference values are used to indicate possible pesticide contamination. The system is designed to be compact, economical, and suitable for field applications, thereby providing an alternative to conventional laboratory methods.

2. LITERATURE SURVEY

This section reviews existing research work related to pesticide residue detection and vegetation-based spectral analysis techniques used in agricultural applications.

2.1. ATR–FTIR Based Detection Techniques

Horiguchi *et al.* [9] proposed a method for detecting pesticide particles in water using the Attenuated Total Internal Reflection (ATR) technique. ATR spectroscopy enables surface-level analysis of solid, liquid, and powdered samples by placing them in contact with an ATR prism. In their experimental setup, sprayed pesticides were collected using water-sensitive paper and polyethylene sheets. Infrared radiation was directed onto the collected samples, and the reflected spectrum was analyzed.

The pesticide concentration was estimated using Fourier Transform Infrared (FTIR) spectroscopy based on the Lambert–Beer law, where absorbance is directly proportional to concentration. Although the technique demonstrated reliable qualitative analysis, it required sophisticated spectroscopy equipment and computational support, making the system bulky and expensive for field applications.

2.2. Spectral and NDVI-Based Agricultural Monitoring

Riczu *et al.* [10] conducted spectral surveys in apple orchards using multiple spectral instruments. The collected data were processed to generate Normalized Difference Vegetation Index (NDVI) maps. Strong linear correlations were observed among different spectral measurements during early senescence stages. The study demonstrated that spectral sensing can non-destructively evaluate crop vigor and health.

The NDVI is calculated using reflected red and near-infrared (NIR) wavelengths as:

$$\mathrm{NDVI} = \frac{(\mathrm{NIR} - \mathrm{Red})}{(\mathrm{NIR} + \mathrm{Red})}$$

The commercial sensor GreenSeeker 505 is widely used for NDVI-based crop monitoring. It emits red light (656 nm) and near-infrared light (774 nm) toward the crop canopy and measures the reflected signals to estimate vegetation health. Although effective for nutrient and vigor assessment, such systems are primarily designed for crop management rather than direct pesticide residue detection.

Similarly, Bhandari *et al.* [11] utilized satellite-based multispectral imagery to generate NDVI maps for vegetation classification. Geostatistical analysis was applied to study spatial variability in soil nutrients and crop characteristics. NDVI thresholds were used to create false color composite images for land feature identification. While the technique is valuable for precision agriculture and environmental monitoring, it does not directly address surface-level chemical contamination.

2.3. Extraction and Chromatographic Techniques

Fernandes *et al.* [12] reviewed various extraction methods for pesticide residue analysis in fruits and juices. Traditional methods such as Solid Phase Extraction (SPE) and Solid Phase Microextraction (SPME) were discussed. A more recent technique, QuEChERS (Quick, Easy, Cheap, Effective, Rugged, and Safe), was highlighted for its improved efficiency and selectivity. When combined with chromatographic and mass spectrometric techniques, QuEChERS offers reliable quantitative analysis. However, these methods still require laboratory infrastructure and trained personnel.

Rodrigues *et al.* [14] determined insecticide residues in fruit samples using gas chromatography with an electron capture detector (GC-ECD). The analysis was performed using Perkin Elmer AutoSystem XL. Parameters such as limit of detection (LOD), limit of quantification (LOQ), precision, and recovery were evaluated. Although accurate, the approach involved complex sample preparation and laboratory-based instrumentation.

Bhadekar *et al.* [13] summarized conventional detection methods including spectrophotometry, chromatography (GC, LC), capillary electrophoresis (CE), electroanalytical techniques, enzyme-linked immunosorbent assay (ELISA), flow injection analysis, and biosensor-based approaches. These techniques provide high sensitivity but are time-consuming, expensive, and unsuitable for rapid field deployment.

2.4. Biosensor-Based Approaches

Bueno *et al.* [15] presented an automated biosensor characterization system using Sequential Injection Analysis (SIA) for detecting organophosphate pesticides. The biosensor comprised three essential components: a bioactive molecule, a physicochemical transducer, and an electronic processing unit. Automation improved response time and enabled multi-sensor operation. Despite these advantages, biosensor systems may suffer from limited stability and require periodic calibration.

2.5. Chlorophyll and Optical Monitoring Techniques

Rodriguez *et al.* [16] utilized the SPAD-502 to assess plant health by measuring chlorophyll content through optical density at two wavelengths. Strong correlations were observed between SPAD values and chlorophyll concentration. Although useful for nitrogen management and crop health evaluation, chlorophyll meters are not intended for detecting pesticide residues on fruit surfaces.

2.6. Research Gap

From the reviewed literature, it is evident that most existing pesticide detection methods rely on laboratory-based analytical techniques such as chromatography and spectroscopy, which are costly and require skilled operation. Remote sensing and NDVI-based approaches are primarily used for crop health assessment rather than direct residue detection. Biosensor-based systems offer portability but may involve stability and maintenance challenges.

Therefore, there is a clear need for a compact, cost-effective, and non-destructive detection system suitable for on-field applications. The present work aims to address this gap by developing a portable NDVI-based microcontroller system for rapid pesticide residue detection on fruits and vegetables.

3. PRINCIPLE OF OPERATION

The system operates based on reflectance differences between red and near-infrared (NIR) light. The NDVI is calculated using:

(NDVI= B-A/A+B)

where:

A = Red band intensity

B = Infrared band intensity

Changes in surface characteristics due to pesticide application alter reflectance properties, resulting in measurable NDVI variations.

4. SYSTEM ARCHITECTURE

The developed prototype consists of:

- IR emitter (NIR source)
- Red LED source
- Photodiode sensor
- ATmega8 microcontroller
- LCD display
- Power supply (5V, battery-operated)

The IR and red light are projected onto the fruit surface. Reflected light is captured by the photodiode and converted into voltage signals. These analog signals are digitized using the microcontroller's internal ADC. The NDVI value is computed and displayed on the LCD in real time.

The entire circuit is implemented on a general-purpose PCB, making the device compact and portable.

5. EXPERIMENTAL SETUP

Experiments were conducted on:

- Apple samples (25 untreated, 25 treated)
- Sweet lemon samples (25 untreated, 25 treated)

Each sample's red and IR reflectance values were recorded, and NDVI values were calculated.

6. RESULTS AND DISCUSSION

6.1. Prototype Implementation

The developed prototype consists of an IR emitter–photodiode sensing unit interfaced with the ATmega8 microcontroller. The complete circuit, including power supply, LCD display, and signal conditioning unit, was fabricated on a general-purpose PCB.

During operation, the fruit sample is placed between the IR source and the photodiode sensor. The emitted near-infrared (NIR) and red light beams are partially absorbed and reflected by the sample surface. The reflected

signals are detected by the photodiodes and converted into voltage levels. These analog voltages are digitized using the inbuilt ADC of the ATmega8 microcontroller.
The microcontroller processes the received red and infrared intensity values and computes the NDVI using (1):
(NDVI= B-A/A+B)
where
A = Red band intensity
B = Infrared band intensity
The calculated NDVI value is displayed on the LCD panel in real time.

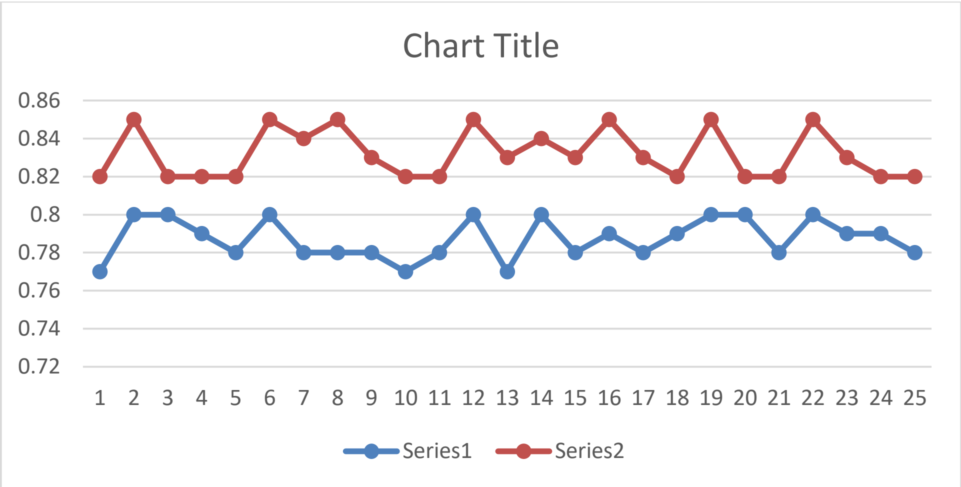
6.2. Experimental Results for Apple

A total of 25 samples were tested for apples under two conditions:

1. Without pesticide (organic condition)
2. With pesticide (treated condition)

The observed NDVI values for untreated apples ranged between **0.77 and 0.80**, with a mean value of **0.7872**.
For pesticide-treated apples, NDVI values ranged between **0.82 and 0.85**, with a mean value of **0.832**.
The average difference in NDVI between treated and untreated samples was observed to be approximately **0.04–0.05**. This consistent variation indicates that pesticide presence influences the reflectance characteristics of the fruit surface.
1) Statistical Analysis (Apple)

- Mean (Without pesticide), $\bar{X}$ = 0.7872
- Mean (With pesticide), $\bar{Y}$ = 0.832
- Standard Deviation (X) = 0.010614
- Standard Deviation (Y) = 0.01291



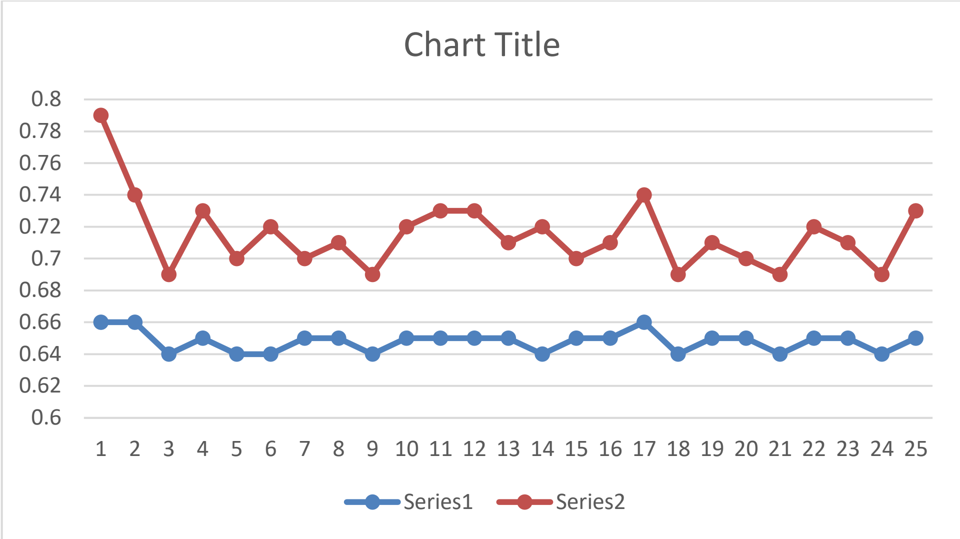
Statistical Analysis for Organic Vs Inorganic subject. (For Apple)

The Pearson's correlation coefficient was calculated using standard statistical procedures. The obtained correlation coefficient:
r=0.46
This moderate positive correlation validates that the developed hardware system is capable of distinguishing between treated and untreated samples with measurable consistency.

6.3. Experimental Results for Sweet Lemon

Similar experiments were conducted on 25 sweet lemon samples.
For untreated sweet lemon samples, NDVI values ranged from **0.64 to 0.66**, with a mean value of **0.648**.
For pesticide-treated samples, NDVI values ranged from **0.69 to 0.74**, with a mean value of **0.7148**.
The observed NDVI difference between treated and untreated samples was more significant compared to apples, indicating better distinguishability in citrus fruits.
1) Statistical Analysis (Sweet Lemon)

- Mean (Without pesticide), $\bar{X}$ = 0.648
- Mean (With pesticide), $\bar{Y}$ = 0.7148
- Standard Deviation (X) = 0.006455
- Standard Deviation (Y) = 0.022383



Statistical Analysis for Organic Vs Inorganic subject. (For Sweet Lemon)

The Pearson's correlation coefficient was calculated as:

$$r=0.73$$

The higher correlation value for sweet lemon indicates stronger consistency and improved detection capability of the proposed system for this fruit category.

7. DISCUSSION

From the experimental results, it is evident that pesticide-treated samples consistently exhibit higher NDVI values compared to untreated samples. This variation occurs due to changes in surface reflectance characteristics caused by pesticide residues.

The results demonstrate that the proposed portable NDVI-based detection system can effectively differentiate between organic and pesticide-treated fruits. The correlation analysis further validates the reliability of the system, particularly for sweet lemon samples where stronger correlation was observed.

Although the system does not directly quantify the chemical composition of pesticide residues, it provides a rapid, non-destructive, and cost-effective screening method. The developed prototype is compact, economical, and suitable for field-level applications.

8. CONCLUSION AND FUTURE SCOPE

8.1. Conclusion

The developed system utilizes Near-Infrared (NIR) sensing principles to evaluate the organic condition of fruits and vegetables using the Normalized Difference Vegetation Index (NDVI). The device emits infrared radiation onto the surface of the sample, and the reflected signal is captured using a photodiode. The detected signal is converted into a corresponding voltage through the inbuilt Analog-to-Digital Converter (ADC) of the ATmega8 microcontroller. Based on the measured red and infrared intensity values, the NDVI is computed and displayed on an LCD panel for user interpretation.

Experimental results demonstrate that pesticide-treated samples exhibit measurable variation in NDVI values compared to untreated samples. Statistical validation using Pearson's correlation coefficient confirms that the developed prototype provides reliable differentiation between organic and treated samples with acceptable error margins for day-to-day applications.

Compared to conventional laboratory-based pesticide detection techniques, which require sophisticated equipment, trained personnel, and significant processing time, the proposed system offers a rapid, non-destructive, and portable alternative. The device is economical, with an estimated manufacturing cost below Rs. 4000 per unit, making it accessible to the general public.

The system operates at 5V and can be powered using standard AA batteries, enhancing its portability and field usability. Due to its compact design and ease of operation, the device can serve as a practical consumer-level screening tool for assessing food safety.

8.2. Future Scope

Although the proposed system demonstrates promising results, several enhancements can further improve its performance and application range:

1. Multiple Sensor Integration:
   Incorporating multiple IR sensors and averaging their readings can enhance measurement stability and reduce random error.
2. High-Precision Optical Sensors:
   Using higher sensitivity photodetectors and calibrated NIR sources can improve detection accuracy and reduce noise in NDVI computation.
3. Multi-Parameter Analysis:
   Additional spectral bands and sensing parameters may be integrated to strengthen pesticide residue detection capability.
4. Advanced Chemical Detection:
   The system can be extended to detect other harmful agrochemicals such as weedicides, fungicides, and insecticides through improved spectral analysis techniques.
5. IoT-Based Monitoring:
   Future versions may include wireless communication modules for data logging, cloud storage, and large-scale monitoring applications.
   With further refinement, the proposed system has the potential to evolve into a reliable, affordable, and widely deployable food safety screening device.

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