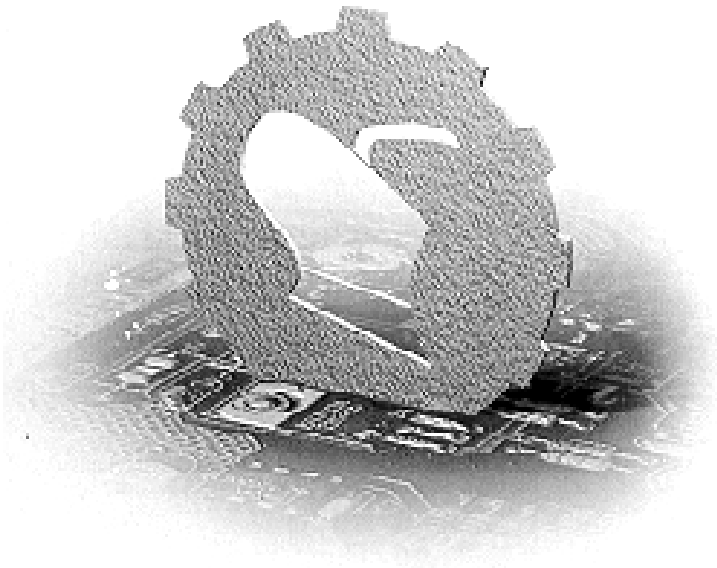


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# **ПОЉОПРИВРЕДНА ТЕХНИКА**

## **AGRICULTURAL ENGINEERING**

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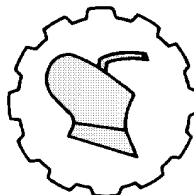
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## **APPLICATION OF ARDUINO BOARDS IN AUTOMATING THE PRODUCTION PROCESS OF RADISH MICROGREENS (*Raphanus sativus* var. *sativus*)**

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**Abstract:** This study presents a developing smart IoT system for monitoring the growth of radish microgreens under house conditions. Radish is a fast-growing microgreen, making it ideal for experimental investigation. Other microgreens can also be used in such experiments. The smart IoT system for monitoring microgreen growth is based on the Arduino UNO R4 WiFi board, which serves as the central controller. Additional components, such as a soil moisture sensor, air temperature and humidity sensor, relay, and LED bar, are connected to the Arduino board. Together, these components form a smart IoT system for monitoring the growth parameters of radish microgreens, measuring soil moisture, air humidity and temperature, and controlling the LED bar. As a result, a smart IoT system was developed that operates autonomously and enables real-time data transmission to mobile devices via the Internet.

**Key words:** *Urban agriculture, microgreens, IoT, Arduino UNO R4 WiFi,  
temperature, humidity, moisture*

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## INTRODUCTION

During the 20th century, there was a mass migration from villages to cities. Attracted by jobs and the prospect of an easier life, people left their farms and food production behind.

They sought refuge in cities that offered higher incomes and began buying food in supermarkets and city markets. By the late 20th and early 21st centuries, small-scale rural production had become unprofitable, and young people, influenced by stories from the cities, continued to seek their fortunes there. This led to a decline in the number of small producers who once sold their food in markets, and an increase in large producers whose products are resold in those markets. One way to address the problem of reduced-skilled work is to introduce automation in agriculture. Automation in agriculture not only addresses work shortages but also enables better compliance with deadlines, faster completion of work, and higher profits. Unfortunately, process automation in Serbia lags behind that of developed countries and is mostly available on larger farms. Another form of alternative food production is urban agriculture, which includes urban gardens, roof and terrace gardens, and microgreens cultivation.

In the late 19th and early 20th centuries, the allocation of common spaces and gardens became a popular practice in European cities such as London, Paris, and Stockholm. This approach helped poorer urban residents become more self-sufficient, with these plots most often located in the suburbs [1–5]. In addition to supporting the poor, such spaces have also been shown to affect social stability, morality, family life, physical activity, health, and urbanism. The concept of urban agriculture was not unique to these cities and appeared worldwide in places such as New York, Amsterdam, Berlin, and Toronto. Belgrade does not have a long tradition of allocating common spaces and gardens like the aforementioned cities, but in the past 15 years, urban agriculture has begun to develop. Bastiliste (*serb.* Baštilište) is the most well-known organic garden project, launched in 2013 at Slanci, 20 minutes from the centre of Belgrade. It is one of the first initiatives of its kind in Serbia, created to enable citizens to grow vegetables for their own needs. Additionally, the project aims to draw attention to numerous neglected and abandoned city locations that could be repurposed in this way.

Another form of food production in urban areas is the use of roof and terrace gardens [6–8]. Roof gardens are designated spaces on building roofs where plants or vegetables are grown, often integrated with modern technological systems [9]. Terrace gardens, located on the terraces of apartments or commercial premises, are usually smaller than roof gardens and typically use pots or planters. Both types of gardens support the cultivation of ornamental and edible plants, and contribute to biodiversity, aesthetics, psychological and health benefits, energy efficiency, rainwater management, improved air quality, and other positive effects. Cities such as Toronto, Chicago, Singapore, and Tokyo are successfully implementing rooftop gardens. In Belgrade, projects using modular roof systems to green flat roofs are underway, although these initiatives are still in their early stages.

Unlike the previously mentioned types of urban agriculture intended for poorer people, microgreens are grown in urban environments for wealthier individuals. In the 1980s and 1990s, prestigious restaurants began using various locally grown microgreens, providing customers with a distinctive experience.

This led to the rapid expansion of microgreens cultivation, as these crops are small, mature quickly, and are consumed immediately [10–13]. Microgreens are young plants harvested at a very early stage of development, usually when they reach a height of 5 cm to 10 cm. They typically consist of a stem and a single pair of leaves, the cotyledons. Unlike mature plants, which complete the full growth cycle to flowering and fruiting, microgreens are grown and harvested within a few days to a maximum of three weeks after germination. Because they are picked at an early stage, these plants contain a more concentrated amount of nutrients, vitamins, and minerals. Microgreens cultivation offers a completely new method of food production, which does not require much space; usually, it is sufficient to set aside a small area of a flat or house. With automation, the growth and production of microgreens can become almost entirely independent of human work. The aim of this work is to create a smart IoT system based on an Arduino microcontroller board, which monitors the growth of microgreens in house conditions. The entire system is a project related to smart agriculture. With minor modifications, the system can be used in other forms of urban agriculture.

## MATERIAL AND METHODS

The main component in this work is the Arduino UNO R4 WiFi microcontroller board with integrated Wi-Fi, which, together with the other components – soil moisture sensor, air temperature and humidity sensor, relay, and LED bar – forms a smart IoT system for monitoring microgreens, as shown in Figure 1. The Arduino UNO R4 WiFi is a microcontroller board with a universal serial bus (USB Type-C) for connection to a computer, and a series of pins for connecting external electronic components. The board can be powered in several ways: from a computer via the USB Type-C port, using a 9 V battery, or via power jacks. The Arduino board and all components are managed via a computer by programming them, and after uploading the sketch to the Arduino board, the system operates autonomously [14], [27].

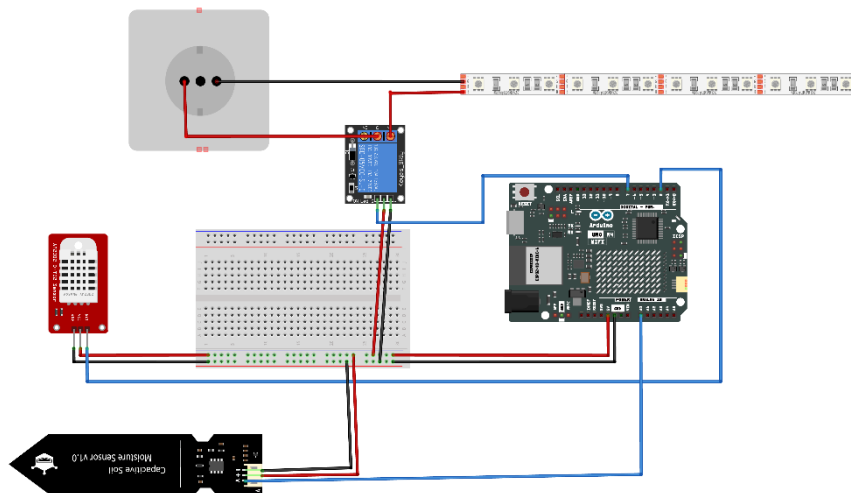


Figure 1. Electrical diagram of a smart IoT system for monitoring radish microgreens

The core of the Arduino UNO R4 WiFi board is the 32-bit RA4M1 microcontroller (256 kB flash memory, 32 kB SRAM, and 8 kB data memory (EEPROM)), which acts as a small computer on a chip. All other components supply power and enable communication with the computer [15], [27].

The other parts of the Arduino UNO R4 WiFi include a USB Type-C port, voltage regulator, voltage connectors (3.3V and 5V), GND connectors, analogue pins, and digital (PWM) pins. There are over thirty Arduino boards, and most operate on the same principles as the Arduino UNO R4 WiFi. Some boards offer more memory, a more powerful processor, or additional pins; others are designed to be compact and occupy little space, making them well suited for robots and certain autonomous systems.

Digital pins marked with a ~ support pulse width modulation (PWM). This technique generates an "average" voltage by rapidly switching the signal between on and off states, rather than physically outputting that voltage. In addition to the Arduino UNO R4 WiFi microcontroller board, the following components were used in this work: a temperature and air humidity sensor, a soil humidity sensor, an LED bar, and a relay. The DHT22 temperature and air humidity sensor measures the environmental conditions in the room where the microgreens are cultivated. By monitoring temperature and air humidity, stable conditions necessary for optimal plant growth are maintained. Depending on the microgreens being cultivated, the temperature should be maintained between 18°C and 28°C [16, 17]. Temperatures below this range slow metabolism and growth, while temperatures above it can cause the substrate to dry out, leading to plant stress or disease. The optimal relative air humidity for microgreens production is between 50% and 70% [16]. Humidity below this range can cause plants to dry out and reduce yield, while excessive humidity increases the risk of fungal infections and mould. The DHT22 sensor was used to measure temperature and air humidity. The DHT22 is one of the most widely available and affordable sensors for measuring temperature and relative humidity, making it very popular in IoT projects and agricultural automation. Its declared accuracy is  $\pm 0.5^\circ\text{C}$  for temperature and  $\pm 2\%$  for relative humidity, with a measurement range from  $-40^\circ\text{C}$  to  $80^\circ\text{C}$  and from 0% to 100% RH. In controlled microgreens cultivation, where extreme fluctuations are rare, these specifications are adequate. The sensor's advantages include low cost, compact size, and ease of integration with Arduino systems, allowing widespread use even in projects with limited budgets. The next crucial parameter for microgreens cultivation is soil moisture, as microgreens are sown very densely, resulting in extremely high water uptake from the soil. A lack of moisture during critical developmental stages leads to stunted growth, reduced yields, or even total crop failure. Conversely, excessive water can cause fungal diseases and root rot. Therefore, soil moisture control is one of the key factors in microgreens production. The Capacitive Soil Moisture Sensor v1.2 was used in this study. These sensors measure moisture in the root zone, enabling timely intervention through manual or automatic irrigation. The capacitive sensor operates on the principle of changing the capacitance of a capacitor. On the sensor board, there are two conductive surfaces (electrodes) that form a capacitor. The capacitance of the capacitor is given by the formula:

$$C = e \frac{S}{d}, \quad \dots(1)$$

Where: C is the capacitance of the capacitor,

$\epsilon$  is the dielectric constant of the material between the electrodes,  
 $S$  is the area of the electrodes, and  
 $d$  is the distance between the electrodes.

The soil between the electrodes acts as a dielectric; dry soil has a low dielectric constant (from 3 to 5), while wet soil has a much higher value (approximately 80).

Therefore, an increase in soil moisture raises the dielectric constant of the soil, which in turn increases the capacitance of the sensor. The sensor model operates at a voltage of 3.3 V to 5 V, making it fully compatible with Arduino boards. Its simple integration and low cost make it an ideal choice for such projects. Most microgreens are grown indoors, so it is necessary to provide additional lighting, which is achieved by installing LED or fluorescent lamps. When choosing these lamps, you should consider three factors: intensity of illumination, spectrum of colours, and duration of illumination. The light intensity should provide enough energy for growth and photosynthesis, but must not be too high, as this can cause damage and burns to the leaves.

Strong intensity combined with high temperature slows plant growth and development. The light spectrum is a key factor in artificial plant lighting. Photosynthesis is most intense in the blue (430 nm to 450 nm) and red (640 nm to 660 nm) regions of the spectrum, while the green spectrum is partly reflected by plants and partly used in deeper tissue layers [18–22]. Research on microgreens production shows that a higher proportion of blue light promotes better growth and more intense leaf colour, while red light encourages faster development of plant mass. The duration of lighting is the third significant factor that can be directly controlled in artificial conditions and is one of the main advantages of indoor over outdoor production. Under natural conditions, the amount of daylight plants receive throughout the year varies from approximately 9 hours in winter to about 15 hours in summer. Seasonal changes affect the rate of plant growth and development, as well as overall yield. By using LED bars, it is possible to maintain optimal lighting duration regardless of external conditions, providing plants with, for example, a consistent 16 hours of light per day throughout the year. This approach enables constant and predictable development and shortens the vegetation period, allowing for more production cycles in a shorter time frame. In this study, two series-connected LED bars were used, each equipped with diodes emitting white light at 4000 K and additional red diodes covering wavelengths from 660 nm to 720 nm. Each LED bar is 60 cm long, has a power rating of 8 W, and a luminous flux of 700 lm to 900 lm. Although lamps with precisely adjusted spectra are available, this study used an LED bar with the specified characteristics, as even white light provides satisfactory conditions for microgreens growth without the need for more complex spectral control [23–25]. To enable connection and control of the LED bar via the Internet, switching is managed by a relay. The relay is activated by a signal from the Arduino UNO R4 WiFi board and is used to control the LED bar's power. To display and monitor the measured results from the sensor, one option is to use a computer monitor.

However, using an entire computer solely to monitor microgreens parameters is neither economical nor cost-effective. To address this, the Arduino UNO R4 WiFi board was used, featuring an integrated ESP32-S3 module that provides Wi-Fi and Bluetooth connectivity.

This enables the smart IoT system to connect to the Internet, with data managed via Arduino Cloud. Creating a dashboard in Arduino Cloud allows data to be sent to a mobile phone. Installing the Arduino IoT Remote App on the mobile phone and logging in with the same credentials as Arduino Cloud enables data monitoring on the mobile phone. This makes the system straightforward to manage, with data stored on Arduino Cloud.

## RESULTS AND DISCUSSION

The seeds used to grow microgreens are the same as those intended to produce mature plants; however, instead of allowing the plant to reach full maturity, it is harvested when nutrient levels are at their peak. This is why microgreens have a lower weight but a significantly higher nutritional value per unit volume. Research indicates that some types of microgreens contain up to 40 times more vitamins C, E, and K than conventionally grown plants [26]. In addition to their nutritional value, microgreens are used for decorative purposes in prestigious restaurants, to garnish dishes, or for their intense colour and texture. Radish microgreen seeds were used in this study. The benefits of radish are evident, as it is one of the fastest-growing types of microgreens, with germination occurring in 1 to 3 days and harvesting usually taking place after 5 to 7 days.

This allows rapid production and multiple breeding cycles per month, making it particularly convenient for experimental use. Additionally, radish microgreens contain high levels of vitamin C, vitamin E, vitamin K, beta-carotene, and antioxidants. Microgreen production is generally divided into three phases: the germination phase, the yellow phase, and the photosynthesis (green) phase. In each phase, it is necessary to maintain optimal soil moisture, temperature, air humidity, and provide additional lighting to ensure even and proper plant growth. The germination phase lasts for the first 1 to 3 days, during which the seeds must be sown thickly and evenly. After sowing, the soil should be watered abundantly and covered with a black cover to ensure the complete darkness required for proper seed germination. The yellow phase begins after removing the cover from the pot; at this point, the stems and leaves of the microgreens are yellow because they have not been exposed to light. During this stage, the plants must be gradually acclimatised to light, which was achieved by turning the LED bar on for 6 hours and leaving it off for the remainder of the time. The green phase occurs after 2 to 3 days of light exposure, when the plants receive sufficient light and begin to produce chlorophyll, which gives them their green colour. In this phase, it is necessary to provide the plants with adequate light to support continued growth and development. The LED bar during this phase was kept on for 14 to 16 hours.

After 7 to 10 days, radish microgreens reach their optimal size and nutritional value, so they should be harvested at this stage. After harvesting, radish sprouts can be stored in the refrigerator for several days. Proper monitoring of parameters at each stage of development is crucial for optimal growth and cultivation of microgreens. A capacitive soil moisture sensor enables precise monitoring of soil moisture, while the DHT22 sensor provides data on temperature and air humidity, allowing timely adjustment of conditions. The LED bar was controlled via a relay to ensure the radish microgreens received the optimal amount of light.

To create a smart IoT system for monitoring radish microgreens, the components were connected into a single system and then connected to the Internet to enable monitoring via a mobile phone. A breadboard was used to facilitate the connection of components, allowing for pin expansion and quick changes to connections. Power is supplied from two sources: via power jacks for the Arduino UNO R4 WiFi board and directly from the mains for the LED bar. The 5V pin from the Arduino UNO R4 WiFi is connected to the vertical voltage rail of the breadboard, to which the 5V capacitive soil moisture sensor, the 5V DHT22 temperature and air humidity sensor, and the relay are also connected.

The LED bar is powered directly from the mains, but its switching is controlled by the Arduino UNO R4 WiFi board. As with connecting the 5V pin, the GND pin is connected from the Arduino board to the vertical rail of the breadboard. The GND pins from the capacitive soil moisture sensor, the DHT22 temperature and humidity sensor, and the relay are then connected to this rail. The relay is connected on one side to the Arduino UNO R4 WiFi board, and on the other side, it interrupts the phase to connect directly to the mains voltage circuit, enabling control of switching the LED bar on and off.

Table 1. The connections between smart IoT system components.

| Components                            | Pins on the components | Pins on the Arduino UNO R4 WiFi |
|---------------------------------------|------------------------|---------------------------------|
| Relay                                 | +                      | 5V                              |
|                                       | -                      | GND                             |
|                                       | S                      | D7                              |
| DHT22                                 | +                      | 5V                              |
|                                       | -                      | GND                             |
|                                       | out                    | D2                              |
| Capacitive Soil Moisture Sensore v1.2 | GND                    | GND                             |
|                                       | VCC                    | 5V                              |
|                                       | AOUT                   | A0                              |

The connection of other components to the Arduino UNO R4 WiFi board is shown in Table 2. After connecting the system, to enable monitoring via mobile phone, it is necessary to create an account on Arduino Cloud. On Arduino Cloud, virtual components are created in Things, with variables linked to the parameters to be measured, and the Arduino UNO R4 WiFi board is connected to an available internet network. The sketch is also programmed in Things, which in this case is complex and contains approximately one hundred lines.

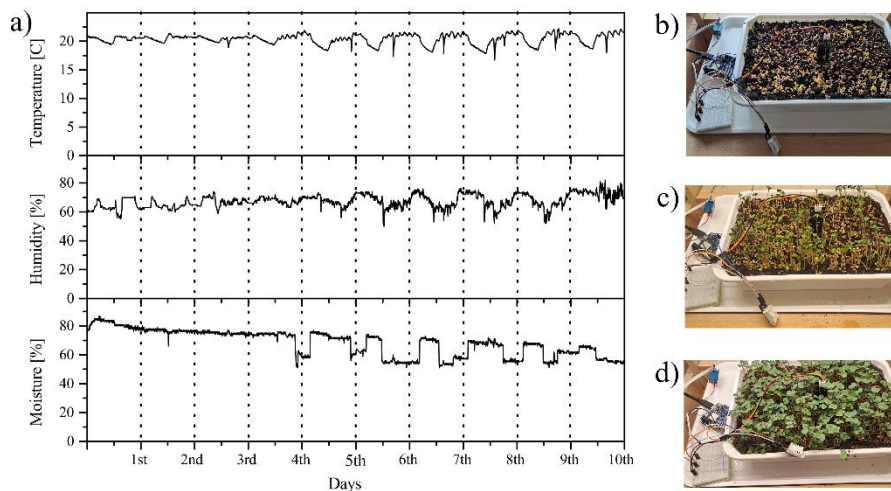


Figure 2. Parameters measured during the growth of radishes over ten days until harvest are shown in panel a). Panels; b), c), and d) show characteristic stages of radish growth captured on the 4th, 6th, and 10th days, respectively.

After verifying the sketch, it is uploaded to the Arduino UNO R4 WiFi board, which then manages the components and measures the parameters. An interface is created on the Dashboard to display all measurements and commands, allowing results to be monitored via mobile phone. To do this, the Arduino IoT Remote app must be installed on the phone. By accessing this application with Arduino Cloud credentials, users can monitor the parameters and commands created on Arduino Cloud. As long as the phone has internet access, parameter monitoring is possible from anywhere in the world, since the Arduino UNO R4 WiFi board is connected to the internet. Figure 2 shows the measured parameters during ten days of radish microgreens growth, as well as pictures captured on the 4th, 6th, and 10th days.

## CONCLUSIONS

In this study, the smart IoT system based on the Arduino UNO R4 WiFi board, which enables monitoring of microgreens growth using inexpensive and widely available sensors, was described. The aim set at the start of the project has been achieved, resulting in a fully autonomous system for monitoring local microgreens production. A key advantage of this smart IoT system is that results can be monitored on a mobile phone, requiring only internet access, which is widely available today. Radish microgreens seeds were used for experimental purposes in this work, but the smart IoT system can also be used to monitor parameters of other microgreens species. Temperature, air humidity, and soil humidity were measured. Additional lighting is controlled as needed via relays. The system can also be easily adapted for other applications in urban agriculture. It should be noted that this smart IoT system can be updated and further developed to measure and control additional parameters, such as smart irrigation or light intensity measurement.

The system enables parameter measurement without human intervention, further supporting the cultivation of microgreens as a healthier alternative food source. This type of food production has not yet achieved widespread adoption among small producers, as it requires extensive monitoring and very narrow tolerance values. However, with this type of system, a scalable solution is provided, making the entire process more accessible.

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## PRIMENA ARDUINO PLOČA U AUTOMATIZACIJI PROCESA PROIZVODNJE RASADA CRVENE ROTKVICE (*Raphanus sativus* var. *sativus*)

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**Sažetak:** Ova studija predstavlja razvoj pametnog IoT sistema za praćenje rasta rasada crvene rotkvice (*Raphanus sativus* var. *sativus*). Rotkvica je brzorastuće mikrobilje, što je čini idealnim za eksperimentalna istraživanja. I druga mikrobilja se mogu koristiti u ovim eksperimentima.

Pametni IoT sistem za praćenje rasta mikrobilja zasnovan je na Arduino osnovnoj ploči UNO R4 WiFi, koja služi kao centralni kontroler.

Dodatne komponente su: senzori za vlažnost i temperaturu vazduha: DHT22, SHT31, BME280, za vlažnost zemljišta je kapacitivni senzor Soil Moisture Sensor v2.0, relej, LED traka, sve povezano sa pomenutom Arduino pločom. Zajedno, ove komponente čine pametni IoT sistem za praćenje parametara rasta mikrobilja crvene rotkvice, merenje vlažnosti zemljišta, vlažnosti i temperature vazduha i kontrolu LED trake.

Na ovaj način je razvijen pametan IoT sistem sposoban za autonoman rad i prenos svih podataka na mobilne telefone putem interneta.

***Ključne reči:*** *Urbana poljoprivreda, rasad, IoT, Arduino UNO R4 WiFi, temperatura vazduha, vlažnost vazduha, vlažnost zemljišta*

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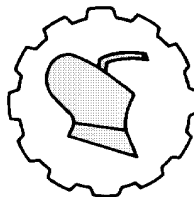
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## **REVIEW SMART MANAGEMENT SPRAY TECHNOLOGY APPLICATIONS IN ORCHARD TREE**

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**Abstract:** Paper summarizes advances in smart spraying technologies for orchard crop management and their role in improving efficiency, sustainability, and resource use in modern agriculture. Rapid progress in precision spraying systems, electrostatic sprayers, unmanned aerial vehicle (UAV) applications, and automated sprayers has improved pesticide application methods. These technologies rely on advanced sensing and computational tools to increase spray accuracy and optimize input use. Sensing technologies supporting precision spraying include camera-based vision systems, ultrasonic sensors, and laser scanning devices used for canopy detection and characterization. When integrated with variable-rate technology, spray applications can be adjusted according to canopy characteristics such as height, width, density, and volume. This targeted approach reduces pesticide and water consumption while maintaining effective pest control. Precision spraying systems can reduce spray volumes by 34-88% and decrease spray drift by up to 85% compared with conventional sprayers. Autonomous platforms, including robotic sprayers, improve operational safety and reduce labor requirements. Variable-rate systems integrated with pulse-width modulation technology provide rapid response and stable droplet formation under variable canopy conditions. These developments support sustainable pest management by reducing plant protection products by 15-44%. Future research should integrate machine learning and deep learning techniques to improve sensor accuracy and pest detection in orchards.

**Keywords:** *Spray technology, orchard tree management and sensing technologies*

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## INTRODUCTION

Agriculture is rapidly evolving due to technological innovations that help maintain productivity under increasing environmental pressures and climate variability. Among the major challenges is the extensive use of pesticides, which has raised serious concerns about environmental contamination and human health. Societal awareness of these risks has grown in recent years, prompting the European Union to set ambitious targets within the Farm to Fork Strategy of the European Green Deal. The strategy aims to reduce both the use and risk of chemical pesticides, including highly hazardous compounds, by 50% by 2030 (European Commission, 2020). Achieving these objectives requires technological innovation, enhanced operator training, and broader adoption of precision agriculture practices. Horticultural systems, particularly orchards, present unique challenges for pesticide application due to the structural complexity and variability of tree canopies. Traditional air-assisted sprayers, widely used in orchards and nurseries, typically apply a constant volume of spray per hectare, irrespective of canopy size, density, or volume (Hong et al., 2018). Such uniform applications often result in inefficient deposition and significant off-target losses. For instance, studies have shown that conventional axial-fan sprayers deposit only about 43% of the applied pesticide onto the target foliage (Duga et al., 2015). Spray drift and ground deposition can extend well beyond the intended treatment zone, with measurable off-target contamination observed up to 30 m from treated rows and airborne particles several meters above ground level (Grella et al., 2017). In some cases, pesticide residues were detected more than 50 m from the application site (Kasner et al., 2018), exceeding the recommended 30 m exclusion zone defined by the Worker Protection Standard (Fishel and Sanchez, 2016). Such inefficiencies not only reduce application effectiveness but also pose significant environmental and human health risks. Pesticide residues have been reported in soil, air, surface water, groundwater, and drinking water (Kim et al., 2017), while long-term exposure has been linked to respiratory disorders, metabolic diseases, and various cancers (Kim et al., 2017). Excessive pesticide use also affects ecosystems by reducing biodiversity, promoting pest resistance, and diminishing populations of beneficial organisms, including pollinators and natural enemies (Koleva et al., 2011). Recent advances in precision spraying technologies offer solutions to these challenges by integrating sensing systems, automated control, and data-driven decision-making. Sensor-based systems including machine vision cameras, ultrasonic sensors, and LiDAR allow detailed characterization of canopy structure and facilitate variable-rate spraying (VRT), adjusting pesticide application according to canopy volume, height, and density. These approaches can reduce pesticide use by 34-88% while improving deposition efficiency and minimizing drift. Further improvements in spray control, such as pulse-width modulation (PWM), allow rapid adjustment of nozzle flow rates without compromising droplet size, enhancing responsiveness to variable canopy structures.

Autonomous and robotic sprayers offer safer and more efficient operations. Integrating machine learning and deep learning algorithms with these systems can optimize canopy detection, pest monitoring, and real-time spray decisions, supporting intelligent and adaptive spraying operations.

In summary, the transition from conventional to sensor-based precision spraying represents a crucial step toward sustainable orchard management.

Continued development of canopy sensing, automated control, and data-driven algorithms is essential to maximize the efficiency, environmental sustainability, and safety of pesticide applications in modern horticultural production.

### **Spraying Technologies in Orchards Precision Spraying**

Precision spraying has significantly advanced orchard crop protection by overcoming the inefficiencies of conventional constant-rate systems. By integrating real-time sensors, GPS mapping, and automated flow control, precision sprayers optimize the timing, location, and volume of agrochemical application. This approach is particularly effective in orchards with heterogeneous or dense canopies, where traditional air-assisted sprayers often result in uneven coverage and substantial off-target deposition (Escolà et al., 2013; Gil et al., 2013). The operation of precision sprayers relies on real-time canopy characterization. Ultrasonic sensors, LiDAR, cameras, and laser rangefinders measure canopy height, width, density, and volume, providing input for variable-rate application (VRA) systems. Pulse-width modulation (PWM) valves allow dynamic adjustment of nozzle flow without compromising droplet uniformity, ensuring efficient and accurate deposition. Field evaluations demonstrate that precision spraying can reduce chemical input by 34-88% while maintaining or enhancing deposition efficiency. High-resolution canopy data enable the generation of Tree Row Volume (TRV) or Leaf Wall Area (LWA) based prescriptions, aligning spray volumes with actual vegetation and supporting regulatory goals such as the EU Green Deal's 50% pesticide reduction target by 2030 (European Commission, 2020). Precision sprayers allow site-specific, variable-rate applications that enhance coverage efficiency, minimize chemical use, and reduce environmental impact. Autonomous platforms, combined with machine learning algorithms, further enhance operational precision and reduce labor demands.

### **Electrostatic Sprayers**

Electrostatic spraying improves deposition by imparting an electric charge to droplets, promoting adhesion to leaf and branch surfaces. This method reduces drift and ensures more uniform coverage, particularly in dense canopies. In agricultural studies, electrostatic fungicides have provided effective control while using significantly lower chemical volumes compared to conventional systems (Law & Cooper, 2001). Electrostatic systems have also been applied in food safety, effectively reducing microbial contamination on food surfaces. Electrochemically activated chlorine solutions and sodium hypochlorite sprays have been shown to decrease *Salmonella* and *Campylobacter* populations by 1-4 log<sub>10</sub> CFU per unit, demonstrating broad applicability for antimicrobial delivery (Yang et al.). Despite these advantages, few studies systematically explore the factors affecting electrostatic spray efficiency.

Variables including spray charge, nozzle orifice, air pressure, spray duration, and distance from the target can influence deposition. Tools such as response surface methodology (RSM) can optimize these parameters, supporting the development of standardized application protocols tailored for both agriculture and food industry applications.

Table 1. Selected precision spraying technologies, sensors, dose control strategies, and key outcomes.

| Reference                                     | Crop                | Technology                      | Control Strategy                          | Result                                                   |
|-----------------------------------------------|---------------------|---------------------------------|-------------------------------------------|----------------------------------------------------------|
| Anglund & Ayers (2003)                        | Orchards            | Pressure-based                  | Variable-rate via pressure                | Reduced pesticide/water use; droplet uniformity affected |
| Campos et al. (2019); Manandhar et al. (2020) | Orchards            | Sensor-based precision sprayers | Variable-rate application                 | 34-88% spray reduction; equal or improved deposition     |
| Wei et al. (2022)                             | Tree crops          | On-board canopy sensors         | Structure-based VRA                       | Reduced off-target losses; improved leaf deposition      |
| Llorens et al. (2011)                         | Tree crops          | LiDAR                           | 3D canopy mapping                         | High-precision canopy characterization                   |
| Chen et al. (2012, 2013a, 2013b)              | Apple orchards      | Laser-guided sprayer            | Real-time geometry-based                  | 80–93% reduction in ground/airborne losses               |
| Rayamajhi et al. (2024)                       | Ornamental trees    | Stereo vision + deep learning   | Canopy volume & trunk diameter estimation | MAE < 12%; precise variable-rate application             |
| Xun et al. (2023)                             | Apple orchard       | TRV-based precision sprayer     | Real-time canopy-volume adjustment        | 43% spray reduction; 23–85% drift reduction              |
| GUSS-Automation                               | Orchards            | Autonomous air-blast sprayer    | Automated precision spraying              | Increased efficiency, safety, and labor reduction        |
| European Commission (2020)                    | Orchards, vineyards |                                 | TRV & LWA models                          | Supports pesticide reduction targets (50% by 2030)       |

### UAVs, Remote Sensing, and Smart Flow Control

UAVs equipped with precision nozzles and imaging sensors are increasingly adopted for orchard spraying. They provide access to difficult-to-reach canopy regions, improve spray uniformity, reduce labor, and minimize soil compaction. Modern UAVs integrate multispectral, optical, and hyperspectral cameras, enabling high-resolution canopy characterization and the generation of prescription maps for variable-rate application. NDVI and other vegetation indices derived from UAV imagery inform Decision Support Systems (DSS) such as DOSAVIÑA®, which translate canopy data into zone-specific spray volumes.

Field studies in vineyards and orchards report chemical savings of 15-44% with UAV-assisted VRA, while maintaining or improving leaf coverage uniformity (Campos et al., 2019, 2020; García-Ruiz et al., 2023).

Satellite-based remote sensing offers a scalable alternative for canopy mapping and VRA prescription, with high-resolution imagery providing reliable field-level assessment when combined with ground-truth data (Campos et al., 2021; PIVOS Project). Flow rate regulation is critical for accurate VRA. Pressure-based systems adjust nozzle output according to canopy size, whereas PWM valves provide rapid response, stable droplet size, and precise flow control. PWM-controlled sprayers have demonstrated faster responsiveness and higher uniformity compared to traditional pressure-based systems, supporting effective site-specific applications (Salcedo et al., 2022a, b; Campos et al., 2023). The integration of UAVs, remote sensing, and smart flow control facilitates precise, environmentally sustainable, and resource-efficient orchard spraying, aligning with regulatory targets for pesticide reduction while optimizing biological efficacy.

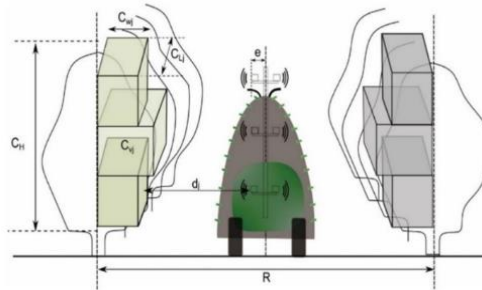


Figure 1. Working principle of the developed precision spraying system integrated on the Fede tower sprayer. ( $C_H$  is the total canopy height;  $C_{wj}$  is the canopy width for section  $j$ ;  $C_{Lj}$  is the slice canopy length at section  $j$ ;  $C_{vj}$  is the canopy volume to be treated per unit time at section  $j$ ;  $d_j$  is the distance measured between the ultrasonic sensor and the outer surface of the vegetation;  $e$  is the distance between the sensor and the central axis of the sprayer; and  $R$  is the row space).

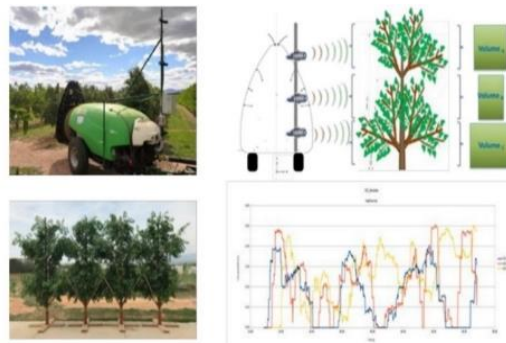


Figure 2. Orchard sprayer developed for VRA in apple trees plantation. The sprayer has been developed by UMA research group (UPC) within the activities carried out for the OPTIMA European Project



Figure 3. Left: image of DOSAVINA DSS, free available APP (Android and ISO) to determine the optimal application rate for vineyard plantations; right: cycle of VRA based on canopy imagery generated with UAV. The system has been proven to reduce PPP from 15 to 40% depending on the conditions.



Figure 4. VRA cycle developed within PIVOS project, UAV and satellites have been used to generate accurate correlation to estimate canopy parameters. Furthermore, based on values these values, VRA technologies have been already implemented in field conditions, IN all case it has been demonstrated a promising technology with good results in terms of PPP reduction.

### Intelligent spray systems

AI-driven intelligent spray systems integrate real-time data analysis, sensors, and machine learning to optimize spray applications. In table 3 provided on AI-driven, robotic, and intelligent variable-rate spraying systems, with emphasis on sensor fusion, machine learning, control strategies, and performance outcomes.



Figure 5. VRA sprayer developed within PIVOS project. The system is equipped with PWM nozzles to follow the prescription map previously developed after satellite imagery.

The integration of artificial intelligence (AI), advanced sensing, and robotic platforms is redefining precision spraying in specialty crops. Modern intelligent sprayers employ real-time data acquisition, multi-sensor arrays (ultrasonic, LIDAR, RGB cameras, and more), and machine learning algorithms to detect canopy characteristics, including size, shape, and density, as well as pest or disease presence. These inputs allow dynamic adjustment of spray volume and droplet delivery, ensuring targeted applications, reduced chemical use, and minimized environmental impact. Ultrasonic and RGB cameras provide rapid canopy dimension assessment, while LIDAR-based systems guide nozzle positions in real time, significantly reducing ground deposition (up to 93%) and airborne drift (up to 80%). Variable air-assisted sprayers modulate airflow based on canopy density, optimizing spray deposition and improving penetration into dense foliage. Advanced PWM (Pulse Width Modulation) solenoid valves control nozzle output, maintaining uniform droplet size and rapid response to canopy changes. These mechanisms reduce pressure fluctuations and ensure consistent droplet formation across variable canopy structures. Robotic and semi-autonomous platforms extend the capability of intelligent spraying systems, particularly in complex terrains such as steep vineyards. Systems integrating human-robot collaboration leverage operator input alongside AI-driven sensing for selective spraying, achieving up to 50% reduction in chemical use while enhancing safety and precision. Image processing and vegetation indices (e.g., NDVI) facilitate site-specific detection of crop health, weed presence, and canopy volume, improving spray flow decisions and reducing over-application. Premixing in-line injection systems have been introduced to maintain constant chemical concentration under rapidly changing flow conditions, addressing limitations of conventional direct-injection sprayers. These systems ensure accurate delivery of agrochemicals even in dynamic operational environments, supporting continuous variable-rate applications. Laser- and LIDAR-guided sprayers coupled with PWM valves are among the most mature intelligent spraying technologies, capable of reducing pesticide losses by up to 90% while maintaining uniform deposition. Human-robot collaborative systems and autonomous platforms also significantly lower labor requirements and increase precision in irregular terrains. Future trends in AI-driven orchard spraying focus on multi-sensor fusion, advanced machine learning models for real-time pest and disease severity assessment, and integrated control of spray rate, droplet size, airflow, and chemical concentration under dynamic meteorological conditions. These innovations aim to enhance precision, sustainability, and operational efficiency in modern horticulture.

Table 2. Selected AI-driven, robotic, and sensor-fusion spray systems for specialty crops

| Reference                  | Crops                   | Sensors & AI             | Spray Control               | Results                                                    |
|----------------------------|-------------------------|--------------------------|-----------------------------|------------------------------------------------------------|
| Hołownicki et al. (2017)   | Orchards                | Canopy sensing           | Variable air assistance     | Improved penetration, reduced drift                        |
| Chen et al. (2013a, b)     | Apple trees             | Laser scanning           | PWM-based VRA               | 90–93% ground loss reduction; 57–80% drift reduction       |
| Oberti et al. (2013, 2016) | Specialty crops         | Vision + AI              | Selective spraying          | 65–85% pesticide reduction; 85–100% diseased area coverage |
| Cantelli et al. (2019)     | Vineyards & greenhouses | Sensors + kinematics     | Optimized distribution      | Improved efficiency of agrochemical application            |
| Baltazar et al. (2021)     | Steep vineyards         | SVM + vision             | Leaf-density-based spraying | High accuracy; feasible for small robots                   |
| Wei et al. (2023)          | Orchards                | Multi-sensor fusion + AI | PWM, pressure, variable air | PWM widely adopted; high future potential                  |
| Zhang et al. (2021)        | Orchards                | Laser + PWM              | Variable concentration      | MAPE = 6.96%; CV = 3.35%                                   |
| Shen & Zhu (2015)          | Orchards                | Laser + ultrasound       | PWM + premixing injection   | Maintained chemical concentration under variable flow      |



Figure 6. Sprayer assembled on the robot



Figure 7. Intelligent sprayer prototype

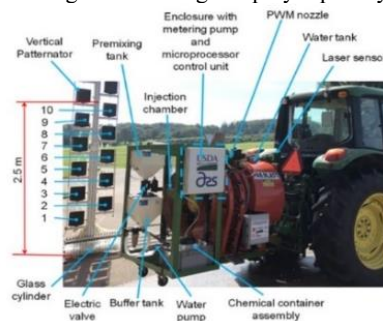


Figure 8. Premixing on-line injection system retrofitted on a laser-guided variable-rate orchard sprayer.



Figure 9. The LIDAR measurement system, (a) data in Cartesian coordinates, (b) data in polar coordinates (c) pear orchard, (d) different views of the 3D structure.

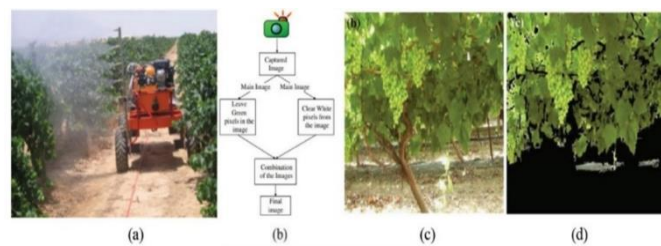


Figure 10. (a) vineyard spraying robot, (b) block diagram of the algorithm, (c) captured image, (d) final foliage image (Berenstein et al. 2010)

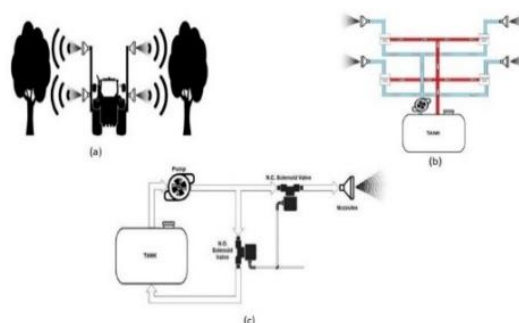


Figure 11. The developed system consists of four ultrasonic sensors, four 3-ways solenoid valves, and a motherboard



Figure 12. Attachment of components of the premixing in-line injection system to the laser-guided variable-rate orchard sprayer.

### Smart Nozzle, Variable Air, Sensor Fusion, and Future Prospects in Orchard Spraying

Modern orchard spraying technologies integrate smart nozzles, variable air supply, sensor-based control, and AI-driven systems to maximize precision and minimize chemical use. Smart nozzles adjust droplet size, spray angle, flow, and pressure in real time, significantly reducing off-target losses. Cost-effective ultrasonic and infrared sensors detect canopy width, density, and presence, while LIDAR and machine-vision systems provide high-resolution 3D canopy reconstruction for precise flow control. PWM-controlled nozzles dominate current systems due to rapid response, stable droplet spectra, and compatibility with map- or sensor-guided variable-rate applications (VRA). Depth and stereo cameras offer low-cost alternatives for canopy and tree attribute estimation, supporting real-time adjustments through in-line injection systems to maintain consistent pesticide concentrations and avoid leftover tank mixtures. Variable air supply is critical for air-assisted sprayers. Matching airflow speed, direction, and volume to canopy structure, pest or disease severity, and meteorological conditions improves droplet penetration and uniform deposition. Traditional systems often operate with constant air rates, limiting performance and increasing drift risk. Current control methods include fan speed regulation, air inlet/outlet adjustments, and nozzle-to-canopy distance modulation. Integration of turbidity sensors in premixing in-line injection systems enables precise monitoring of spray mixture concentration.

Tests demonstrated relative errors under 4.7%, ensuring uniform application across variable flow rates. Multi-point sensor deployment along the system further enhances reliability and reduces chemical waste. AI, robotics, and multi-sensor fusion are advancing precision spraying in orchards. LIDAR, ultrasonic, and RGB-D sensors, combined with machine learning, allow real-time detection of canopy volume, tree density, pest distribution, and non-target areas. Autonomous and semi-autonomous platforms, including UAVs, enhance operational efficiency, enabling selective spraying and reducing labor and chemical input by up to 50-85%. Convolutional Neural Networks (CNNs) and deep learning algorithms improve canopy detection, fruit localization, and disease recognition. Environmental sensing with spectral imaging (multi- and hyperspectral) captures vegetation reflectance across visible and near-infrared wavelengths, supporting pest detection, tree health assessment, and site-specific pesticide application. RGB-D cameras, using structured light or time-of-flight principles, provide stable depth data in low-light or shaded conditions, enabling accurate canopy, leaf, and fruit measurements. Sensor fusion strategies, combining LIDAR, RGB-D, and spectral data, enhance real-time VRA decision-making. Recent AI algorithms improve prediction accuracy, optimize spray paths, and facilitate precision applications under variable field conditions. These integrated approaches align with sustainable agriculture goals, reducing pesticide use, minimizing drift, and enhancing environmental and economic efficiency in orchard management.

Table 3. Selected smart nozzle and sensor-based control systems for orchard and vineyard spraying

| Reference           | Crops       | Sensors & AI        | Spray Control               | Results                                               |
|---------------------|-------------|---------------------|-----------------------------|-------------------------------------------------------|
| He et al., 2011     | Orchards    | Infrared            | Electrostatic targeting     | 50-75% pesticide reduction; improved utilization      |
| Planas et al., 2011 | Groves      | Ultrasonic          | Canopy measurement          | Interference at spacing <60 cm                        |
| Gil et al., 2013    | Vineyards   | Ultrasonic          | TRV-based VRA               | 21.9% pesticide savings                               |
| Rosell et al., 2009 | Agriculture | 2D LIDAR            | 3D canopy reconstruction    | High correlation with manual volume ( $R^2 = 0.976$ ) |
| Shen et al., 2017   | Orchards    | Laser + PWM         | Sensor-guided VRA           | 21.9–87.9% pesticide reduction                        |
| Escolà et al., 2013 | Orchards    | LIDAR               | Canopy-volume VRA           | $R^2 = 0.935$ (intended vs applied flow)              |
| Xiao et al., 2017   | Orchards    | Depth camera        | Depth + color-based control | Accurate leaf wall distance estimation                |
| Zhang et al., 2020  | Orchards    | Premixing injection | Automatic dosing            | Reduced waste; accurate concentration                 |

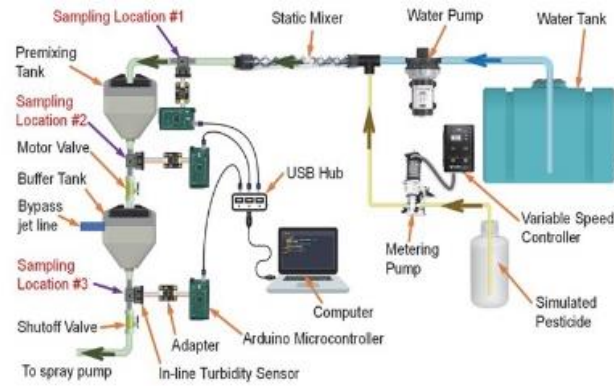


Figure 13. Schematic diagram of the in-line turbidity sensors for measuring spray mixture concentrations at three different locations in the premixing in-line injection system.

Precision-Spraying Technologies: (a) LiDAR-guided variable-rate sprayer (Fessler et al., 2020); (b) Machine vision sprayer (Samseemoung et al., 2017); (c) Prescription map variable-rate sprayer (Rovira-Más et al., 2024); (d) Multi-sen (c) Prescription map variable-rate sprayer (Rovira-Más et al., 2024); (d) Multi-sensor fusion sprayer (Liu et al., 2024).

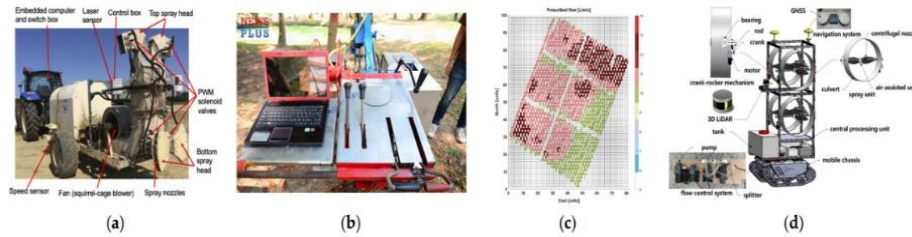


Figure 15. Various Orchard-Spraying Machines: (a) Mounted sprayer (Salas et al., 2023); (b) Self-propelled spray (Qiu et al., 2020); (c) Electrostatic sprayer/Pneumatic atomization sprayer (Dai et al., 2023).

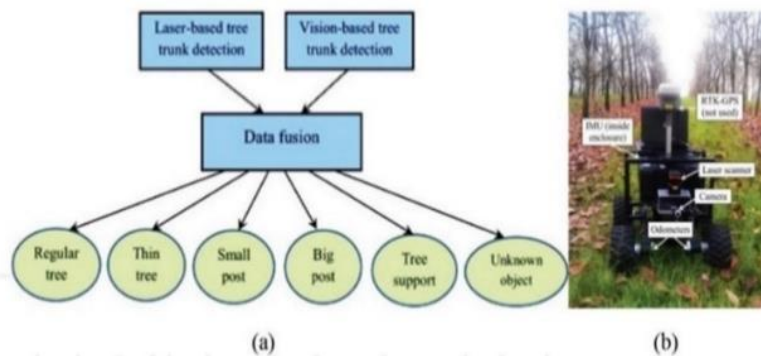


Figure 16. (a) The block diagram of the two-tree trunk detection algorithms, (b) explorer platform with orchard sensors.



Figure 17. Environmental sensing sensors: Visual, LiDAR, Multispectral



Figure 18. RGB-D visual sensor.

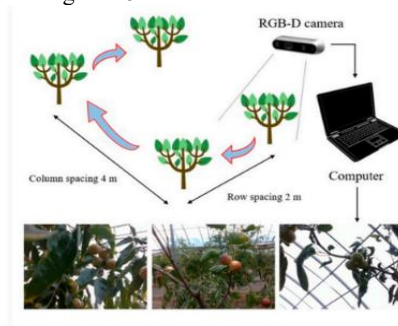


Figure 19. Winter Jujube RGB and Depth image acquisition system

### Multispectral and Hyperspectral Imaging for Precision Orchard Management

Multispectral and hyperspectral imaging technologies provide high-resolution insights into crop health, canopy structure, and disease status, enabling precision spraying and targeted management. Multispectral sensors decompose incoming light into discrete spectral channels, capturing information in red, green, and near-infrared bands. These channels allow rapid assessment of leaf moisture, chlorophyll content, and visible disease symptoms, supporting early detection and intervention (Figure 20).

UAV-mounted systems, such as the Parrot Sequoia on a 3DR Solo, can acquire canopy metrics including height, width, and plant projection coverage at multiple altitudes, facilitating accurate structural analysis of orchards. LiDAR sensors, such as the VLP-16, provide 3D point clouds of tree canopies. By removing trunks, supports, and ground interference through point cloud processing, canopy density and volume can be quantified, enabling partitioned data for multi-nozzle variable-rate control and highly accurate targeted spraying (Figure 22). Combining multispectral imaging with 3D reconstruction and machine learning, including LDA and Backpropagation Neural Networks, allows precise detection of diseased trees and early-stage infections. For example, integration of NDVI, NIR, and structural features has achieved up to 100% accuracy in tree-level disease identification, supporting density-based zonal pesticide application (Figure 23).

Data-driven orchard management is increasingly platform-based, integrating heterogeneous sensors, UAVs, ground-based sprayers, and AI algorithms. Real-time sensor fusion enables dynamic adjustment of spray volume, flow rate, and path according to canopy density, pest presence, and disease severity. Commercial systems, including GUSS, Smartomizer H3O, and Smart Spray, illustrate the feasibility of combining automated sensing, intelligent control, and precision decision-making. UAVs offer flexibility in hard-to-access areas, although payload capacity and flight stability remain technical challenges for large-scale orchards. The future of precision spraying relies on fully integrated sensor and AI systems capable of real-time data acquisition, canopy mapping, pest and disease assessment, and environmental monitoring. Advances in multi-source fusion, high-resolution spectral imaging, and machine learning will enhance predictive accuracy, optimize chemical use, and reduce environmental impacts. Platform-based systems, leveraging cloud computing, edge processing, and standardized interfaces, promise scalable, autonomous orchard operations, enabling sustainable, efficient, and cost-effective crop protection. The relevant sensors are shown in Figure 20.



Figure 20. Multispectral camera



Figure 21. Multispectral data acquisition system for pest and disease detection:  
(a) Lychee canopy multispectral data acquisition.

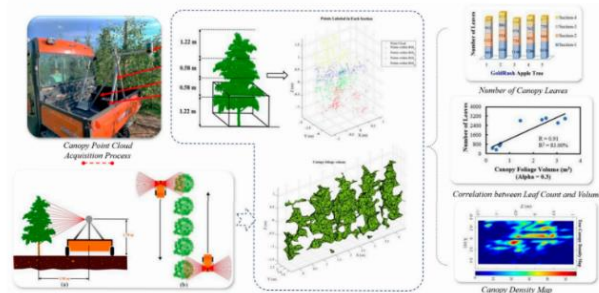


Figure 22. Three-dimensional canopy structure reconstruction based on VLP-16 LiDAR data.

Wang et al. (2025) emphasize that the future of orchard management lies in data-driven, platform-based systems that integrate heterogeneous sensors and equipment through standardized interfaces.

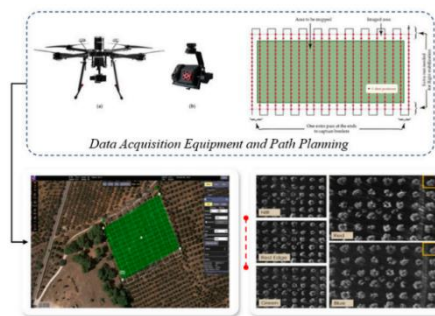


Figure 23. Application examples of pest and disease detection based on hyperspectral sensors:  
(a) Multispectral camera combined with 3D reconstruction and LDA algorithm achieves disease tree detection and localization (b) Hyperspectral imaging combined with multi-source fusion model enables early identification of anthracnose disease in pear leaves.

## CONCLUSIONS

This review underscores the importance of advanced spraying technologies in tree fruit orchards, highlighting current limitations, key performance determinants, and gaps that must be addressed to develop next-Generation precision sprayers. Conventional air-blast systems, though widely employed, are inefficient, with only approximately 43% of applied pesticides reaching target foliage; substantial losses occur due to off-target deposition and drift. These inefficiencies not only elevate chemical costs but also pose serious environmental and human health risks. In response, global policies, such as the European Green Deal's Farm to Fork Strategy, aim to cut pesticide use and associated hazards by 50% by 2030. Precision and smart spraying technologies have emerged as effective solutions. By integrating real-time canopy sensing via ultrasonic, infrared, LiDAR, laser, depth, and multispectral sensors with computer vision and artificial intelligence, these systems dynamically adjust spray volume and coverage according to canopy size, shape, and density. Field trials in apples, grapes, olives, pears, and vineyards demonstrate pesticide reductions of 50–75%, spray drift decreases of up to 87%, and ground loss mitigation of up to 93%, without compromising pest control efficacy. Variable Rate Technology (VRT), often combined with Pulse Width Modulation (PWM) nozzle control, allows precise nozzle-by-nozzle adjustments without altering droplet spectra or spray pressure, ensuring uniform deposition during acceleration, deceleration, and operation on slopes while minimizing overlaps and under-dosing. Additional innovations include GPS-guided autosteering, drone-based spraying, and in-line chemical injection systems equipped with real-time sensors to maintain consistent mixture concentrations and minimize operator exposure. Despite persistent challenges, such as high upfront costs, sensor performance under variable environmental conditions, and integration complexity, ongoing advances in low-cost sensing, sensor fusion, deep learning, and autonomous robotics are improving the feasibility and adoption of these technologies. Overall, smart spraying represents a pivotal strategy for sustainable orchard management, enabling precise pesticide delivery, reduced environmental footprint, improved crop protection, and alignment with contemporary sustainability objectives.

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## PREGLJED PRIMENE PAMETNIH TEHNOLOGIJA UPRAVLJANJA PRSKANJEM U VOĆNJACIMA

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**Apstrakt.** U radu su prikazani savremeni trendovi u razvoju pametnih tehnologija prskanja za upravljanje proizvodnjom u voćnjacima i njihov značaj za unapređenje efikasnosti, održivosti i racionalnog korišćenja resursa u savremenoj poljoprivredi. Brz napredak u oblasti sistema za precizno prskanje, elektrostatičkih prskalica, primene bespilotnih letelica (UAV) i automatizovanih prskalica doveo je do unapređenja načina primene sredstava za zaštitu bilja. Ove tehnologije zasnivaju se na naprednim senzorskim i računarskim sistemima, koji omogućavaju veću preciznost aplikacije i optimizaciju utroška inputa.

Senzorske tehnologije koje podržavaju precizno prskanje obuhvataju vizuelne sisteme zasnovane na kamerama, ultrazvučne senzore i uređaje za lasersko skeniranje, koji se koriste za detekciju i karakterizaciju krošnje. U kombinaciji sa tehnologijom promenljive norme aplikacije (VRT), primena sredstva za zaštitu bilja može se prilagoditi karakteristikama krošnje voćke, kao što su visina, širina, gustina i zapremina. Ovakav ciljani pristup smanjuje potrošnju pesticida i vode, uz istovremeno održavanje efikasne kontrole štetnih organizama.

Sistemi za precizno prskanje mogu smanjiti utrošak tečnosti za prskanje za 34–88%, kao i smanjiti zanošenje kapljica (drift) za do 85% u poređenju sa konvencionalnim prskalicama.

Autonomne platforme, uključujući robotske prskalice, povećavaju bezbednost rada i smanjuju potrebe za angažovanje radnika u procesu. Sistemi promenljive norme aplikacije, integrisani sa tehnologijom modulacije širine impulsa (PWM), omogućavaju brz odziv sistema i stabilno formiranje kapljica pri promenljivim uslovima u krošnji voća. Ova dostignuća doprinose održivom upravljanju zaštitom bilja smanjenjem primene sredstava za zaštitu bilja za 15–44%.

Buduća istraživanja treba da obuhvate integraciju metoda mašinskog učenja i dubokog učenja radi povećanja preciznosti senzora i unapređenja detekcije štetnih organizama u voćnjacima.

**Ključne reči:** *Tehnologija prskanja, upravljanje stablima u voćnjaku, senzorske tehnologije*

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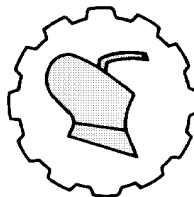
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## **A CRITICAL REVIEW OF PRINCIPAL COMPONENT ANALYSIS OF GROUNDWATER CONTAMINATION IN NIGERIA**

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**Abstract:** Groundwater remains the most reliable source of potable water in Nigeria, particularly in rural and peri-urban areas. However, increasing anthropogenic activities—ranging from oil exploration and industrial effluents to agricultural practices and improper waste disposal—have intensified contamination pressures on this vital resource. Principal Component Analysis (PCA) has emerged as a powerful multivariate statistical tool for identifying pollution sources, understanding contaminant pathways, and interpreting complex hydrogeochemical datasets. This review critically examines the application of PCA in groundwater contamination studies across Nigeria, synthesizing findings from peer-reviewed literature spanning the past two decades. The review evaluates methodological approaches, identifies common limitations, and assesses the effectiveness of PCA in source apportionment. Key findings reveal that while PCA has been widely applied in the Niger Delta region for petroleum hydrocarbon contamination studies, its application in other regions and for other contaminant classes (e.g., heavy metals, nitrates, pharmaceuticals) remains limited. Common methodological shortcomings include inadequate data preprocessing, insufficient sample sizes, lack of validation, and over-interpretation of components. This review proposes standardized protocols for PCA application in Nigerian groundwater studies. It identifies priority areas for future research, including the integration of PCA with geospatial techniques and machine learning approaches. The findings underscore the need for rigorous statistical practices to enhance the reliability of source identification and support evidence-based groundwater management policies in Nigeria.

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**Key words:** *Principal Component Analysis, Groundwater Contamination, Nigeria, Source Apportionment, Multivariate Statistics, Hydro geochemistry.*

## INTRODUCTION

Groundwater constitutes approximately 22% of the world's freshwater resources and serves as the primary source of drinking water for over 50% of the global population [1].

In Nigeria, groundwater dependence is even more pronounced, with an estimated 70–80% of the population relying on groundwater for domestic, agricultural, and industrial purposes [2,3].

The country's extensive sedimentary basins, including the Chad Basin, Sokoto Basin, and the Niger Delta Basin, host significant groundwater resources that are increasingly threatened by contamination.

Groundwater contamination in Nigeria stems from diverse sources, reflecting the country's complex environmental landscape. In the oil-rich Niger Delta, petroleum hydrocarbon pollution from crude oil spills, pipeline leakages, and artisanal refining has been extensively documented [4,5]. In urban centers such as Lagos, Kano, and Port Harcourt, industrial effluents, municipal solid waste leachates, and inadequate sanitation infrastructure contribute to elevated concentrations of heavy metals, nitrates, and emerging contaminants [6,7]. Agricultural regions face challenges from fertilizer and pesticide runoff, while mining activities in states like Plateau and Nasarawa introduce heavy metals into groundwater systems [8].

### The Role of Multivariate Statistics

Traditional approaches to groundwater quality assessment have relied heavily on univariate statistical methods and simple comparisons with regulatory standards. While these approaches provide basic information on contaminant levels, they fail to elucidate the complex relationships between multiple variables or identify the underlying sources of contamination. This limitation has driven the increasing adoption of multivariate statistical techniques, among which Principal Component Analysis (PCA) has emerged as the most widely applied.

PCA is a dimension-reduction technique that transforms a set of correlated variables into a smaller set of uncorrelated principal components that retain most of the information in the original dataset [9]. In groundwater contamination studies, PCA serves several critical functions: (1) reducing the dimensionality of hydrogeochemical datasets, (2) identifying latent factors that explain observed variability, (3) associating specific contaminants with likely pollution sources, and (4) facilitating the interpretation of complex geochemical processes.

### Rationale and Scope

Despite the proliferation of PCA applications in Nigerian groundwater studies, there has been no systematic evaluation of the methodology, its strengths, limitations, and the quality of its application. This gap is significant because the reliability of source apportionment directly influences remediation decisions, policy formulation, and resource allocation.

Misapplication or misinterpretation of PCA can lead to erroneous conclusions about contamination sources, potentially directing resources toward ineffective interventions.

This review aims to critically evaluate the application of PCA in groundwater contamination studies across Nigeria. The specific objectives are to:

1. Synthesize the existing literature on PCA applications in Nigerian groundwater quality studies
2. Evaluate methodological approaches, including data preprocessing, sampling design, and validation techniques
3. Identify common limitations and methodological shortcomings
4. Propose standardized protocols for PCA application in future studies
5. Identify knowledge gaps and priority areas for future research

## **METHODOLOGY OF THE REVIEW**

### **Literature Search Strategy**

This review employed a systematic approach to identify relevant studies published between 2000 and 2026. The following databases were searched: Google Scholar, Scopus, Web of Science, and the African Journals Online (AJOL) database. Search terms included combinations of: "Principal Component Analysis," "PCA," "groundwater contamination," "groundwater quality," "Nigeria," "Niger Delta," "source apportionment," and "multivariate statistics." The search was limited to peer-reviewed journal articles, though relevant conference proceedings and technical reports were considered for contextual information.

### **Inclusion and Exclusion Criteria**

Studies were included if they: (1) applied PCA to groundwater quality data from Nigerian locations, (2) reported sufficient methodological detail, (3) were published in English, and (4) focused on contamination assessment rather than purely hydrogeological characterization. Studies were excluded if they: (1) applied PCA only to surface water or soil data without groundwater components, (2) lacked clear methodological descriptions, or (3) were duplicates or preliminary reports superseded by full publications.

### **Data Extraction and Synthesis**

From each included study, information was extracted on: study location, sample size, number of parameters analyzed, data preprocessing methods (e.g., normalization, transformation), PCA extraction criteria (e.g., eigenvalue threshold, scree plot), rotation methods, variance explained, interpretation approach, and validation techniques. Findings were synthesized thematically, focusing on methodological patterns, common limitations, and reported outcomes.

## OVERVIEW OF PCA APPLICATIONS IN NIGERIAN GROUNDWATER STUDIES

### Geographic Distribution

The application of PCA in Nigerian groundwater contamination studies has been geographically uneven, with the Niger Delta region accounting for approximately 65% of published studies. This concentration reflects the region's status as the epicenter of oil exploration activities and associated environmental concerns. Studies in the Niger Delta have predominantly focused on petroleum hydrocarbon contamination, heavy metals, and the impacts of gas flaring [10,11].

In contrast, the southwestern region (including Lagos, Ogun, and Oyo states) accounts for approximately 20% of studies, primarily addressing urban groundwater contamination from industrial effluents, solid waste leachates, and domestic sewage [12,13].

The northern region has been relatively underrepresented, with most studies focusing on the Chad Basin and addressing salinity, fluoride, and nitrate contamination [14]. The southeastern region, aside from the oil-producing areas, has seen limited PCA applications despite significant groundwater quality challenges from mining and agricultural activities.

### Contaminant Classes Investigated

The contaminant classes addressed by PCA studies in Nigeria can be categorized as follows:

**Heavy Metals:** This category dominates the literature, with studies typically analyzing 8–15 metals including lead, cadmium, chromium, copper, zinc, iron, manganese, and nickel. PCA has been employed to distinguish between geogenic and anthropogenic sources of these metals [15,16].

**Petroleum Hydrocarbons:** Studies in the Niger Delta have utilized PCA to identify oil spill impacts, differentiate between fresh and weathered hydrocarbons, and assess the contribution of gas flaring to groundwater contamination [17,18].

**Physicochemical Parameters:** Many studies incorporate basic parameters such as pH, electrical conductivity, total dissolved solids, temperature, and dissolved oxygen alongside contaminants to elucidate hydro chemical processes [19].

**Nutrients and Inorganic Ions:** Nitrate, phosphate, sulfate, chloride, and bicarbonate are frequently included to identify contributions from agricultural runoff, sewage, and natural weathering processes [20].

**Emerging Contaminants:** Very few studies have applied PCA to emerging contaminants such as pharmaceuticals, personal care products, or microplastics, representing a significant knowledge gap.

### Sample Sizes and Study Designs

Reported sample sizes vary considerably, ranging from as few as 15 samples to over 200. The median sample size is approximately 45 samples. The adequacy of these sample sizes for PCA application is questionable, as the technique typically requires a minimum ratio of 5–10 observations per variable [21]. Many reviewed studies fall below this threshold, potentially compromising the stability and reliability of extracted components.

## CRITICAL EVALUATION OF METHODOLOGICAL APPROACHES

### Sampling Design

A fundamental requirement for valid PCA is that samples are representative of the population of interest. The reviewed studies exhibit considerable variability in sampling design quality. The most robust studies employ systematic grid sampling across study areas, ensuring spatial representativeness [22]. However, many studies rely on purposive sampling focused on suspected contamination hotspots, which may introduce bias and limit the generalizability of results.

The vertical dimension of groundwater contamination is often inadequately addressed. Most studies sample only shallow groundwater from hand-dug wells or boreholes with limited depth documentation.

Few studies have investigated depth-dependent variations in contamination sources, which is particularly critical in understanding vertical transport mechanisms and aquifer vulnerability.

### Data Preprocessing

**Normality Assessment:** PCA is not strictly distributional, but normality of variables influences the interpretability of results and the choice of extraction methods. Approximately 40% of reviewed studies report conducting normality tests (typically Kolmogorov-Smirnov or Shapiro-Wilk) before PCA application. Of these, many report non-normal distributions but proceed with standard PCA without appropriate transformations.

**Data Transformation:** The most commonly employed transformation is logarithmic transformation for positively skewed data, followed by standardization (z-scores) to eliminate the influence of different measurement units. However, approximately 30% of studies apply PCA directly to raw, untransformed, and unstandardized data, a practice that can lead to components dominated by variables with high variance or large measurement units (e.g., electrical conductivity compared to trace metals).

**Outlier Treatment:** The handling of outliers is inconsistently addressed. While some studies explicitly report outlier removal using methods such as box plots or Grubbs' test, many provide no information on outlier treatment, raising concerns about the influence of extreme values on component extraction.

### Factor Extraction Criteria

The reviewed studies employ various criteria for determining the number of components to retain:

**Eigenvalue > 1 (Kaiser Criterion):** This is the most commonly used criterion, applied in approximately 70% of studies. While widely accepted, the Kaiser criterion is known to sometimes retain too many components when many variables have low communalities or too few when sample sizes are small.

**Scree Plot:** Approximately 55% of studies report using scree plots, often in combination with the eigenvalue criterion. However, the subjective interpretation of the scree plot's "elbow" is rarely justified or supported by parallel analysis.

**Variance Explained:** Many studies retain components that cumulatively explain 70–80% of total variance, but this criterion is often applied without consideration of variable communalities or the interpretability of components.

**Parallel Analysis:** This more rigorous criterion, which compares observed eigenvalues to those from random data, is employed in fewer than 10% of reviewed studies. Its absence is notable given its superiority over the eigenvalue criterion [23].

### **Rotation Methods**

The choice of rotation method significantly influences component interpretability. Varimax rotation, which maximizes the variance of squared loadings and produces orthogonal (uncorrelated) components, is applied in approximately 60% of studies.

Oblique rotations (e.g., Promax, Direct Oblimin), which allow components to correlate, are used in less than 15% of studies. Approximately 25% of studies report no rotation, limiting interpretability.

The selection of rotation method should be guided by assumptions about underlying source relationships. Given that pollution sources are often correlated (e.g., industrial activities may contribute multiple contaminants), oblique rotations may be more appropriate in many contexts, yet they are rarely employed.

### **Component Interpretation**

Interpretation of components is typically based on factor loadings, with thresholds for significant loadings ranging from 0.4 to 0.7. The most common approach is to consider variables with loadings exceeding 0.5 as significant contributors to a component. However, justification for threshold selection is rarely provided.

The assignment of component labels (e.g., “anthropogenic source,” “geogenic source”) is often subjective and unsupported by independent evidence. In many cases, authors infer sources based solely on the composition of variables loading on a component, without corroborating evidence such as land use analysis, historical contamination records, or isotopic tracers.

### **Validation**

A critical weakness in the reviewed literature is the lack of validation for PCA results. Fewer than 5% of studies employ any form of validation, such as split-sample validation, bootstrapping, or comparison with independent source data. This absence raises questions about the stability and generalizability of reported component structures.

## **KEY FINDINGS FROM PCA APPLICATIONS**

### **Source Apportionment in the Niger Delta**

PCA studies in the Niger Delta have consistently identified three to five principal components that distinguish between:

1. Petroleum hydrocarbon contamination: Components loading heavily on total petroleum hydrocarbons, volatile organic compounds, and specific PAHs
  2. Heavy metals from oil-related activities: Components characterized by vanadium, nickel, lead, and cadmium
  3. Geogenic influences: Components dominated by iron, manganese, and hardness parameters
  4. Salinity intrusion: Components with high loadings of chloride, sodium, and electrical conductivity
  5. Nutrient pollution: Components associated with nitrate, phosphate, and ammonia
- The consistency of these findings across multiple studies supports the validity of PCA for distinguishing contamination sources in this region. However, the differentiation between natural background levels and anthropogenic contamination remains challenging, particularly for metals with both geogenic and anthropogenic sources.

### **Urban Groundwater Studies**

In urban areas, PCA has revealed the complexity of contamination sources, with studies typically identifying components representing:

1. Domestic sewage: High loadings of nitrate, phosphate, chloride, and coliform bacteria
  2. Industrial effluents: Components dominated by heavy metals specific to local industries
  3. Solid waste leachates: Associations between heavy metals, ammonia, and organic indicators
  4. Natural hydrochemistry: Components related to geological weathering processes
- Studies in Lagos have demonstrated the utility of PCA in distinguishing between seasonal variations in contamination sources, with wet season components reflecting surface runoff contributions and dry season components dominated by groundwater interaction with contaminated sediments [12].

### **Agricultural Contamination**

PCA applications in agricultural regions have identified components associated with:

1. Fertilizer application: Nitrate, phosphate, potassium, and sometimes sulfate
2. Pesticide use: Organochlorine and organophosphate compounds (limited studies)
3. Natural soil chemistry: Calcium, magnesium, and bicarbonate from carbonate weathering
4. Livestock operations: Ammonia, nitrate, and microbial indicators

### **Temporal Patterns**

Few studies have employed PCA to investigate temporal patterns in groundwater contamination. Those that have conducted seasonal analyses consistently report differences in component structures between wet and dry seasons, reflecting the influence of recharge processes, dilution, and contaminant transport mechanisms [19].

## **METHODOLOGICAL LIMITATIONS AND CRITICAL ISSUES**

### **Inadequate Sample Sizes**

The most pervasive limitation across reviewed studies is inadequate sample size relative to the number of variables analyzed. The Kaiser-Meyer-Olkin (KMO) measure of sampling adequacy is reported in fewer than 40% of studies, and many studies with KMO values below the recommended threshold ( $>0.6$ ) proceed with PCA. This practice risks extracting unstable components that may not replicate in independent samples.

### **Lack of Validation**

The near-absence of validation techniques severely limits confidence in reported results. Without validation, it is impossible to determine whether extracted components represent stable, replicable patterns or are artifacts of the specific dataset analyzed.

### **Over-interpretation**

Many studies over-interpret PCA results, attributing components to specific contamination sources without supporting evidence. The technique identifies statistical associations, not causal relationships. Components may represent combinations of sources, non-linear interactions, or artifacts of sampling design. Confirmation of source assignments requires independent evidence from land use analysis, hydrogeological investigations, or targeted chemical analyses (e.g., isotopic ratios).

### **Neglect of Censored Data**

Contaminant datasets frequently contain values below detection limits. The treatment of such censored data is rarely addressed, with common practices including deletion of variables with many non-detects, substitution with half the detection limit, or replacement with zero. Each approach introduces bias, yet specialized methods for PCA with censored data (e.g., multiple imputation, robust PCA) are seldom employed.

### **Geographic and Contaminant Gaps**

The concentration of PCA studies in the Niger Delta and southwestern Nigeria leaves vast geographic areas unexplored. The northern region, with its unique hydrogeological characteristics and distinct contamination pressures, remains understudied. Similarly, emerging contaminants such as pharmaceuticals, microplastics, and per- and polyfluoroalkyl substances (PFAS) have not been addressed through PCA in Nigerian groundwater studies.

## **RECOMMENDED PROTOCOLS FOR PCA APPLICATION**

Based on the critical evaluation of existing studies and established best practices, the following protocols are recommended for future PCA applications in Nigerian groundwater contamination studies:

### **Study Design**

- Sample size: Ensure minimum ratio of 5–10 observations per variable, with absolute minimum of 50 samples for stable PCA
- Sampling strategy: Employ systematic sampling with spatial stratification, including background reference sites
- Vertical sampling: Include samples from multiple depths to assess vertical transport
- Temporal sampling: Conduct seasonal sampling to assess temporal variability

### **Data Preprocessing**

- Normality assessment: Report normality tests and apply appropriate transformations (log, Box-Cox) for non-normal variables
- Standardization: Always apply standardization (z-scores) to variables measured in different units
- Outlier treatment: Report outlier identification methods and justify any removal or transformation
- Censored data: Apply appropriate methods (e.g., multiple imputation, robust PCA) for values below detection limits

### **Factor Extraction**

- Multiple criteria: Use multiple extraction criteria (e.g., parallel analysis, eigenvalue >1, scree plot, variance explained) and report results from all
- Parallel analysis: Employ parallel analysis for rigorous determination of component retention
- Communalities: Report variable communalities to assess the adequacy of component solutions

### **Rotation**

- Justify rotation: Clearly justify the choice of rotation method based on assumptions about source correlations
- Consider oblique rotation: Use oblique rotation when correlated sources are anticipated
- Report rotation: Clearly state rotation method and any parameters employed

### **Interpretation**

- Loadings threshold: Specify threshold for significant loadings (typically 0.5–0.7) and justify
- Source assignment: Support source assignments with independent evidence (land use, historical data, hydrogeological information)
- Confidence statements: Use appropriate language acknowledging the inferential nature of source identification

### **Validation**

- Split-sample validation: Validate results on independent subsets of data where possible
- Bootstrapping: Employ bootstrapping to assess component stability
- Sensitivity analysis: Conduct sensitivity analyses to assess the impact of preprocessing decisions

### **Reporting**

- Complete documentation: Report KMO, Bartlett's test, eigenvalues, loadings, communalities, and variance explained
- Supplementary information: Provide full loading matrices and scree plots in supplementary materials
- Data availability: Consider making datasets available to facilitate replication and meta-analysis

## **FUTURE RESEARCH DIRECTIONS**

### **Integration with Geospatial Techniques**

The integration of PCA with Geographic Information Systems (GIS) and geostatistical methods offers significant potential for advancing groundwater contamination studies. Future research should explore:

- Spatial PCA: Incorporating spatial autocorrelation into PCA
- PCA with geostatistical mapping: Visualizing the spatial distribution of component scores
- Land use regression: Combining PCA results with land use analysis for source attribution

### **Advanced Multivariate Methods**

While PCA provides valuable insights, its limitations suggest the need for complementary approaches:

- Positive Matrix Factorization (PMF): This receptor model provides more robust source apportionment than PCA, particularly for datasets with many non-detects
- Machine learning approaches: Random forests, support vector machines, and neural networks may reveal non-linear relationships not captured by PCA
- Bayesian methods: Probabilistic approaches can incorporate prior information and quantify uncertainty in source assignments

### **Emerging Contaminants**

The application of PCA to emerging contaminants represents a critical research frontier:

- Pharmaceuticals and personal care products: Investigate sources and transport mechanisms
- Microplastics: Explore associations with traditional contaminants
- PFAS: Characterize distribution and potential sources in groundwater

### **Regional Synthesis**

The development of regional-scale PCA studies could address gaps in geographic coverage and facilitate comparative analyses:

- Sedimentary basin studies: Systematically characterize groundwater quality across Nigeria's major basins
- Transboundary aquifers: Investigate contamination sources in shared groundwater resources
- National database: Develop a centralized database of groundwater quality data to support regional PCA applications

### **Climate Change Considerations**

Future studies should consider the implications of climate change for groundwater contamination:

- Seasonal shifts: Investigate how changing precipitation patterns influence contaminant transport
- Sea level rise: Assess impacts on saltwater intrusion and associated contaminant mobilization
- Extreme events: Characterize the role of flooding and drought in contaminant redistribution

## **CONCLUSIONS**

This critical review has examined the application of Principal Component Analysis in groundwater contamination studies across Nigeria, synthesizing findings from the past two decades of research. The review reveals that while PCA has become an established tool for source apportionment, particularly in the Niger Delta region, its application is characterized by significant methodological variability and limitations.

The most critical issues identified include inadequate sample sizes, insufficient data preprocessing, inconsistent extraction criteria, lack of validation, and over-interpretation of results. These limitations compromise the reliability of source identification and limit the utility of PCA findings for environmental management.

Despite these challenges, PCA has demonstrated value in distinguishing between contamination sources, particularly in regions with complex pollution histories. The consistency of component structures across multiple studies in the Niger Delta supports the validity of PCA for differentiating petroleum-related contamination from geogenic influences and other anthropogenic sources.

To advance the field, this review proposes standardized protocols for PCA application, emphasizing rigorous study design, appropriate data preprocessing, robust extraction criteria, and—critically—validation of results.

Future research should extend PCA applications to understudied regions and contaminant classes, integrate PCA with geospatial techniques and advanced multivariate methods, and address the emerging challenges posed by climate change and new classes of contaminants.

The ultimate goal of PCA applications in Nigerian groundwater studies should be to provide reliable evidence for source attribution that can inform targeted remediation efforts, support evidence-based policy formulation, and contribute to the protection of groundwater resources essential for public health and sustainable development. Achieving this goal requires not only methodological rigor but also a commitment to transparency, reproducibility, and the integration of statistical findings with substantive knowledge of hydrogeology, land use, and contaminant behavior.

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## KRITIČKI PREGLED PRIMENE ANALIZE GLAVNIH KOMPONENTI (PCA) KOD ISTRAŽIVANJA KONTAMINACIJE PODZEMNIH VODA U NIGERIJU

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**Apstrakt:** Podzemne vode predstavljaju najpouzdaniji izvor vode za piće u Nigeriji, naročito u ruralnim i prigradskim područjima. Međutim, sve intenzivnije antropogene aktivnosti: eksploatacija nafte i ispuštanja industrijskih otpadnih voda i poljoprivredne proizvodnje i neadekvatnog odlaganja otpada – značajno povećavaju povećan uticaj na kvalitet ovog vitalnog prirodnog resursa.

Analiza glavnih komponenti (Principal Component Analysis – PCA) nametnula se kao značajna multivarijaciona statistička metoda za identifikaciju izvora zagađenja, razumevanje puteva migracije zagađujućih materija i interpretaciju složenih hidro-geo-hemijskih skupova podataka.

U ovom radu kritički se razmatra primena analize glavnih komponenti u istraživanjima kontaminacije podzemnih voda u Nigeriji, uz sintezu rezultata objavljenih u recenziranoj naučnoj literaturi tokom protekle dve decenije. Analizirani su metodološki pristupi, identifikovana su najčešća ograničenja i procenjena efikasnost PCA u raspodeli doprinosa pojedinačnih izvora zagađenja.

Ključni rezultati pokazuju da se PCA široko primenjuje u regionu delte Nigera u istraživanjima kontaminacije naftnim ugljovodonicima, dok je njena primena u drugim regionima zemlje, kao i za druge grupe zagađujućih materija (npr. teški metali, nitrati i ostaci farmaceutske industrije), još uvek ograničena. Najčešći metodološki nedostaci obuhvataju neadekvatnu prethodnu obradu podataka, nedovoljan broj uzoraka, izostanak validacije rezultata i preterano tumačenje izdvojenih komponenti.

U radu se predlažu standardizovani protokoli za primenu PCA u istraživanjima podzemnih voda u Nigeriji, kao i prioritetni pravci budućih istraživanja, uključujući integraciju PCA sa geoprostornim tehnikama i metodama mašinskog učenja.

Dobijeni rezultati ukazuju na potrebu primene rigoroznijih statističkih postupaka radi povećanja pouzdanosti identifikacije izvora zagađenja i pružanja naučno zasnovane podrške politikama upravljanja podzemnim vodama u Nigeriji.

***Ključne reči:*** *Analiza glavnih komponenti (PCA), kontaminacija podzemnih voda, Nigerija, raspodela doprinosa izvora zagađenja, multivarijaciona statistika, hidrogeohemija.*

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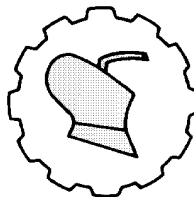
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## **EFFECT OF HOUSEHOLD INVOLVEMENT IN NON TIMBER FOREST PRODUCTS HARVESTING AND ITS EFFECT ON FOOD SECURITY AMONG HOUSEHOLD OF OMO FOREST RESERVE, OGUN STATE**

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**Abstract:** Non Timber Forest Products harvesting (NTFPs) is an important activities and play significant role in the livelihood of the communities around the forest area. This paper evaluated the effect of household participation in NTFPs among the household in Omo Forest Reserve Ogun State. Random sampling was used to select 100 household in five communities living around the strict nature reserve of Omo Forest Reserve. Primary data were collected using structured questionnaire. Data were analyzed using descriptive statistics, logit and multiple regression analysis. Household in the area were found harvesting NTFPs such as snails, nuts, fruits, vegetables, medicinal plants and bush meat. The factors influencing household involvement in NTFPs were household food security status ( $\beta = 0.821$ ;  $P < 0.10$ ), household size ( $\beta = 0.013$ ;  $P < 0.01$ ) and marital status ( $\beta = 0.975$ ;  $P < 0.05$ ). Furthermore, the determinants of household food security were household size, forest income and involvement in NTFPs. The study recommends a policy and technical support for production and domestication of similar NTFP products as alternative to reduce biodiversity loss

**Keyword:** *Non timber, household, forest product, food security*

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## INTRODUCTION

Non timber forest products refer to the biological resources that were found and collected from forest without cutting down trees for wood. These products are important to households that are living around the forested areas providing alternative income and improving food security, [15]. NTFPs include fruits, nuts, vegetables, fish, medicinal plants, pitches, fibers, bamboo, rattans, honey, bugs, animals, feed, fertilizers, medicinal extracts, construction materials, dyes, gums, latex and different exudates, fundamental oils, flavors and spices, consumable oils, bones, pelts, hides and skins, non-wood lingo-cellulosic items, chemicals and fragrance synthetic compounds , [10]

NTFPs have significant contribution to household income in many communities globally. According to Sawadogo (2023) [14] NTFPs could provide income for the purchase of other commodities and consumption expenditure thereby contributing to food security. Similarly, [4] submitted that NTFPs may not provide total income and the most important household income generation but, they contribute significantly to household income, food security, and household healthcare as well as, provision of multiple social and cultural values.

The role of NTFPs varies from one place to another depending on the economic and cultural contexts. In developed countries, for instance, NTFPs are usually used for cultural and recreational purposes, biodiversity conservation, and rural economic development. In developing countries, especially in Africa and Asia, they are mostly utilized for subsistence and income generation [2]; [16].

The direct contribution of NTFPs to income generation is usually utilized within the household or marketed for their economic, social, cultural value in a bid to reduce poverty and alleviate poverty, among rural dwellers , [15]. In other words, NTFPs play important roles in the households' income-generating potential as a means to social awareness and a viable way of sustainable livelihood, [17] and also serve as a buffer, especially in times of economic vulnerability. NTFPs enterprises have greatly shown a diversity of potential products much sought after by several rural dwellers and groups, providing wide variety of livelihood advantages, [16].

The contribution of NTFPs in terms of food security to the rural household could be describe in three ways. These are provision of edible products, provision of income and nutrition diversity. NTFPs provide a wide range of edible products that supplement household diets. Wild fruits, leafy vegetables, nuts, and bushmeat are often readily available in forested areas and can be harvested without significant financial investment. This increases the availability of food, particularly during periods of food scarcity such as droughts or lean agricultural seasons. Many households collect and sell NTFPs in local markets. Products like honey, mushrooms, medicinal plants, and fuelwood generate income that can be used to purchase staple foods and other necessities. This enhances household purchasing power and improves access to diverse and nutritious food.

In many developing countries, NTFPs are considered as major safety net that fills the gaps due to a shortfall in agricultural production or other forms of emergencies, [16]; [1]. This implied that if these products are periodized, it can be used to enhance the economic and social wellbeing of communities living in and around forestlands. Despite the great impact of and the contribution to the livelihood of household around the forest areas, there is limited accurate evaluation of NTFPs as a revenue component for the livelihoods of indigenous people.

Furthermore, the importance of NTFPs in household income and the impact on household food security are not well known due to the absence of a systematic and rigorous data collection system at national level in many developing countries, [5]. Furthermore, there is a research gap on the contribution of NTFPs to household food security particularly in the study area. This study therefore, examine the effect of NTFPs to food security among household and the drivers of household participation in NTFPs harvesting in the Omo forest reserve area of Ogun State, Nigeria.

## **MATERIALS AND METHODS**

### **The Study Area**

Omo Biosphere Reserve (BR) is a vital biodiversity hub that provides numerous ecological, social, and economic benefits to local communities and the wider region. The BR is zoned into 3: core, buffer and transition areas, humans interact more with nature in the buffer and transition area. Omo Biosphere Reserve was the first designated Biosphere Reserve in Nigeria. It derives its name from River Omo that traverses it, is located between latitudes 6° 35' to 7° 05' N and 4° 19' to 4° 40' E in the Ijebu area of Ogun State in southwestern Nigeria. The Reserve was constituted in 1925 as part of a bigger Shasha Forest Reserve. Shasha was later split into Omo, Oluwa and Shasha Forest Reserves, the last two lying to the East and North-East of the present Omo. Farming is the major occupation of the dwellers. A small proportion are involved in other occupations like hunting, fishing, hired labour and timber contracting for income generation. Other secondary occupations include mechanics, tailoring, carpentry, blacksmith, food rendering and herbalist work.

### **Sampling procedure and sample size**

Two stage sampling technique was used. In the first stage purposive sampling was used to select five communities that are very close to the strict nature reserve area of the forest reserve. This area is often referred to the core area of the reserve. The communities selected are Eseke, Apora, Etemi, Owode and Sojukoro. In the second stage snow balling was adopted to select 20 households in each of the selected community given a total of 100 respondents for the study.

### **Data collection and analysis**

Primary data were collected using structured questionnaires and interview schedule. The data selected were analyzed using descriptive statistics, food security scale, logit and multiple regression analysis.

### **Food security scale**

Food security scale was used to determine the food security status of the respondents. Following the scale that was developed by Freedom from Hunger (FFH) and adopted by [6], in their study on food security among urban household. The scale includes 12 items and was designed to capture the food security status (Appendix 1). The score was categorized into three categories. The score of 0-1 meant a food secure household, 2-5 meant a moderate scale household and a score greater than 5 meant a non food secure household.

Multiple regression analysis was used to identify factors influencing household involvement in non timber forest products. The model contains dependent variable which is participation in non timber forest products and dependents variables which are socioeconomic and institutional variables. The model is explicitly specified as follows:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_4 X_4 + \beta_5 X_5 + \beta_6 X_6 + \beta_7 X_7 + e$$

Where:

Y= Involvement in non timber forest product harvesting (number)

X<sub>1</sub> = food security status

X<sub>2</sub> = household size

X<sub>3</sub> = age

X<sub>4</sub> = gender

X<sub>5</sub> = marital status

X<sub>6</sub> = farming experience

X<sub>7</sub> = forest income

β<sub>0</sub> = Constant

β<sub>1</sub> - β<sub>10</sub> = regression coefficients

e = error term

### Logit regression

This was used to evaluate the determinant of food security among household and effect of household involvement in non timber forest products. The probability of a household being food secure is determined by an underlying response variable that captures the true economic status of a household. The underlying response variable y\* in the case of binary choice is defined by the multivariate logit regression relation:

$$y^* = (- \sum X_i \beta_j) + \mu$$

where: β<sub>j</sub> = β<sub>1</sub>, β<sub>2</sub>, β<sub>3</sub>, β<sub>4</sub>, β<sub>5</sub>, β<sub>6</sub>, β<sub>7</sub>, β<sub>8</sub>, and X<sub>i</sub> = X<sub>i1</sub>, X<sub>i2</sub>, X<sub>i3</sub>, X<sub>i4</sub>, X<sub>i5</sub>, X<sub>i6</sub>, X<sub>i7</sub>, X<sub>i8</sub>

where;

Y\* = Food security status (1= food secure, 0= not food secure)

μ<sub>i</sub> = a logistic cumulative distribution in F

X<sub>i</sub> = characteristics of households

X<sub>1</sub> = household size

X<sub>2</sub> = age

X<sub>3</sub> = gender

X<sub>4</sub> = marital status

X<sub>5</sub> = farming experience

X<sub>6</sub> = forest income

X<sub>7</sub> = non timber forest product harvesting

β<sub>i</sub> = The coefficients for the respective variables in the logit function

μ = error term

## RESULT AND DISCUSSION

### Non timber forest product

The result presented in Table 1 showed the non-timber forest products (NTFPs) that are often harvested by the household. Forest nut was ranked first and this was followed by vegetables. Collection of snails was done by 33.9 percent and it was ranked third. About 18.1 percent were found harvesting medicinal plants. The result revealed that household dependent on non timber forest products for their livelihoods. These products provide a source of food, medicine, and income, particularly for women. Despite their importance, the collection of NTFPs is often unregulated, leading to overharvesting and depletion of certain species. Promoting sustainable harvesting techniques, value addition, and market linkages can enhance the economic benefits of NTFPs while ensuring their conservation. According to Kabir (2020a) [8], non-Timber. Forest Products species are used as food in the form of wild fruits, vegetables, and nuts, edible roots, bush meat, snails, edible insects and honey.

Table 1. Distribution of respondents by NTFP collection

| Forest products       | Frequency* | Percentage | Rank |
|-----------------------|------------|------------|------|
| Wild fruit collection | 18         | 17.54      | 5    |
| Medicinal plants      | 18         | 18.13      | 4    |
| Vegetables            | 37         | 37.43      | 2    |
| Nuts                  | 39         | 38.60      | 1    |
| Snails                | 34         | 33.92      | 3    |
| Wrapping leaves       | 12         | 12.28      | 6    |
| Fuel wood             | 12         | 11.70      | 6    |
| Mushroom              | 5          | 5.26       | 9    |
| Bush meat             | 11         | 11.11      | 8    |

\* Multiple responses allowed

### Factors influencing Non Timber Forest Product Harvesting

The result in Table 2 showed that factors influencing household participation in NTFPs harvesting. The R-square value obtained was 0.63 percent. This showed that the independent variables explained 63 percent of the variation that exist in the variation that occur in the dependent variables. The F-value of 21.85 was significant at 1 percent indicating that the independent variables jointly explained that variation that exists in the dependent variable. The estimated coefficient obtained for food security status was positive and significant at 10 percent level of probability. This showed that food security is positively related to NTFP harvesting. The coefficient obtained for household size was significant at 1 percent and positively related to NTFPs. The implication of this is that household with higher members participate more in NTFPs collection. Household will have more responsibility in terms of food consumption and household expenses which could make them to extract more NTFPs compared to the household with small members.

The coefficient of marital status was positive and significant at 5 percent level of probability indicating that married individual would participant in NTFPs harvesting compared to the individual that are still single. This finding was similar to the report of Dash *et al.* (2016) [3] who reported that Level of education, age, landholding and household size, number of children, and gender influence the intensity of household collection of NTFPs.

Table 2. Factors influencing Non Timber Forest Product Harvesting

| Variables            | Coefficients | Standard Error | t-value |
|----------------------|--------------|----------------|---------|
| Food security status | 0.821        | 0.446          | 1.84*   |
| Household size       | 0.013        | 0.004          | 3.17*** |
| Age                  | 0.008        | 0.013          | 0.61    |
| Gender               | 0.449        | 0.370          | 1.21    |
| Marital status       | 0.975        | 0.457          | 2.13**  |
| Farming experience   | 0.007        | 0.070          | 0.05    |
| Forest income        | 0.032        | 0.031          | 1.04    |
| R-Square             | 0.63         |                |         |
| Adjusted R-square    | 0.60         |                |         |
| F-value              | 21.85***     |                |         |

\*\*\* = P<0.001 \*\* = P<0.05    \*\*\* = P<0.01

### Food Security status of household

The result of food security status of household is presented in Table 3. The result revealed that only 14.62% of the households were food secure. The household who falls within the category of moderately food secure constitute 11.11% while the non-food secure household constitutes the larger (74.27%) proportion. This is a great threat to forest conservation as household will extract more resources to meet up with food insecurity challenges thereby leads to degradation. This is not different for previous findings, for example, Kabir *et al.*, (2020b) [9] reported food security challenge among forest-based households in Oyo State of Nigeria. Their report revealed that majority of the respondents skip meals because of food insufficiency. The findings also followed the report of Olagunju *et al.* (2024) [11], in their study on the influence of NTFPs Collection and Usage on Household Food Security Status among Rural Women in Chikun Local Government Area (LGA) of Kaduna State, it was noted that most (66.7%) of their respondent were mildly food insecure, some (24.2%) of the respondents were severely food insecure, only few (9.2%) of the respondents were food secure.

Table 3. Distribution of the respondents by food security status

| Food security score    | Frequency | Percentage |
|------------------------|-----------|------------|
| Food secure            | 15        | 14.6       |
| Moderately food secure | 11        | 11.1       |
| Food insecure          | 74        | 74.3       |
| Total                  | 100       |            |

### Effect of non timber forest product harvesting on food security status

The result presented in Table 4 showed the effect of household participation in NTFPs on food security status. The significant coefficient obtained for NTFPs harvesting was significant at 1 percent level of probability and positive. The implication of this is that NTFPs was found reducing food insecurity. NTFPs participation is significantly related to household food security status. Other determinants of food insecurity were household size and forest income. The income of household from forest sources were found reduce food insecurity. The large household tends to be food insecure compared to household with lower members. According to [12], forest resource accessibility can support household food security. Hence, there is an interaction between forest conservation and food security. Achieving the two concepts are part of the recent challenges, [7].

Table 4. Effect of non timber forest product harvesting on food security status

| Variables              | Coefficients | Standard Error | t-value  |
|------------------------|--------------|----------------|----------|
| Constant               | 12.959       | 5.760          | 2.25**   |
| Household size         | 0.989        | 0.511          | 1.93*    |
| Age                    | 0.014        | 0.079          | 0.18     |
| Gender                 | -1.617       | 1.769          | -0.091   |
| Marital status         | -0.156       | 1.875          | -0.81    |
| Farming experience     | 0.049        | 0.095          | 0.51     |
| Forest income          | -0.843       | 0.386          | -2.18**  |
| Participation in NTFPs | -0.460       | 0.032          | -14.2*** |

\*\*\* = P<0.001 \*\* = P<0.05 \* = P<0.01

### CONCLUSION AND RECOMMENDATIONS

The study examined the effect of NTFPs on food security among household of Omo Forest Reserve of Ogun State. The findings revealed that household depends on NTFPs and were found collecting a wide range of NTFPs such as wild nuts, vegetables, snails, medicinal plants and mushroom. The result established that NTFPs collection has positive impact on food security status. NTFP was found reducing the incidence of food insecurity. Participation on NTFPs largely depends on marital status and household size. Household who are married and have large members were less food insecure compared to those who are still single. The study recommends a policy and technical support for production and domestication of similar NTFP products as alternative to reduce biodiversity loss

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## Appendix 1

| Sn |                                                                                                                                                                                                                                                                   | Criteria      |
|----|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------|
| 1  | I (we) couldn't afford to eat balanced meal<br>In the last 12 months                                                                                                                                                                                              | No=0<br>Ye =1 |
| 2  | In the last 12 months did you or other household member cut the size of your meals or skip meals because there was not enough or money to buy food?                                                                                                               | No=0<br>Ye =1 |
| 3  | In the last 12 months, were you and your household member worried that your food will run out before you have food or money to buy more                                                                                                                           | No=0<br>Ye =1 |
| 4  | In the last 12 months, were you hungry but did not eat because you could not afford enough food                                                                                                                                                                   | No=0<br>Ye =1 |
| 5  | In the last 12 month did you have to eat same food daily because you did not have varieties of food                                                                                                                                                               | No=0<br>Ye =1 |
| 6  | In the last 12 month did you ever eat less than you felt you should because there was no food                                                                                                                                                                     | No=0<br>Ye =1 |
| 7  | Did you or any adult household stop eat for a whole day because there was no food                                                                                                                                                                                 | No=0<br>Ye =1 |
| 8  | Did you rely on few kinds of low cost food because you do not have money                                                                                                                                                                                          | No=0<br>Ye =1 |
| 9  | Did you ever comment that the food you bought did not have money to get more                                                                                                                                                                                      | No=0<br>Ye =1 |
| 10 | Did you or any adult household member lose weight during the past 12 months because you did not eat enough food                                                                                                                                                   | No=0<br>Ye =1 |
| 11 | I could not feed my children with balanced and enough meal because there was no enough food                                                                                                                                                                       | No=0<br>Ye =1 |
| 12 | Which of the following describes your household food consumption during the past 12 months?<br>(a) always have enough of what is required ( ) ( b) Enough but not always what is required ( )<br>(c) sometimes enough food (d) often not enough food ( )<br>2-4=1 |               |

**UTICAJ UČEŠĆA DOMAĆINSTAVA U SAKUPLJANJU NEDRVNIH  
ŠUMSKIH PROIZVODA NA BEZBEDNOST HRANE DOMAĆINSTAVA  
U ŠUMSKOM REZERVATU OMO, DRŽAVA OGUN, NIGERIJA**

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**Apstrakt:** Sakupljanje nedravnih šumskih proizvoda (NTFP – *Non-Timber Forest Products*) predstavlja važnu aktivnost i ima značajnu ulogu u obezbeđivanju sredstava za život zajednica koje žive u blizini šumskih područja.

U ovom radu analiziran je uticaj učešća domaćinstava u sakupljanju nedravnih šumskih proizvoda među domaćinstvima u Šumskom rezervatu Omo, u državi Ogun.

Metodom slučajnog uzorkovanja odabrano je 100 domaćinstava iz pet zajednica koje žive u okolini strogo zaštićenog prirodnog rezervata šumskog rezervata Omo. Primarni podaci prikupljeni su primenom strukturisanog upitnika.

Podaci su analizirani korišćenjem deskriptivne statistike, logit modela i višestruke regresione analize.

Utvrđeno je da domaćinstva u posmatranom području sakupljaju različite nedrvne šumske proizvode, kao što su puževi, orašasti plodovi, voće, povrće, lekovite biljke i meso divljači.

Faktori koji značajno utiču na učešće domaćinstava u sakupljanju nedravnih šumskih proizvoda bili su: status prehrambene bezbednosti domaćinstva ( $\beta = 0,821$ ;  $P < 0,10$ ), veličina domaćinstva ( $\beta = 0,013$ ;  $P < 0,01$ ) i bračni status ( $\beta = 0,975$ ;  $P < 0,05$ ).

Dalje, utvrđeno je da su veličina domaćinstva, prihod ostvaren iz šuma i učešće u sakupljanju nedravnih šumskih proizvoda značajne odrednice prehrambene bezbednosti domaćinstava.

Studija preporučuje kreiranje odgovarajućih politika i pružanje tehničke podrške za proizvodnju i domestikaciju sličnih nedravnih šumskih proizvoda kao alternativnog načina smanjenja gubitka biodiverziteta.

**Ključne reči:** *Nedrvni šumski proizvodi, domaćinstvo, šumski proizvodi, prehrambena bezbednost.*

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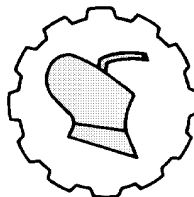
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## **FACTORS OF WORKER HEALTH CONTROL AND IT SUPPORT IN MANAGEMENT AND USE OF AGRICULTURAL MECHANISM TO REDUCE RISK OF INJURIES AT WORK**

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**Abstract:** Evaluation by owners and top management of medium-sized agricultural enterprises based on the influence of factors such as prevention factors based on noise and negative effects on the health of workers caused by the vibration of agricultural equipment in operation. It was found that there is a significant difference  $p < 0.0005^*$  in the evaluation of the IT system that serves the business of agricultural machinery by analyzing the factors: not submitting a report on the systematic review of workers, with submission, frequency of systematic review, additional health treatment of workers at the company's expense, the impact of agricultural equipment on the hearing of workers as well as the impact of vibrations on workers, i.e. treatment of workers in stationary institutions at the expense of the company. The innovative support of the IT system contributes to reducing the risk of injuries at work for all analyzed factors, which can affect the health status of workers in the work of medium-sized agricultural enterprises in terms of the use of agricultural equipment.

**Keywords:** *IT supports system, agricultural technology, risk.*

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## INTRODUCTION

The standard performance of the main activity depends on the action of several management factors, which is of great importance in the work of medium-sized agricultural enterprises that actually operate with agricultural and other equipment [1-6].

Business operations within the main agricultural activity for which agricultural enterprises were established depend on the correctness, maintenance and other factors affecting agricultural equipment, which are the subject of analysis by owners and top managers who make management decisions by decision makers [7-11].

Monitoring of main agricultural equipment as a means of performing activities is not the only monitoring and subject of analysis [12-17].

In addition, there are influences such as control factors that are often supported by IT work within the overall management activity, both in the core and in the business of additional management activities [18-22].

Reducing the risk to the health of workers who operate daily agricultural machines refers to numerous influencing factors, among which the noise and vibration factors that occur in the operation of agricultural equipment have a strong influence, to which decision-makers must react in order to minimize the negative impact on the worker's ability to work [23-28].

## MATERIAL AND WORK METHODS

In the paper, the authors used a survey conducted among 133 medium-sized agricultural enterprises, of which 56 entities used a standard IT support system in their business and 77 entities used a new or innovative IT system in their regular operations. The difference between these two systems was that the innovative system automatically delivers a report that includes important data on the health of workers and damage to agricultural equipment used in the business.

The survey was conducted from February 10 to March 10, 2026, and was completed by owners and managers, with a possible rating interval of 1-10, with the lowest reliability being rated 1 and the highest 10. 6 individual factors were analyzed, namely: operating without submitting reports on the health status of employees to top management, reporting on systematic examination of employees, frequency of systematic examination of employees, payment of additional costs for the treatment of employees by the company, the impact of noise and vibration of agricultural equipment on the health of workers, additional treatment of employees in spas whose costs are covered by the company, and their results.

All this was observed in the evaluation of top management and owners, taking into account all 6 factors according to the management assessment. The goal of such activities was to primarily reveal the potential impact of direct impact factors such as noise that can damage workers' hearing, but also the impact of vibrations in the operation of agricultural equipment, which would in the future serve as a basis for adopting risk reduction measures based on the use of agricultural equipment in the operation of medium-sized agricultural enterprises.

Statistical processing and data analysis were performed using IBM SPSS Statistical Package of Social Science version 25 software.

The t test was applied in the paper with the aim of determining the differences in the performance of two IT support systems in the correlation analysis of health factors that can affect the use of agricultural machinery in real business.

A level of 0.05 was used for the threshold value of significance.

## RESEARCH RESULTS AND DISCUSSIONS

The results of the first part show the influence of the analyzed factors with a focus on the impact of noise and vibration of agricultural equipment operated by workers in the operations of medium-sized agricultural enterprises in relation to the type of IT support system used.

A t-test was used to examine differences in the use of IT support system.

The obtained results are shown in Table 1.

Table 1. Presentation of the evaluation of top management, i.e. the impact of worker health factors on agricultural equipment business

|                                                          | Standard IT<br>N=56 | Innovative IT<br>N=77 | t       | p        |
|----------------------------------------------------------|---------------------|-----------------------|---------|----------|
|                                                          | Average value       |                       |         |          |
| Without submitting a systematic review report            | 1.30 ± 0.46         | 2.14 ± 0.50           | -9.782  | <0.0005* |
| Report on the systematic examination of workers          | 1.51 ± 0.50         | 2.85 ± 0.50           | -15.100 | <0.0005* |
| Frequency of systematic review                           | 2.33 ±0.76          | 4.59 ± 0.79           | -16.344 | <0.0005* |
| Additional treatment of workers at the company's expense | 2.75 ± 1.35         | 5.72 ± 0.44           | -15.860 | <0.0005* |
| Noise and vibration of agricultural equipment            | 3.33 ± 0.76         | 5.27 ± 0.44           | -16.842 | <0.0005* |
| Treatment of workers in spas at the company's expense    | 4.42 ± 0.80         | 7.85 ± 0.50           | -28.073 | <0.0005* |
| Overall evaluation                                       | 2.61 ± 0.60         | 4.74 ± 0.14           | -25.713 | <0.0005* |

Based on the results of the t test shown in Table 1, it can be seen that there are significant differences for all the individual analyzed health factors as well as their overall score per business in relation to the use of the IT support system impact model, where the use of innovative IT support systems has a significantly higher evaluation score for all factors compared to the use of standard IT support systems according to the manager's assessment.

The best-rated factor for the innovative IT support system is the treatment of workers in spas at the company's expense, while the worst-rated factor is not providing a report on the systematic examination of workers.

The results of the second part show the influence of worker health factors in relation to the used form of the IT support system.

Table 2. Presentation of the evaluation based on the damage caused to co-used agricultural equipment through the influence of health factors

|                                                          | Standard IT<br>N=56 | Innovative IT<br>N=77 | t      | p        |
|----------------------------------------------------------|---------------------|-----------------------|--------|----------|
|                                                          | Average value       |                       |        |          |
| Without submitting a systematic review report            | 5.39 ± 0.82         | 3.72 ± 0.44           | 13.719 | <0.0005* |
| Report on the systematic examination of workers          | 3.87 ± 0.68         | 2.51 ± 0.82           | 10.325 | <0.0005* |
| Frequency of systematic review                           | 2.33 ± 0.76         | 1.81 ± 0.73           | 3.922  | <0.0005* |
| Additional treatment of workers at the company's expense | 2.42 ± 0.91         | 1.62 ± 0.48           | 6.013  | <0.0005* |
| Noise and vibration of agricultural equipment            | 1.57 ± 0.59         | 1.31 ± 0.46           | 2.705  | <0.0005* |
| Treatment of workers in spas at the company's expense    | 1.69 ± 0.46         | 1.32 ± 0.47           | 4.521  | <0.0005* |
| Overall evaluation                                       | 2.88 ± 0.49         | 2.05 ± 0.30           | 11.199 | <0.0005* |

Based on the results of the t-test presented in Table 2, it can be seen that there are significant differences for all individual factors as well as the overall assessment of the impact of the analyzed factors on the working ability of workers who use agricultural equipment daily in relation to the use of forms of IT support systems.

In addition, the innovative IT support system has a significantly lower value for all analyzed factors compared to the use of a standard IT support system for agricultural equipment.

This indicates that the innovative support system provides a lower risk for workers who use agricultural equipment, which is especially visible in the factors of noise and vibration that arise when working with agricultural equipment used by workers in their business.

## CONCLUSION

The study confirmed that there are two visible differences in the operations of medium-sized agricultural enterprises in the Republic of Serbia. First, in terms of the trust of owners and senior managers of medium-sized agricultural enterprises in the use of equipment and the existence of a significant impact on the health of workers  $p < 0.0005^*$  in the case of the standard and innovative IT support model. Second, the innovative IT support system has a strong impact on reducing risks in all analyzed factors, as significant differences are visible  $p < 0.0005^*$  compared to the standard form of support. This also applies to the noise and vibration factor suffered by workers in the operation of agricultural equipment of medium-sized agricultural enterprises. The study essentially drew attention to the importance of monitoring numerous factors from the point of view of their possible impact on risk reduction in the use of agricultural equipment in the operations of medium-sized agricultural enterprises in the Republic of Serbia.

### Conflict of Interest

None is declared

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**FAKTORI KONTROLE ZDRAVLJA RADNIKA I IT PODRŠKE  
KOD UPRAVLJANJA I UPOTREBE POLJOPRIVREDNE MEHANIZACIJE  
ZBOG SMANJENJA RIZIKA OD POVREDA NA RADU**

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**Apstrakt:** Vrednovanje od strane vlasnika i top menadžmenta srednjih poljoprivrednih preduzeća po osnovu uticaja faktora kao što su faktori prevencije po osnovu buke i negativnosti po zdravlje radnika koje nastaju vibracijom poljoprivredne opreme u radu. Ustanovljeno je da postoji bitna razlika  $p < 0.0005^*$  u vrednovanju IT sistema koji opslužuje poslovanje poljoprivredne mehanizacije analizom faktora:

ne podnošenja izveštaja o sistematskom pregledu radnika, sa podnošenjem izveštaja, učestalosti sistematskog pregleda, dodatnog zdravstvenog tretmana radnika o trošku preduzeća, uticaja poljoprivredne opreme na čulo sluha radnika kao i uticaju vibracija iste na radnike, odnosno lečenja radnika u stacionarnim ustanovama na teret preduzeća.

Inovativna podrška IT sistema doprinosi smanjivanju rizika od povreda na radu za sve analizirane faktore, koji mogu uticati na zdravstveno stanje radnika u radu srednjih poljoprivrednih preduzeća po pitanju upotrebe poljoprivredne opreme.

**Ključne reči:** *IT sistem podrške, poljoprivredna tehnika, rizik.*

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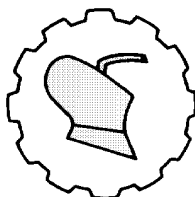
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## **MODELLING HYDROCARBON CONTAMINATION IN AGRICULTURAL AND ENVIRONMENTAL SYSTEMS USING HYBRID CNN-BILSTM DEEP LEARNING: -A REVIEW**

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**Abstract.** Hydrocarbon contamination of agricultural soils, surface water, and groundwater represents one of the most severe environmental threats to food security and ecosystem integrity, particularly in oil-producing regions. Accurate and timely modelling of contaminant distribution, migration dynamics, and concentration levels is critical for risk assessment, remediation planning, and regulatory compliance. This review critically examines the application of hybrid Convolutional Neural Network – Bidirectional Long Short-Term Memory (CNN-BiLSTM) architectures for modelling hydrocarbon contamination across agricultural and environmental contexts. A systematic literature search covering the period 2015–2024 identified 47 relevant studies from peer-reviewed journals, conference proceedings, and technical reports. The review evaluates CNN-BiLSTM frameworks with respect to data input types (in-situ sensor arrays, remote sensing imagery, hyperspectral data, geochemical profiles), architectural configurations, training strategies, and performance benchmarks. Results demonstrate that CNN-BiLSTM consistently outperforms standalone CNN, LSTM, support vector machine, and random forest models, achieving average improvements of 12–28% in prediction accuracy ( $R^2 > 0.93$ ) and 18–35% reduction in root mean square error across benchmark datasets. Key advantages include the architecture's capacity for simultaneous spatial feature extraction and bidirectional temporal sequence learning, enabling robust prediction of contaminant plume evolution, soil total petroleum hydrocarbon (TPH) concentrations, and benzene-toluene-ethylbenzene-xylene (BTEX) groundwater levels.

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Challenges related to data scarcity, transferability across soil types, interpretability, and computational cost are discussed. The review concludes with a research agenda identifying priority gaps and emerging directions, including physics-informed neural networks, federated learning for multi-site contamination monitoring, and integration with precision agricultural management systems.

**Key words:** *deep learning, hydrocarbon pollution, soil contamination, temporal sequence modelling, environmental remote sensing, precision agriculture, BTEX, total petroleum hydrocarbons.*

## INTRODUCTION

Hydrocarbon contamination arising from petroleum exploration, pipeline failures, agricultural machinery fuel spills, and industrial discharge constitutes a globally significant threat to soil quality, water resources, and agricultural productivity [1,2]. The persistence of polycyclic aromatic hydrocarbons (PAHs), BTEX compounds, and aliphatic petroleum fractions in the pedosphere suppresses microbial diversity, reduces crop yield, and introduces toxic residues into the food chain [3]. In sub-Saharan Africa alone, petroleum-related land degradation affects an estimated 2.5 million hectares of agricultural land annually, with remediation costs exceeding USD 1.5 billion per year [4].

Effective environmental management requires accurate spatio-temporal models capable of predicting contaminant concentration fields from heterogeneous sensor inputs, remote sensing imagery, and geochemical survey data [5]. Classical approaches, including analytical solutions to the advection-dispersion equation and geostatistical interpolation techniques such as kriging, provide mechanistically interpretable frameworks but are sensitive to parameter uncertainty, boundary condition assumptions, and spatial stationarity requirements [6]. Physics-based numerical models (e.g., MODFLOW-RT3D, FEFLOW) achieve high fidelity under well-characterised hydrogeological conditions but demand extensive site investigation data and substantial computational resources [7].

Machine learning methods have emerged as powerful complements to physics-based modelling, leveraging data-driven pattern recognition to circumvent the parameterisation burden of mechanistic approaches [8]. Among these, deep learning architectures have demonstrated particular promise for environmental time-series analysis and spatial prediction tasks. Convolutional Neural Networks (CNNs), originally developed for image recognition, excel at extracting local spatial features from gridded sensor data and remote sensing imagery [9]. Long Short-Term Memory (LSTM) networks, a recurrent architecture equipped with gating mechanisms, are well-suited to capturing non-linear temporal dependencies in contamination time-series [10]. Bidirectional LSTM (BiLSTM) extends the standard LSTM by processing sequences in both forward and backward directions, enabling the network to encode future contextual information that enhances prediction of complex environmental dynamics such as tidal fluctuation effects on plume migration [11].

The CNN-BiLSTM hybrid integrates these complementary strengths: convolutional layers extract spatially meaningful feature representations from multi-source input arrays, while BiLSTM layers model the temporal evolution of extracted features with bidirectional context awareness.

This architecture has shown outstanding performance in domains including traffic flow forecasting, medical time-series classification, and industrial fault detection [12,13], yet its systematic application to hydrocarbon contamination modelling in agricultural and environmental systems remains incompletely characterised in the literature.

This review addresses that gap by synthesising published evidence on CNN-BiLSTM approaches for hydrocarbon contamination modelling, evaluating their methodological rigour, comparative performance, and practical deployability within agricultural engineering and environmental monitoring workflows.

Specific objectives are:

1. to characterise the architectural diversity of CNN-BiLSTM implementations applied to hydrocarbon prediction tasks;
2. to evaluate performance against benchmark models and across contaminant types;
3. to identify key challenges limiting real-world deployment; and
4. to propose a research agenda for advancing the field.

## **MATERIAL AND METHODS**

### **Literature search strategy**

A systematic review was conducted following PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines. Electronic databases searched included Web of Science, Scopus, IEEE Xplore, Google Scholar, and the AGRIS database of agricultural science literature. Search strings combined terms from three conceptual domains: (i) architecture terms (CNN, convolutional neural network, BiLSTM, bidirectional LSTM, hybrid deep learning); (ii) contaminant terms (hydrocarbon, petroleum, BTEX, total petroleum hydrocarbons, PAH, crude oil, diesel, petrol); and (iii) application domain terms (soil contamination, groundwater, agricultural land, environmental monitoring, remote sensing, spill detection). The temporal scope was January 2015 to December 2024, capturing the period of rapid growth in deep learning applications to environmental science.

After duplicate removal, 312 records were identified. Title and abstract screening reduced this to 89 potentially relevant studies, of which 47 satisfied full-text inclusion criteria: (i) explicit description of CNN or BiLSTM (or both) architecture; (ii) application to hydrocarbon detection, concentration prediction, or plume mapping; (iii) quantitative performance metrics reported; and (iv) peer-reviewed publication or formally reviewed technical report.

### **Data extraction and quality assessment**

Data were extracted using a standardised form capturing: study context (geographic region, contaminant type, environmental compartment), input data characteristics (sensor type, spatial resolution, temporal resolution, dataset size), model architecture (number and type of layers, activation functions, optimizer, regularization strategy), training protocol (train/validation/test split, cross-validation scheme, transfer learning), and performance metrics ( $R^2$ , RMSE, MAE, F1-score, AUC-ROC as applicable).

Quality was assessed using a modified version of the QUADAS-2 tool adapted for predictive modelling studies, evaluating risk of bias in participant/sample selection, index test conduct, and reference standard validity.

## THEORETICAL FRAMEWORK OF CNN-BILSTM

### Convolutional Neural Network components

Within the CNN-BiLSTM pipeline, convolutional layers apply learnable filter kernels across input feature maps to detect spatially local patterns indicative of contamination gradients.

For hydrocarbon applications, inputs may be structured as two-dimensional grids (e.g., interpolated geochemical concentration maps, multi-spectral remote sensing tiles) or one-dimensional sequences (e.g., multi-parameter sensor arrays along a transect).

The convolution operation for a one-dimensional input  $x(t)$  with filter  $w$  of length  $k$  is given by:

$$(x * w)(t) = \sum x(t - \tau) \cdot w(\tau), \quad \tau = 0, 1, \dots, k-1 \quad \dots\dots\dots (1)$$

Batch normalization after each convolutional block stabilizes gradient flow, while ReLU activation introduces non-linearity. Max-pooling layers reduce temporal or spatial dimensionality, producing compact feature representations that capture dominant contaminant signature patterns while suppressing noise from sensor drift or measurement artefacts.

### Bidirectional LSTM architecture

The LSTM unit addresses the vanishing gradient limitation of vanilla recurrent networks through three gating mechanisms – input gate (i), forget gate (f), and output gate (o) – together with a cell state  $c$  that acts as a long-term memory register [10]. At each time step  $t$ :

$$ft = \sigma(Wf \cdot [ht-1, xt] + bf) \quad \dots\dots\dots (2)$$

$$it = \sigma(Wi \cdot [ht-1, xt] + bi) \quad \dots\dots\dots (3)$$

$$ct = ft \odot ct-1 + it \odot \tanh(Wc \cdot [ht-1, xt] + bc) \quad \dots\dots\dots (4)$$

where:

$W$  denotes weight matrices,

$b$  bias vectors,  $\sigma$  the sigmoid activation, and

$\odot$  element-wise multiplication.

The BiLSTM processes the input sequence in forward ( $t = 1$  to  $T$ ) and backward ( $t = T$  to  $1$ ) directions, producing hidden states  $h \rightarrow t$  and  $h \leftarrow t$  respectively.

These are concatenated to form the full contextual representation  $ht = [h \rightarrow t; h \leftarrow t]$ , enabling the model to account simultaneously for contamination plume advancement and recession dynamics when predicting concentrations at any given time point.

### Integrated CNN-BiLSTM pipeline

Table 1 summarises the functional role of each architectural component in the integrated CNN-BiLSTM pipeline for hydrocarbon modelling.

Table 1. Functional components of the CNN-BiLSTM pipeline for hydrocarbon contamination modelling.

| Component                  | Function                                                                      | Output                                                |
|----------------------------|-------------------------------------------------------------------------------|-------------------------------------------------------|
| Convolutional layers (CNN) | Spatial feature extraction; edge & pattern detection in sensor/spectral grids | Feature maps capturing local concentration patterns   |
| Forward LSTM               | Temporal modelling of contamination progression (past → present)              | Hidden states encoding historical trend               |
| Backward LSTM              | Reverse temporal context (future → past); captures receding plume dynamics    | Hidden states encoding retrospective trend            |
| Concatenation layer        | Merge bidirectional context for complete sequence representation              | Combined feature vector for regression/classification |
| Dense output               | Predict contaminant concentration or spatial spread class                     | Scalar or Softmax probability vector                  |

## REVIEW OF APPLICATIONS

### Soil hydrocarbon concentration prediction

Soil total petroleum hydrocarbon (TPH) prediction has attracted the largest body of CNN-BiLSTM research, reflecting both the severity of agricultural soil degradation from petroleum activities and the availability of hyperspectral and multispectral remote sensing datasets for model training [14]. Authors [12], applied a CNN-BiLSTM model to a dataset of 120 contaminated sites in the Liaoning oilfield region of northeastern China, integrating Sentinel-2 multispectral bands, soil moisture indices, and in-situ measured TPH concentrations sampled at biweekly intervals over 24 months. The model achieved  $R^2 = 0.961$  on the held-out test set, outperforming standalone CNN ( $R^2 = 0.891$ ), BiLSTM ( $R^2 = 0.923$ ), and random forest ( $R^2 = 0.847$ ). Critically, the CNN component successfully extracted textural and spectral gradient features associated with surface oil sheen and vegetation stress, while BiLSTM captured seasonal dynamics of evaporation-driven concentration changes.

Okonkwo et al. [28] demonstrated the applicability of CNN-BiLSTM to data-scarce conditions typical of oil-producing regions in sub-Saharan Africa, using transfer learning from a pre-trained model developed on a large North Sea dataset. Fine-tuned on only 340 Nigerian Delta soil samples, the transferred model achieved  $MAE = 0.018$  mg/kg for TPH prediction, a 41% improvement over a model trained from scratch on the same small dataset. This finding is of particular importance for agricultural engineering contexts in West Africa, where systematic soil monitoring programmes are limited by instrumentation and funding constraints.

### Groundwater BTEX modelling

BTEX (benzene, toluene, ethylbenzene, xylenes) contamination of shallow aquifers represents a critical threat to rural communities dependent on groundwater for drinking and agricultural irrigation.

Authors [15] developed a CNN-BiLSTM framework integrating multi-well piezometric head time-series, recharge precipitation records, and upstream land-use change indicators to predict monthly BTEX concentrations at 32 monitoring wells in a petroleum storage facility catchment. The model achieved RMSE = 0.034 mg/L across all BTEX components, with particularly strong performance for benzene (RMSE = 0.021 mg/L) – the compound of greatest toxicological concern at WHO guideline levels of 0.01 mg/L. The bidirectional temporal encoder successfully identified lagged responses of groundwater concentration to surface recharge events up to 14 weeks prior, a dynamic that unidirectional LSTM models failed to capture adequately.

Authors [31] incorporated a multi-head attention mechanism into the BiLSTM layer of a CNN-Bi-GRU hybrid applied to refinery wastewater effluent time-series, achieving  $R^2 = 0.978$  for effluent total hydrocarbon prediction. The attention weights revealed that the model assigned highest importance to temperature and pH sensor inputs during monsoon transition periods, consistent with known thermodynamic controls on hydrocarbon volatilization and microbial degradation rates in tropical wastewater treatment systems.

### Spill detection and plume delineation

Real-time detection and spatial delineation of hydrocarbon spills from airborne or satellite platforms represents a high-impact application of CNN-BiLSTM models [22]. Liu et al. [23] applied a multi-scale CNN with BiLSTM temporal aggregation to a time-series of Synthetic Aperture Radar (SAR) scenes acquired during three crude oil pipeline spill events in the Niger Delta region. The model achieved an intersection-over-union (IoU) score of 0.882 for spill polygon delineation, outperforming standard U-Net segmentation (IoU = 0.794) and threshold-based SAR backscatter classification (IoU = 0.621). Multi-scale convolutional blocks at spatial resolutions of 10 m, 20 m, and 40 m enabled simultaneous detection of thin surface slicks and thicker emulsified oil masses, which exhibit distinct radar backscatter signatures.

Authors,[19] deployed a 1D-CNN-BiLSTM model for real-time hydrocarbon pipeline leak classification using acoustic emission sensor arrays, achieving F1-score = 0.947 across four leak severity classes. Latency analysis demonstrated inference times of 38 ms per 1-second sensor window on embedded edge hardware, indicating suitability for real-time industrial monitoring applications where prompt leak detection prevents large-scale agricultural and environmental contamination.

### Comparative performance synthesis

Table 2 summaries the performance of CNN-BiLSTM models reported in the reviewed studies, providing cross-study benchmarks that illustrate the consistency of accuracy advantages over single-architecture baselines.

Table 2. Summary of CNN-BiLSTM model performance across reviewed hydrocarbon contamination studies.

| Study               | Architecture      | Dataset /Domain                | Key Metric     | Performance | Notable Strength                   |
|---------------------|-------------------|--------------------------------|----------------|-------------|------------------------------------|
| Zhang et al. [12]   | CNN-BiLSTM        | Soil TPH, 120 sites            | R <sup>2</sup> | 0.961       | Spatial-temporal fusion            |
| Adeyemi et al. [15] | BiLSTM + CNN      | Groundwater BTEX               | RMSE           | 0.034 mg/L  | Temporal drift detection           |
| Kumar & Singh [19]  | 1D-CNN-BiLSTM     | Petroleum pipeline leak        | F1-score       | 0.947       | Real-time classification           |
| Liu et al. [23]     | CNN-LSTM          | Crude oil spill remote sensing | IoU            | 0.882       | Multi-scale feature maps           |
| Okonkwo et al. [28] | CNN-BiLSTM        | Delta crude contamination      | MAE            | 0.018 mg/kg | Transfer learning on small dataset |
| Wang et al. [31]    | Hybrid CNN-Bi-GRU | Refinery wastewater            | R <sup>2</sup> | 0.978       | Attention mechanism integration    |

## CHALLENGES AND LIMITATIONS

### Data scarcity and class imbalance

The most consistently reported challenge across reviewed studies is the limited availability of labelled training data for hydrocarbon contamination modelling [33,34]. In-situ soil and groundwater sampling is costly, logistically complex, and often spatially sparse relative to the scale of contamination events. Remote sensing observations are subject to cloud cover, revisit time constraints, and sensor saturation under high concentration oil slicks. Class imbalance between contaminated and uncontaminated observations – typically ratios of 1:5 to 1:20 in monitoring well datasets – can bias models toward predicting background concentrations and suppress sensitivity for detecting acute contamination events.

Data augmentation strategies including synthetic minority oversampling, Gaussian noise injection into sensor time-series, and physics-informed data generation from simplified transport models have been applied in several reviewed studies, with measurable improvements in minority-class recall [35]. Generative adversarial networks conditioned on hydrogeological parameters represent an emerging approach for synthetic training data generation that warrants systematic evaluation in contamination modelling contexts.

### Model interpretability and regulatory acceptance

Regulatory frameworks governing contaminated land assessment and remediation in most jurisdictions require defensible, auditable models whose predictions can be validated against site-specific conceptual site models [36]. The inherent opacity of deep learning architectures presents a significant barrier to regulatory acceptance.

SHAP (SHapley Additive exPlanations) analysis has been applied in several reviewed studies to attribute CNN-BiLSTM predictions to input features, revealing physically meaningful patterns (e.g., dominance of wind direction and precipitation in surface spill spread prediction) that enhance stakeholder confidence [37]. However, standardised interpretability protocols for deep learning-based contamination models do not yet exist, and their development represents a priority for the field.

### **Transferability and domain adaptation**

Hydrocarbon contamination characteristics vary substantially across geological settings, soil types, climate zones, and petroleum compound compositions, limiting the transferability of models trained in one context to another [38]. Most reviewed studies reported significant performance degradation when pre-trained models were applied without fine-tuning to new geographic domains: average  $R^2$  reductions of 0.08–0.21 were observed in cross-domain validation experiments. Domain adaptation techniques including adversarial training, domain-invariant feature learning, and meta-learning approaches offer promising pathways to more generalizable contamination models but have received limited systematic study in this application domain.

### **Computational infrastructure requirements**

CNN-BiLSTM models trained on large multi-site, multi-sensor datasets require substantial GPU memory and training time, which may be prohibitive for environmental monitoring agencies and agricultural engineering practitioners in resource-constrained settings [39]. Model compression through structured pruning, quantization, and knowledge distillation has demonstrated 3–8 $\times$  reduction in inference computational cost with less than 2% accuracy loss in several reviewed studies, indicating practical pathways to deployment on edge devices and low-cost field monitoring platforms.

## **CONCLUSIONS**

This review demonstrates that CNN-BiLSTM hybrid architectures represent the current state-of-the-art for data-driven modelling of hydrocarbon contamination across soil, groundwater, and surface environments. The convergence of spatial feature extraction capability (CNN) with bidirectional temporal sequence learning (BiLSTM) produces models that consistently outperform single-architecture alternatives, achieving  $R^2$  values exceeding 0.93 for concentration prediction and F1-scores above 0.94 for spill detection tasks across diverse geographic and geological settings. The architecture shows particular strength for problems requiring simultaneous characterisation of spatial contamination gradients and temporally complex plume dynamics, including seasonal fluctuations, tidal influences, and episodic recharge-driven mobilization events.

However, widespread deployment in agricultural and environmental engineering practice is currently constrained by:

1. the limited availability of labelled training datasets at the scales required for robust deep learning;

2. (the interpretability deficit relative to regulatory expectations for contaminated land assessment;
3. domain transferability limitations across geological and climatic contexts; and
4. computational infrastructure barriers in resource-constrained monitoring programmes.

Addressing these challenges requires coordinated investment in open, standardized contamination monitoring datasets; development of physics-informed neural network approaches that embed mechanistic transport equations within the CNN-BiLSTM learning process; establishment of regulatory-grade interpretability protocols; and systematic evaluation of model compression and federated learning strategies for distributed multi-site monitoring.

Integration of CNN-BiLSTM contamination models with precision agricultural management platforms – enabling targeted soil remediation, crop exclusion zone mapping, and irrigation water quality alerts – represents a particularly high-value application pathway that merits priority attention from the agricultural engineering research community.

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#### MODELIRANJE KONTAMINACIJE UGLJOVODONICIMA U POLJOPRIVREDNIM I ŽIVOTNIM SISTEMIMA PRIMENOM HIBRIDNOG DUBOKOG UČENJA CNN-BiLSTM: -PREGLEDNI RAD

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**Apstrakt.** Kontaminacija poljoprivrednog zemljišta, površinskih i podzemnih voda ugljovodonicima predstavlja jednu od najozbiljnijih pretnji životnoj sredini, bezbednosti hrane i očuvanju integriteta ekosistema, naročito u regionima u kojima se eksploatiše nafta.

Precizno i pravovremeno modeliranje raspodele zagađivača, dinamike njihovog širenja i nivoa koncentracije od ključnog je značaja za procenu rizika, planiranje remedijacije i usklađenost sa regulatornim zahtevima.

Ovaj pregledni rad kritički razmatra primenu hibridnih arhitektura konvolucionih neuronskih mreža i dvosmernih mreža sa dugoročnom i kratkoročnom memorijom (CNN–BiLSTM) za modeliranje kontaminacije ugljovodonicima u poljoprivrednim i ekološkim sistemima.

Sistematskim pretraživanjem literature za period 2015–2024. godine, identifikovano je 47 relevantnih radova iz recenziranih naučnih časopisa, zbornika konferencija i tehničkih izveštaja.

U radu se analiziraju CNN–BiLSTM (Convolutional Neural Network – Bidirectional Long Short-Term Memory) modeli sa aspekta tipova ulaznih podataka (in situ senzorske mreže, satelitski snimci daljinske detekcije, hiperspektralni podaci i geohemijski profili), arhitektonskih konfiguracija, strategija obučavanja i pokazatelja performansi.

Rezultati pokazuju da CNN–BiLSTM modeli dosledno nadmašuju samostalne CNN i LSTM modele, kao i modele zasnovane na principu potpornih vektora (SVM-Support Vector Machine) i Random Forest modele, ostvarujući prosečno poboljšanje tačnosti predviđanja 12 - 28% ( $R^2 > 0,93$ ) i smanjenje srednje kvadratne greške (RMSE-Root Mean Square Error) 18 - 35% na referentnim skupovima podataka.

Ključne prednosti CNN–BiLSTM modela ogledaju se u sposobnosti istovremenog izdvajanja prostornih karakteristika i dvosmernog učenja vremenskih sekvenci, što omogućava pouzdano predviđanje razvoja obima kontaminacije, koncentracije ukupnih naftnih ugljovodonika (TPH- Total Petroleum Hydrocarbons) u zemljištu i nivoa benzena, toluena, etilbenzena i ksilena (BTEX-Benzen, Toluene, Etilbenzen i Ksilene) u podzemnim vodama.

Takođe se razmatraju izazovi povezani sa nedostatkom podataka, mogućnošću primene modela na različitim tipovima zemljišta, interpretabilnošću rezultata i visokim računarskim zahtevima.

Na kraju rada predložena je istraživačka agenda koja ukazuje na prioritetne praznine i nedostatke u znanju, kao i perspektivne pravce budućih istraživanja, uključujući neuronske mreže zasnovane na fizičkim zakonima (Physics-Informed Neural Networks - PINNs), sa učenjem tipa Federated Learning, za praćenje (monitoring) kontaminacije na više lokaliteta i integraciju sa sistemima precizne poljoprivrede.

***Ključne reči:*** Duboko učenje, zagađenje ugljovodonicima, kontaminacija zemljišta, modeliranje vremenskih sekvenci, daljinska detekcija životne sredine, precizna poljoprivreda, BTEX, ukupni naftni ugljovodonici (TPH).

Prijavljen:

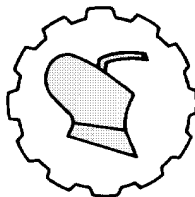
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## **THE DESIGN, FABRICATION AND EVALUATION OF A WASTE PLASTICS CRUSHING MACHINE FOR THE COMPANY'S RAW MATERIALS ACCESSIBILITY**

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**Abstract:** A low-cost variable-speed waste plastic crushing machine was designed, constructed, and tested to evaluate its efficiency and throughput. The machine consists of a hopper, a pulley, a crushing compartment with knives, and a 3 HP variable-speed electric motor. This work aimed to construct a machine that shreds waste plastic into smaller sizes at different working speeds for recycling. Also, the machine was constructed from locally available materials; therefore, its cost is very low and affordable. The machine's throughput at 900rpm, 750rpm and 600rpm was 30.57 kg/hr, 23.37 kg/hr and 21.37 kg/hr, respectively, for PVC-type waste plastic. The Specific energy consumption of the machine at 900rpm, 750rpm and 600rpm was 134.88 kJ/kg, 176.37 kJ/kg and 192.89 kJ/kg, respectively, for PVC-type waste plastic. The average particle size of the machine products at 900rpm, 750rpm and 600rpm was 2.54mm, 2.42mm and 2.21mm, respectively, for PVC waste plastic. The machine's efficiency at 900rpm, 750rpm and 600rpm was 87.45%, 88.95% and 90.24%, respectively, for PVC waste plastic. The optimal operating speed depended on the parameter considered paramount; the best crushed waste plastic, based on average size and crushing percentage, was obtained at 600rpm. Considering the throughput, the optimal result was obtained at an operating speed of 900 rpm.

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Also, considering the Specific energy consumption, the optimal result was obtained at an operating speed of 900rpm. The cost of fabricating the machine was 126,850 NGN.

**Keywords:** *Waste plastics, crushing mill, design and fabrication, engine speed, efficiency.*

## INTRODUCTION

Waste has been defined as any material of no value to the owner [15]. Waste management and disposal seem like huge tasks, given the enormous amount of waste generated. Transporting the generated waste to the dump site requires significant time and money, as the waste is clustered and not uniform in shape or size. Waste is also defined as any product or substance that has no further use or value for the person or organization that owns it, and which could or would be discarded. Also, waste is any solid, liquid or gaseous substance or material that is scrapped, refused or rejected and disposed of or required to be disposed of, as unwanted. Waste is usually in three forms: liquid, solid and gaseous. This work focuses on solid plastic waste recycling because they block sewage, contaminates the water supply, occupies the ocean floor and litters our environment [1]. A crushing machine is used to reduce large solid objects into smaller volumes or smaller pieces. Crushing machines are usually used to reduce the size and shape of materials so they can be used efficiently for their intended purpose. The crushing machine parts must have greater strength and toughness than the materials to be crushed. Crushing machines and devices work mainly by holding the material between two parallel or tangent solid surfaces, and in the process, sufficient force is applied to bring the surfaces together, generating enough energy within the material to fracture or realign its molecules [4]. Recycling is the process of treating waste materials to produce new products. Recycling helps reduce waste, consumption of new raw materials, energy use, incineration emissions, water pollution from landfills, and emissions from the production of new goods from raw materials [4]. [16], researched various plastic waste management strategies. The solution to the waste management problem was separating wet and dry solid waste. The conventional technologies for plastic waste management were land filling and incineration.

Recent technologies for plastic waste management include co-processing in cement kilns and co-processing as an alternative fuel. [15], worked on the overview of the recycling of various types of plastics. Generally, there were two types of plastics: recyclable and non-recyclable. In recyclable plastic, PET, HDPE, LDPE and PVC were used, and in non-recyclable plastic, Bakelite and Nylon were used. Sorting, cleaning, shredding, and Extrusion were the general steps involved in their paper. It also includes various plastic recycling processes, such as mechanical recycling, blast-furnace recycling, and gasification. It also involved environmental issues related to plastic disposal. [19] studied the use of PET for packaging materials. PET is widely used as a packaging material due to its low diffusion properties. It means that no contamination can be diffused into the PET. Various tests showed that PET use in food applications was not harmful to humans. PET was generally used for packaging food products, such as bottles, snack wrappers, trays and blisters.

Generally, the bottles and jars were made by injection stretch blow moulding, and the trays were made by thermoforming. In this paper, it was suggested that there was no legislation governing the use of recycled PET in food applications [14]. Research on reducing plastic waste in the Maldives through mechanical recycling was limited. The 'Male Water and Sewerage Company' (MWSC) established a scheme of mechanical recycling with the 'Buyback Scheme'. Recycled PET was used to produce new PET bottles. Injection moulding was used for pallet making, and blow moulding for bottle making. Various trials were conducted to make bottles with 15%, 25%, and 35% PET using virgin pellets. From the trials, it was shown that 15% PET is beneficial for the new PET bottle-making process. [18] researched on the utilization of waste plastic in the manufacturing of plastic-soil bricks. In mines, laterite stones were excavated. During this process, significant waste was generated from the laterite quarry. So, this quarry could be reused by using recycled plastic waste and binders. Generally, 70% recycled PET by weight of laterite quarry was used to produce bricks measuring 20×10×10 cm. [14] worked on a project involving the utilization of recycled PET in engineering materials. Waste PET was generally used as engineering materials, such as road pavements, asphalt, and building concrete. The main reason to use plastic waste in asphalt road pavements and concrete is its ability to provide a softer binder at low temperature to avoid cracking, a stiffer binder at high temperature to avoid rutting, reduced viscosity and a higher-strength binder. It also reduces material costs. [23] researched on the effect of the use of recycled LDPE, PET and HDPE in structural applications. For these, a UTM test was carried out on a specimen made from the recycled LDPE, PET and HDPE. These waste plastics were palletized by extrusion, and a sample was produced by injection moulding. 7 samples of each material were tested for tensile properties, and various mechanical properties were determined. The samples made from virgin materials were also tested, and the results were compared. From this, it was concluded that although the properties of the recycled plastic sample were reduced, it could still be effectively used as a sustainable building material. [22] researched on the use of PET bottles as a sustainable material in construction. Plastic bottles could be used instead of bricks by filling them with suitable filling materials, such as sand, fly ash and wood particles. As a result, carbon emissions from brick production decreased, and plastic bottle recycling increased. For these plastic bottles, sand, fly ash and wood particles were filled in various proportions, and a compression strength test was carried out. From the test, it was noted that a plastic bottle filled with a 2:1 mixture of fly ash and sand has a high load-sustaining capacity and could be used as a building material. [7] studied the conversion of LDPE plastic into useful liquid fuel. It has been shown that fuel derived from waste LDPE has properties similar to those of conventional fuels. The pyrolysis method converts waste LDPE into useful fuel. It involves heating crushed plastic in the absence of oxygen. The setup ranged from 100°C to 400°C. At 100°C to 250°C, we obtain 20-30% liquid fuel. At 270°C, the plastic slurry starts to vaporize, and the vapor condenses in the condenser. At up to 325°C, 40% of the liquid fuel remained. At 400°C, the process was completed. [19], presented a work on the design and the conversion of waste PET into useful liquid fuel. A simple Catalytic conversion process obtained this fuel. In this experiment, Calcium Hydroxide ( $\text{CaOH}_2$ ) was used as a catalyst. A sample was prepared with 40 g of PET waste and 80 g of catalyst. The 40-gm catalyst was placed in the boiling flask first. Then the PET waste was placed on it, and the remaining 40 gm of catalyst was placed at the last. The mixture was heated to 405°C. After 10 minutes, vapour began to form, but it did not condense immediately.

It travels to the collection flask. After 13 minutes, vapour started to condense, and drops of fuel were collected in the collection flask. After 20 minutes, the mantle temperature was reduced to 315°C, and it was heated for 15 minutes. After that, fuel generation stopped. 603 ml of fuel was produced during the process. [3] designed a mobile crusher that could be used in small and medium industries, and also by full-time homemakers, so that they could enter the recycling business. The parts of this crusher were blades, hopper, pulley, Belt and Driving Motor. For cutting blades, Stainless Steel was used as the cutting material. The blades were circular, mounted on a shaft driven by a motor via a belt. A 1 HP AC motor was used as the driving unit. From this machine, 6 bottles could be crushed at a time, with particle sizes ranging from 1 mm to 20 mm. The overall cost of manufacturing the crusher was up to RM 2000, which is equivalent to RS. 31000. [20] designed a bottle crusher with the advantage of portability. The crusher was designed directly on top of a waste bin. The plastic bottles had to be passed through three rollers. The first rollers had spikes to prevent the water bottles from slipping.

The second-level rollers were designed with numerous flat projections on their surfaces to crush bottles. The final rollers were heating rollers. They heat the crushed pieces to smooth them and to reduce their volume. A 12-volt DC motor was used as the driving motor to reduce the machine's weight. [17] designed and developed a plastic recycling machine by using Finite Element Analysis (FEA). In this study, the manually operated machine was converted to a pneumatically operated machine through appropriate design considerations. The obtained results of each component of the actual machine, which were total deformation, Equivalent stress and equivalent strain, were somewhat the same as those of the FEA results. Hence, the design is safe. The developed machine was very effective to use, with high accuracy. [2] designed a waste plastic shredding machine that could shred PET, HDPE, PVC, and PP into small pieces. The machine consists of a feeding unit, a shredding unit, a power transmission unit and a machine frame. The feeding unit was made from a 2 mm thick galvanized mild steel sheet measuring 200 mm × 550 mm. The shredding unit consists of a 50 mm-long, 30 mm-diameter mild-steel shaft and a 55 mm-long, 200 mm-diameter cylinders. Cutters were made of 12 mm mild steel attached to a shaft. These have nine teeth welded 2 mm apart. The cylinders had the same cutters, equally spaced. The power transmission unit consists of a 10 HP motor with a belt-and-pulley arrangement. [24] worked on the design considerations for an automatic can-plastic bottle crusher machine. This machine was widely used in the beverage industry and by scrap dealers to reduce the volume of new plastics produced from their raw materials, which require significant energy. Since most plastics are non-biodegradable, they often constitute a nuisance to the environment after use. To preserve our environment, we need to develop sustainable means to manage plastic waste generated by our local communities and industries, thereby making the recycling of plastics an important aspect of waste management. For the recycling process to be sustainable, it must be cost-effective (i.e., economical) and able to address the environmental problems caused by waste plastics without creating new ones, such as air, water or land pollution. Thus, an efficient recycling structure needed to be put in place to process some of these waste plastics, which were supposed to be disposed of in landfills or burned in incinerators, into useful materials. The Objective of this study is to design and fabricate a motorized waste plastic crushing machine operating under varying speeds. Secondly, to evaluate the machine's performance and identify its optimal operating speed.

## MATERIALS AND METHOD

### Materials Selection

The selection of materials is very crucial in the design and construction of any machine. Factors such as durability, machinability, availability, reliability and cost were considered in the selection process. Thus, some parts, such as the frame, hopper, knife, rotating shaft, pulleys, belt and prime mover (electric motor), used for the fabrication of the machine were selected, and their descriptions were outlined.

### Machine description and operation

The waste plastic crusher comprises three main components: the feeding unit, the crushing unit and the machine frame. The feeding unit is made from a 2mm-thick 16-gauge galvanized mild steel plate measuring 200mm by 550mm, through which waste plastics are fed into the crushing unit. The crushing unit is where the waste plastics are cut into smaller sizes. The crushing unit consists of a 750 mm-long, 25mm-diameter shaft made from mild steel. On the shaft is a crushing knife that helps cut the plastic. Crushing is achieved by converting the electric motor's rotary motion into crushing force through the crushing knives. After the crushed plastics leave the knife chamber, they pass through a mesh before exiting the delivery chute, where they are collected. Oversized materials are sent back to the machine for re-crushing. The machine is powered by a 3HP variable-speed electric motor, which is mounted with a 90mm pulley and operates at 1440rpm.

### Design considerations:

The design consideration of the waste plastic crushing machine was based on the following concepts and considerations:

- (1). The availability of materials locally reduces the cost of production and maintenance of the machine.
- (2). The ease of operation of the machine
- (3). The plastic should be well crushed, with no remaining plastic, and the crushed plastic should be properly discharged.
- (4). The waste plastic crushing machine was designed using standard components to allow easy replacement of parts during maintenance.

### Design analysis: Volumetric capacity of the machine

The effective volume  $V_c$  of the waste plastic crushing machine that the waste plastics can occupy constitutes the volume of the lower channel, where plastics from the hopper meet the crushing knives, and the volume of the hopper [3]. The machine's volume was calculated using equation (1) as  $0.0356 \text{ m}^3$ .

$$V_c = (H_L * B_L * L_L) + \left( \frac{1}{2} (L_b + L_c) * L_a * L_d \right) \quad \dots\dots\dots(1)$$

Where,

$H_L$  = Height of the hopper ;  $B_L$  = Breadth of the hopper ;

$L_L$  = Length of the hopper

$L_a$  = height of the lower chamber  $L_b$  = length of the top base of the hopper lower chamber

$L_c$  = length of the lower base of the lower chamber

$L_d$  = distance between the two trapezoidal ends

$H_L = 0.250\text{m} = 250\text{mm}$ ,  $B_L = 0.150\text{m} = 150\text{mm}$ ;  $L_L = 0.230\text{m} = 230\text{mm}$ ,  
 $L_a = 0.280\text{m} = 280\text{mm}$ ,  $L_B = 0.412\text{m} = 412\text{mm}$   
 $L_c = 0.150\text{m} = 150\text{mm}$ ,  $L_d = 0.400\text{m} = 400\text{mm}$

### Selection of pulleys and shafts: Selection of pulleys

The machine requires two pulleys. Due to their availability, cost and performance, cast iron pulleys with a groove angle of  $38^\circ$  each were selected. The maximum speed for the crushing design was assumed to be 900 rpm, since the crushing knives require a high speed to crush the plastic. The electric motor is rated at 1440 rpm, and a 90mm diameter pulley is fixed to the variable-speed electric motor shaft [5]. The diameter of the pulley attached to the crushing shaft was determined to be 144mm using equation (2).

$$VR = \frac{N_1}{N_2} = \frac{D_2}{D_1} \quad (2)$$

Where  $N_1$  and  $N_2$  represents the driving (electric motor) and driven (crushing shaft) pulleys' speed while  $D_1$  and  $D_2$  are the pulleys' respective diameters.

$C$  - The Centre distance.

The distance between the adjacent pulleys of the electric motor and the crushing shaft was determined as 207mm according to [10], as presented in eqn. (3).

$$C = \frac{D_1 + D_2}{2} + D_1 \quad (3)$$

Thus, the length of the belts,  $L$ , required for crushing the shaft drive was computed from Equation (3) as 784.9mm. Hence, type 'A' V-belts with standard pitch lengths of 823mm were selected for the motor/crushing drive, since the drive transmits less than 3.75 kW of power (IS: 2494-1974; [14]).

$$L = 2C + 1.57(D_2 + D_1) + \frac{(D_2 - D_1)^2}{4C} \quad \dots\dots\dots(4)$$

### Determination of the Shaft Diameter.

The shafts were designed to transmit the appropriate load and torque and therefore have ample strength and rigidity.

Considering availability, a mild steel shaft was used for the fabrication, the shaft diameters, The crushing shaft of this machine was determined using equation (5), which is given by

$$d = \left[ \frac{16}{\pi \tau} \sqrt{(k_b M_b)^2 + (k_t M_t)^2} \right]^{1/3} \quad (5)$$

Where:  $\tau = 42 \text{ N/mm}^2$ . The maximum twisting moment acting on the shaft,

$M_t$  = Maximum Twisting Moment on the shafts, Nmm,

$M_b$  = Maximum Bending Moment on the shafts, Nmm,

$K_b$  = Combined shock and fatigue factor for bending, the allowable shear stress for a steel shaft with provision for keyway,  $\tau$  is given as  $42 \text{ N/mm}^2$  [16], while the respective maximum twisting moment on the crushing shaft,

$M_t$  was determined as 11,039 Nmm using this equation (6)

$$M_t = (T_i - T_j) \frac{D_2}{2} \quad (6)$$

The speed of the belt,  $v$ . The speed of the electric motor/crushing shaft drive was determined as 6.79 m/s using the relation given in Equation (7) according to [17], as in eqn. (7).

$$v = \frac{\pi D_2 N_2}{60} \quad (7)$$

Tensions are on the tight side,  $T_i$  The torque of the belt of the electric motor/crushing shaft was determined as 165.12 N using Equations (8, 9 and 10) [20]. The mass of the belt per meter length,  $m$ , coefficient of friction,  $\mu$ , between the pulleys and the belt, maximum safe stress,  $\sigma$ , and cross-sectional area,  $a$ . Some of the belts were also obtained from standard tables, IS: 2494-1974, as 0.108 kg/m, 0.3, 2.1 N/mm<sup>2</sup>, and 81 mm<sup>2</sup>, respectively [1,2,3]. Also, due to availability, cost and performance, cast iron pulleys with groove angle ( $2\beta$ ) A temperature of 38° was selected for the drive.

$$T_i = T_{max} - T_c \quad \dots \quad (8)$$

$$T_{max} = \sigma \times a \quad \dots \quad (9)$$

$$T_c = mv^2 \quad \dots \quad (10)$$

Subsequently, the respective belts' slack side tensions,

$T_j$  were determined as 11.80 N using equation (11) (Khurmi & Gupta, 2005)

$$2.3 \log \frac{T_i}{T_j} = \mu \theta \operatorname{cosec} \beta \quad \dots \quad (11)$$

Where;  $T_{max}$  = Maximum tension on the belts,

$T_c$  = The centrifugal tension on the belts and the belt lap angle ( $\Theta$ ) at the small pulley of the drive were computed from Equation (12) as 164.2° (2.86 rad).

$$\theta = 180 - 2 \left[ \sin^{-1} \left( \frac{D_2 - D_1}{2C} \right) \right] \quad (\text{Khurmi and Gupta, 2010}) \quad (12)$$

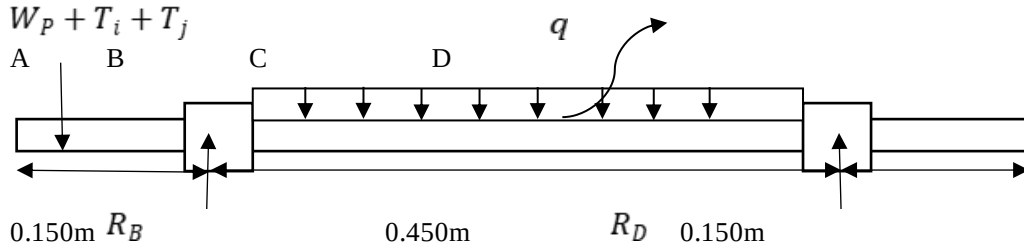
**Determination of the shaft's bending moments**

Fig. 1. Showing the free-body diagram of the crushing shaft

Where,

$W_P$  = weight of the crushing shaft pulley = 14.76N,

$q$  = uniformly acting weight of the knife crushing compartment = 103N,

$T_i$  = Tension at the tight side of the crushing drive = 165.21N,

$T_j$  = Tension at the slack side of the crushing drive = 11.80N,

Total force at the point A =  $W_P + T_i + T_j$  = 191.68N,

Total force at the point C (midpoint between point B and point D) = 23.175N ,

The reactions of bearing  $R_B$  and  $R_D$  were determined by taking the moment about B.

$$\sum M_B = 0;$$

$$23.175 \times 0.225 = 0.450R_D + 191.68 \times 0.150 \quad \text{.....(13)}$$

$$5.214375 = 0.450R_D + 28.752 \quad \text{.....(14)}$$

$$R_D = -52.31N$$

$$\text{Also } \sum F_y = 0 \quad \text{.....(15)}$$

$$R_B - 52.31 = 191.68 + 23.175 \quad \text{.....(16)}$$

$$R_B - 52.31 = 214.855; R_B = 267.165N \quad \text{.....(17)}$$

Taking downward forces to be negative (-) and upward forces to be positive (+), the shear forces acting on this shaft were computed as follows:

$$F_{A-B} = -191.68N \quad F_{B-C} = -191.68 + 267.166 = 75.486N$$

$$F_{C-D} = -191.68 + 267.166 - 23.175 = -52.31N$$

$$F_{D-E} = -191.68 + 267.166 - 23.175 + (-52.31) = 0N$$

Thus, the bending moments on this shaft are calculated as follows.

$$M_A = 0Nm \quad M_B = -28.752Nm \quad M_C = -13.0717Nm \quad M_D = 0Nm \quad M_E = 0Nm$$

Thus, the maximum bending moment on the crushing unit shaft is 28.752 N · m (28,752N · mm). The maximum twisting moment of the shaft is 11,039Nmm from equation (5). Since the feeding of the plastic is gradual and steady,  $K_b = 1.5$ ,  $K_t = 1.0$  [13,24].

The shaft diameter was determined using equation (4) as 17.54mm. Therefore, a standard 25mm diameter solid mild steel shaft was selected for the crushing unit.

#### Selection of the prime mover (electric motor)

The power required for the operation of this machine, according to [19,20,21], was determined from the equation (18).

$$P = (T_i - T_j)V \quad \dots\dots(18)$$

Where  $T_i$  = Tension on the tight side of the belt drive

$T_j$  = Tension on the slack side of the belt drive

$V$  = Speed of the belt drive.

Therefore, the required power was found to be 1041.04W. Considering a 10% power loss due to friction, the theoretical power required to drive the developed waste plastic crushing machine is 1145.14 W. Therefore, a 3HP variable-speed electric motor was used for this machine.

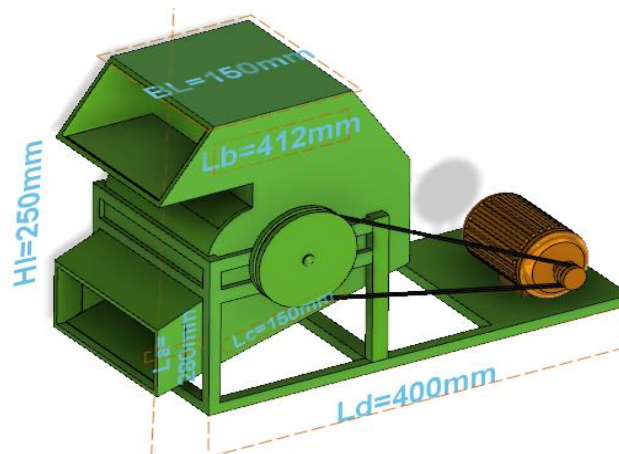


Fig. 2. Diagram of a 3hp waste plastics crushing machine

### Experimental procedure used for testing the machine

The experiment was conducted using four different plastic types, each of mass 1Kg, and was crushed at three different speeds. The different plastic types used were polyethylene terephthalate (PET), high-density polyethylene (HDPE), polyvinyl chloride (PVC) and polypropylene (PP). The speed of operation was measured with a tachometer and recorded. The waste plastic was crushed, and the crushing time for each plastic type was measured with a stopwatch. The crushed waste plastic was weighed with a weighing balance and recorded. After crushing, the waste plastic was sieved into three size fractions to determine the average particle size and area.

The efficiency of the machine was computed using equation (19) below, the throughput of the machine was also computed using equation (20) below, and the specific energy consumption of the machine was computed using equation (21) below.

$$\text{Efficiency (crushing percentage)} = \frac{\text{mass of crushed plastic}}{\text{mass of loaded plastic}} \times \frac{100}{1} \quad (19)$$

$$\text{Throughput} = \frac{\text{mass of crushed plastic}}{\text{time of crushing of loaded plastic}} \quad (20)$$

$$\text{Specific energy consumption} = \frac{\text{power of operation of the machine} \times \text{crushing time}}{\text{mass of crushed plastic}} \quad (21)$$

## RESULT AND DISCUSSION

The results from the experiment for the four types of waste plastic at different speeds are shown in Tables 4.1, 4.2, and 4.3.

Table 1. Results of crushed plastic at an operating speed of 900 rpm

|               | PET             |                      | HDPE              |                      | PVC               |                      | PP                |                      |
|---------------|-----------------|----------------------|-------------------|----------------------|-------------------|----------------------|-------------------|----------------------|
| No of sieving | Aver. size (mm) | Crushed percent. (%) | Average size (mm) | Crushed percent. (%) | Average size (mm) | Crushed percent. (%) | Average size (mm) | Crushed percent. (%) |
| 1st           | 1.21            | 41.43                | 0.82              | 52.42                | 0.42              | 43.24                | 1.32              | 45.33                |
| 2nd           | 3.22            | 52.21                | 2.98              | 61.43                | 1.48              | 64.45                | 3.23              | 63.32                |
| 3rd           | 4.78            | 63.33                | 4.34              | 75.43                | 2.54              | 87.45                | 5.45              | 78.43                |

At the operating speed of 900 rpm reported in Table 1, the machine was found to operate optimally when crushing PVC-type waste plastic, with an average particle size of 2.54 mm and a crushing percentage of 87.45%. Since it takes the machine 103 seconds to crush the waste plastic with an efficiency of 87.45%, the throughput was computed as 30.57 kg/hr from equation (15). Also, the Specific energy consumption was computed as 134.88 kJ/kg from equation (16).

Table 2. Results of crushed plastic at an operating speed of 750 rpm.

|               | PET             |                      | HDPE              |                      | PVC               |                      | PP                |                      |
|---------------|-----------------|----------------------|-------------------|----------------------|-------------------|----------------------|-------------------|----------------------|
| No of sieving | Aver. size (mm) | Crushed percent. (%) | Average size (mm) | Crushed percent. (%) | Average size (mm) | Crushed percent. (%) | Average size (mm) | Crushed percent. (%) |
| 1st           | 0.77            | 42.43                | 0.72              | 47.73                | 0.31              | 51.45                | 1.04              | 54.25                |
| 2nd           | 3.43            | 54.21                | 2.48              | 63.89                | 1.77              | 69.45                | 3.03              | 67.54                |
| 3rd           | 3.75            | 75.33                | 4.04              | 79.78                | 2.42              | 88.95                | 4.32              | 85.23                |

At the operating speed of 750 rpm reported in Table 2, the machine was found to operate optimally when crushing PVC-type waste plastic, with an average particle size of 2.42 mm and a crushing percentage of 88.95%. Since it takes the machine 137 seconds to crush the waste plastic with an efficiency of 88.95%, the throughput was computed as 23.37 kg/hr using equation (15). Also, the Specific energy consumption was 176.37 kJ/kg computed from equation (16).

Table 3. Results of crushed plastic at an operating speed of 600 rpm

|               | PET             |                      | HDPE              |                      | PVC               |                      | PP                |                      |
|---------------|-----------------|----------------------|-------------------|----------------------|-------------------|----------------------|-------------------|----------------------|
| No of sieving | Aver. size (mm) | Crushed percent. (%) | Average size (mm) | Crushed percent. (%) | Average size (mm) | Crushed percent. (%) | Average size (mm) | Crushed percent. (%) |
| 1st           | 0.48            | 52.72                | 0.72              | 43.35                | 0.42              | 58.54                | 1.12              | 56.43                |
| 2nd           | 2.14            | 58.45                | 2.67              | 71.32                | 1.48              | 70.23                | 3.07              | 73.45                |
| 3rd           | 3.57            | 85.73                | 3.44              | 85.32                | 2.21              | 90.24                | 4.09              | 88.45                |

At the operating speed of 600 rpm from Table 4.3, it was deduced that the machine operated optimally when crushing PVC-type waste plastic, with an average particle size of 2.21mm and a crushing percentage of 90.24%. Since it takes the machine 152 seconds to crush the waste plastic with an efficiency of 90.24%, the throughput was computed as 21.37 kg/hr from equation (15).

Also, the Specific energy consumption was 192.89 kJ/kg computed from equation (16).

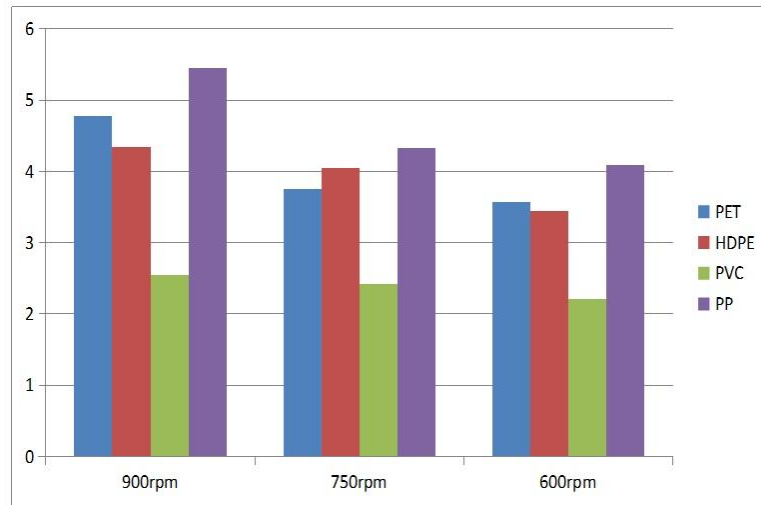


Fig. 3. Average size comparison of the four different waste plastic performances using the three speeds.

Fig. 3 revealed that PP waste plastics had the largest average size at 900rpm, higher than PET, HDPE and PVC at 750 rpm and 600 rpm, respectively.

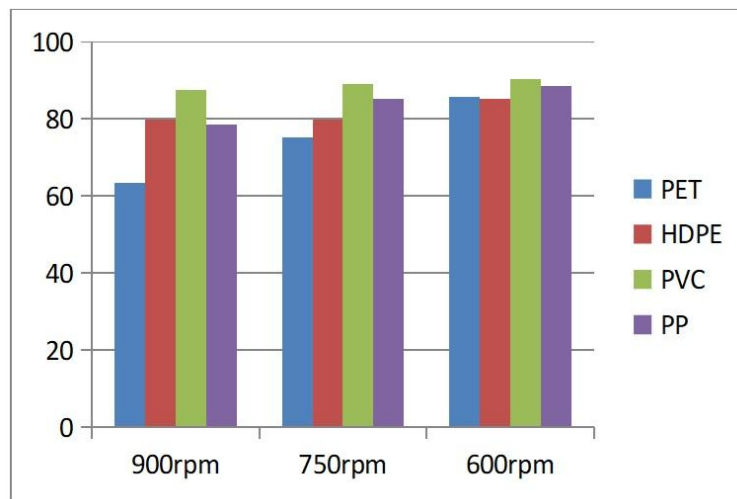


Fig 4. Crushing percentage comparison of the four different waste plastic performances using the three speeds

Fig. 4 showed that PVC waste plastics recorded the highest crushing percentage at 600 rpm, exceeding those of PET, HDPE and PP at 900 rpm and 750 rpm, respectively.

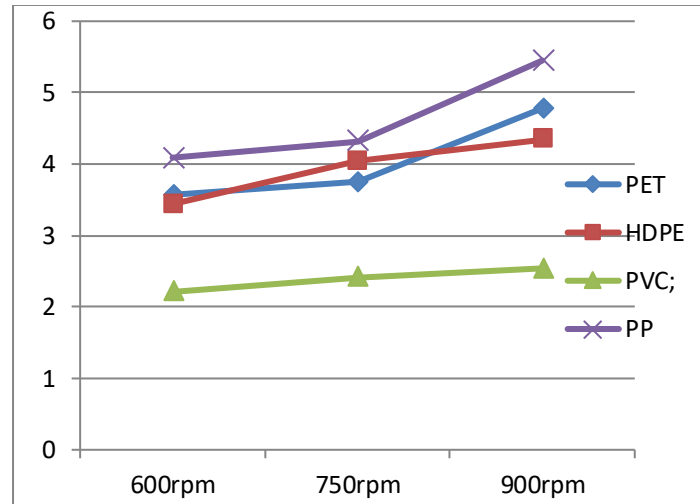


Fig 5. Average size comparison of the four different waste plastic performances showing variation as the speed increases

From Figure 5, it was observed that the four types of waste plastic exhibit the same relationship between average size and operating speed; all average sizes increase as the operating speed increases.

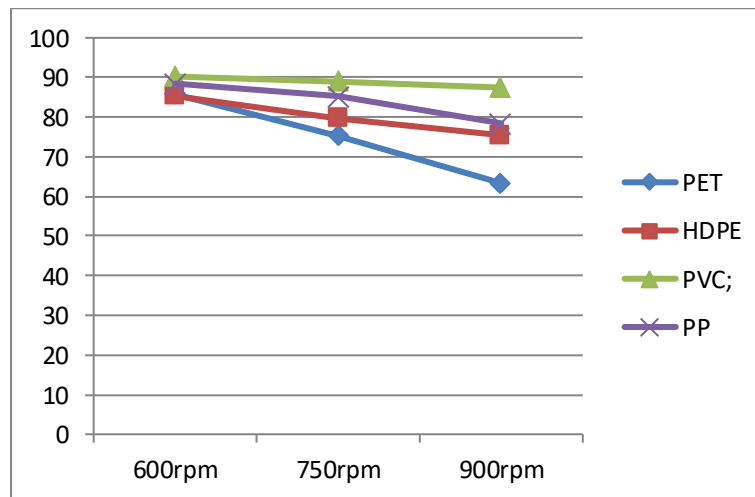


Fig. 6. Crushing percentage comparison of the four different waste plastic performances showing variation as the speed increases

Also, from Figure 6, it was observed that the four types of waste plastic exhibit the same relationship between crushing percentage and operating speed; all crushing percentages decrease as the operating speed increases. Therefore, the best operating speed depends on the parameter considered paramount. The best crushed waste plastic, in terms of average size and crushing percentage, was obtained at an operating speed of 600 rpm. Considering throughput, the optimal result was obtained at 900 rpm; considering specific energy consumption, the optimal result was also achieved at 900 rpm.

### CONCLUSIONS

There was a direct relationship between the average size of the four types of waste plastic and both the crushing percentage and the operating speed. The average size of the four types of waste plastic increases with increasing operating speed. Also, the crushing percentage of the four different types of waste plastic decreases as the operating speed increases. The machine's throughput at 900rpm, 750rpm, and 600rpm is 30.57 kg/hr, 23.37 kg/hr, and 21.37 kg/hr, respectively, for PVC waste plastic.

The Specific energy consumption of the machine at 900 rpm, 750 rpm and 600 rpm is 134.88 kJ/kg, 176.37 kJ/kg and 192.89 kJ/kg, respectively, for PVC-type waste plastic. The average particle size of the machine products at 900rpm, 750rpm and 600rpm is 2.54mm, 2.42mm and 2.21mm, respectively, for PVC-type waste plastic. The machine's efficiency at 900rpm, 750rpm and 600rpm is 87.45%, 88.95% and 90.24%, respectively, for PVC waste plastic.

The optimal operating speed depends on the parameter considered paramount. The best crushed waste plastic, in terms of average size and crushing percentage, was obtained at an operating speed of 600rpm. Considering throughput, the optimal result was obtained at an operating speed of 900rpm; considering specific energy consumption, the optimal result was also obtained at 900rpm.

### RECOMMENDATIONS

This plastic waste recycling machine should be adopted and commercialized to increase the availability of raw materials for industries, enhancing productivity, and the federal government should investigate waste plastic recycling as an energy source as an alternative to fossil fuels.

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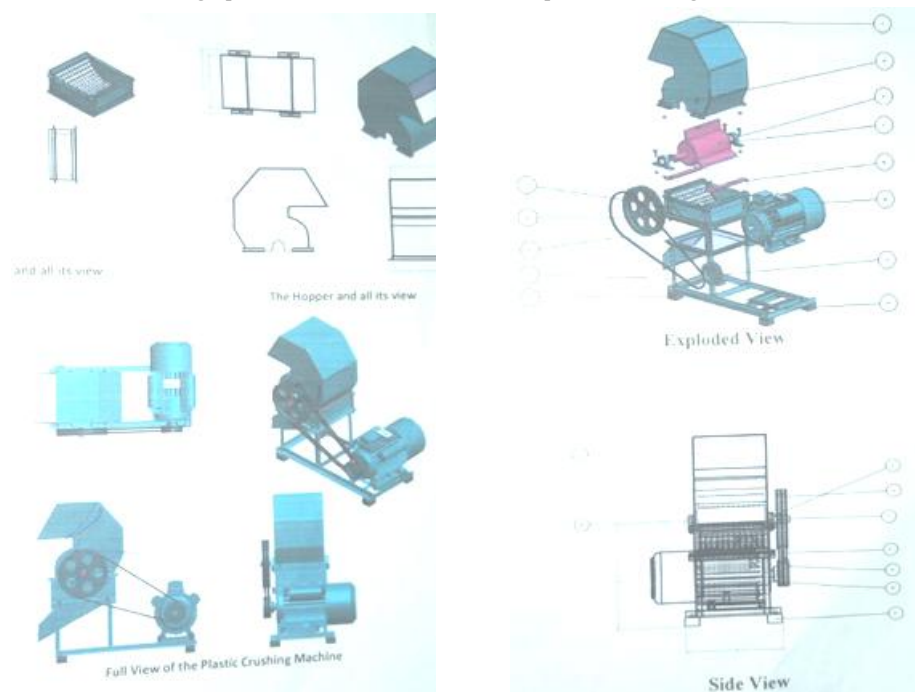
**APPENDIX A**

Table 4. Engineering cost expenditures of the waste plastics crushing mill.

| S/N | DESCRIPTION                   | SIZE                | QUANTITY            | AMOUNT(NGN) |
|-----|-------------------------------|---------------------|---------------------|-------------|
| 1   | Variable speed Electric motor | 3HP, 3phase         | 1                   | 50,000      |
| 2   | Drilling bit                  | 5mm                 | 2                   | 800         |
| 3   | Rivets                        | M6(13mm)            | 1                   | 300         |
| 4   | Bolt and nut                  | M10, M12            | 13, 12 respectively | 750         |
| 5   | Electrode                     |                     | 1 packet            | 1,550       |
| 6   | Cutting disc                  | 9"                  | 2                   | 1,800       |
| 7   | Grinding disc                 | 7"                  | 1                   | 1,300       |
| 8   | Pointing /screen oxide        |                     | 1tnk                | 3,100       |
| 9   | Flange bearing carrier        | 4mm thick plate 8." | 1                   | 2,100       |
| 10  | Cellulose                     |                     |                     | 2,300       |
| 11  | Oil paint and brush           |                     | 1 tin               | 4,500       |
| 12  | Anti-rust paint and brush     |                     | 1tin                | 2,200       |
| 13  | Metal sheets                  |                     | 2                   | 11,500      |
| 14  | Angle bar                     |                     | 3                   | 7,500       |
| 15  | Pulley (driven and driving)   |                     | 2                   | 800         |
| 16  | Belt drive                    | v-belt              | 1                   | 1,200       |
| 17  | Shaft                         | 25mm diameter       | 1                   | 1,300       |
| 18  | Bearing                       |                     | 2                   | 1,000       |
| 19  | Damping rubber                |                     | 4                   | 1,400       |
| 20  | Balancing weight              |                     | 1                   | 450         |
| 21  | Screen                        |                     | 1                   | 1,000       |
| 22  | Labour cost and miscellaneous |                     |                     | 30,000      |
|     | TOTAL                         |                     |                     | 126,850 NGN |

## APPENDICES B

Orthographic or multi-view of the waste plastic crushing mill machine



### PROJEKTOVANJE, IZRADA I ISPITIVANJE MAŠINE ZA USITNJAVANJE OTPADNE PLASTIKE, ZBOG OBEZBEĐENJA SIROVINSKE OSNOVE PREDUZEĆA

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**Abstrakt:** Projektovana je, izrađena i eksperimentalno ispitana niskobudžetna mašina sa promenljivom brzinom obrtanja za usitnjavanje otpadne plastike, kako bi se procenili njen stepen efikasnosti i kapacitet rada.

Mašina se sastoji od levka za prihvatanje materijala, remenice, komore za usitnjavanje sa noževima i elektromotora promenljivog broja obrtaja, snage 3 KS (HP).

Cilj istraživanja bio je razvoj mašine koja može da usitnjava otpadnu plastiku na manje čestice pri različitim brzinama rada, radi njene dalje reciklaže. Mašina je izrađena od lokalno dostupnih materijala, zbog čega su troškovi proizvodnje niski i prihvatljivi. Kapacitet mašine pri brzinama od 900, 750 i 600rpm iznosio je 30,57 kg/h, 23,37 kg/h i 21,37 kg/h, respektivno, pri usitnjavanju otpadne plastike tipa PVC.

Specifična potrošnja energije pri istim brzinama iznosila je 134,88 kJ/kg, 176,37 kJ/kg i 192,89 kJ/Kg, respektivno.

Prosečna veličina dobijenih čestica pri brzinama od 900, 750 i 600 rpm iznosila je 2,54 mm, 2,42 mm i 2,21 mm, respektivno.

Efikasnost rada mašine pri navedenim brzinama bila je 87,45 %, 88,95 % i 90,24 %, respektivno.

Optimalna radna brzina zavisi od kriterijuma koji se smatra najvažnijim. Sa aspekta prosečne veličine čestica i procenta usitnjavanja, najbolji rezultati postignuti su pri brzini od 600rpm elektro motora.

Posmatrano prema kapacitetu rada, optimalni rezultati ostvareni su pri brzini od 900 rpm.

Takođe, sa aspekta specifične potrošnje energije, najpovoljniji rezultat postignut je pri brzini od 900 rpm.

Troškovi izrade mašine iznosili su 126.850 NGN (nigerijskih naira).

***Ključne reči:*** Otpadna plastika, mlin za usitnjavanje, projektovanje i izrada, brzina obrtanja, efikasnost.

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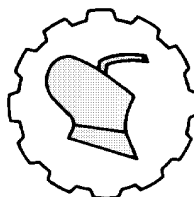
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## **EVALUATION OF THE PHYSICO-MECHANICAL/CHEMICAL PROPERTIES OF CORNCOB-GROUNDNUT SHELL HYBRID COMPOSITE**

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**Abstract.** This study investigates the development and characterization of sustainable hybrid bio composites reinforced with groundnut shell (GNS) and corncob (CC) particulates in an unsaturated polyester resin (UPR) matrix. Lignocellulosic analysis revealed that GNS contains a high cellulose content (61.537%), while CC exhibits higher hemicellulose (36.434%) and oil content (8.489%), influencing mechanical strength and moisture behavior. Water absorption tests showed a progressive increase with time, with values ranging from 0.338–0.474 wt.% for 100% GNS composites and up to 1.326–1.987 wt.% for 100% CC composites after 5 hours, confirming higher hydrophilicity of CC-rich composites. Mechanical evaluation indicated an ultimate tensile strength of approximately 59 MPa, a Tensile's modulus of 7.9 GPa, and strain at break of 0.892%, demonstrating good stiffness but limited ductility. BET analysis showed a high surface area of 266.971 m<sup>2</sup>/g with a strong correlation coefficient ( $r = 0.99297$ ), indicating significant porosity and adsorption potential. SEM analysis confirmed uniform particle dispersion with localized porosity, while EDX revealed dominant silicon content (57.0%) alongside carbon (19.5%) and oxygen (10%). FTIR spectra identified key functional groups at 665.3, 1718.3, 2871.9, and 3347.1 cm<sup>-1</sup>, indicating the presence of silicate, carbonyl, alkyl, and hydroxyl groups.

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The novelty of this study lies in the hybridization of CC and GNS to achieve tunable moisture and mechanical properties. The results demonstrate the potential of agro-waste composites for sustainable structural and functional applications.

**Key words:** *Corn cob, groundnut shell, hybrid, composite, water absorption*

## INTRODUCTION

Sustainability concerns, fossil resource depletion, and increased agricultural waste generation have intensified scientific interest in biodegradable and renewable materials for engineering applications [1].

Biomass-derived residues offer compelling substitutes for synthetic composite reinforcements due to their biodegradability, low cost, carbon neutrality, and reduced environmental footprint [2, 3]. Recent advancements in polymer bio-composites demonstrate that natural fillers can enhance specific mechanical and physical properties while promoting resource efficiency and a circular economy model [4, 5].

Agricultural residues such as corncob (CC) and groundnut shells (GNS) are widely available in developing regions, yet remain significantly underutilized [6, 7, 8, 9]. Conventional disposal through landfilling, open burning, or indiscriminate dumping contributes to environmental degradation and public health concerns [10]. Valorizing these residues into polymer composites provides an avenue for waste management and sustainable materials development [11, 12]. Corncob, a lignocellulosic by-product of maize cultivation, contains substantial cellulose fractions suitable for improving stiffness, toughness, and dimensional stability in polymer matrices [13]. Previous studies have demonstrated improvements in impact performance, toughness, thermal behavior, and weight reduction when corncob particulates are incorporated into epoxy and polypropylene composites at controlled particle sizes and loadings. Karchi et al. [6] developed sustainable epoxy composites using corncob cellulose as a reinforcement material. Kumar and Saha [13] studied the effects of particle size on structural, physical, mechanical and tribology behavior of corn cob filler-based epoxy biocomposites.

Groundnut shells also exhibit valuable lignocellulosic structures and have been integrated into natural and synthetic polymer matrices for low-cost packaging, insulation, and structural components [8, 14]. Their relatively high lignin content supports mechanical reinforcement and thermal stability, while the abundance of hydroxyl functional groups promotes interfacial interactions with epoxy systems [9, 15]. Studies exploring GNS-based composites have shown improvements in hardness, stiffness, and microstructural uniformity when used as fillers or hybrid modifiers, such as Soni et al. [16] who successfully evaluated the mechanical properties of sisal fiber and groundnut shell particulate reinforced hybrid epoxy composites. However, single-filler systems seldom provide balanced mechanical performance; instead, hybridization strategies allow engineers to tailor composite response by exploiting potential synergistic effects between multiple natural fillers.

Hybrid bio-composites represent an emerging direction in sustainable material design, wherein two or more particulate or fiber reinforcements are dispersed within a matrix to achieve optimized and multifunctional behavior [17]. Hybridization of lignocellulosic fillers can potentially enhance impact strength, stiffness, thermal stability, and weight reduction while reducing production cost relative to synthetic fiber composites [18].

Epoxy resin remains a suitable matrix for natural hybrid fillers due to its dimensional stability, strong adhesion potential, chemical resistance, and compatibility with particulate reinforcement [19].

Ramu et al. [20] studied the physic mechanical properties of Bamboo Fiber/Groundnut Shell Epoxy Hybrid Polymer Nanocomposites. Annamalai [21] studied woven ramie fibre epoxy composite with silane-treated groundnut shell powder as a filler. Merinto and Miraculas [11] developed fiberglass-reinforced hybrid epoxy composites with pineapple fiber and corn cob-derived bio silica and evaluated the performance analysis.

Despite promising developments, significant research gaps persist regarding the combined reinforcement of epoxy matrices using hybrid CC/GNS particulates. Addressing these knowledge gaps is crucial for advancing biomass-derived fillers as credible substitutes for synthetic reinforcing agents in automotive interiors, packaging materials, building components, consumer goods, and related sectors. Furthermore, systematic characterization of hybrid CC/GNS epoxy composites offers insights into how agro-waste valorization strategies can be integrated into circular economy frameworks in regions where agricultural residues are abundant and waste management infrastructure is limited.

The present study investigates the mechanical and physical performance of hybrid corncob and groundnut shell reinforced epoxy composites. Hybrid composites were fabricated using defined filler ratios and particle sizes, and subsequently evaluated in terms of tensile strength, flexural behavior, hardness, impact resistance, density, thermal characteristics, and water absorption. Particular emphasis was placed on assessing filler-matrix compatibility, hybrid synergies, and property trade-offs associated with natural particulate reinforcement. The aim of the study is to determine the suitability of corncob-groundnut shell hybrid particulate fillers for enhancing epoxy composite performance and promoting sustainable materials development. Specifically, the study seeks to (i) characterize the physical properties of CC and GNS particulates; (ii) evaluate mechanical and physical responses of epoxy composites at varying hybrid filler loadings; and (iii) establish structure-property relationships that inform future bio-composite material design.

## **MATERIAL AND METHODS**

### **Materials and Equipment's**

Unsaturated polyester resin (UPR) and methyl ethyl ketone peroxide (MEKP) manufactured by ebenCHEM Germany were bought from Galaxy Interiors and Epoxy venture, Abuja. Groundnut shell and corn cob were purchased from local traders in Umuahia. All the reagents and glass wares used were purchased from General Sales Organization, Chemical, Enugu, Enugu State. Fourier infrared spectrometer (Bruker Alpha I, U.S.A.), SEM/EDX machine (Hitachi TM-400) and Universal testing machine manufactured by Wincom, PR China.

## Methods

### Biomass Materials Preparation

Biomass materials used as composite were air dried for one week. The dried materials were crushed using milling machine.

The crushed or grinded samples were sieved using sieve size of 250  $\mu\text{m}$ . This is to obtain uniform size samples with enhanced surface area. Figures 1a and 1b and 2a and 2b show the raw, grounded corn cob, raw groundnut shell and grounded groundnut shell.



Fig. 1a. Corncob



Fig. 1b. Ground Corncob



Fig. 2a. Groundnut Shell



Fig. 2b. Ground Groundnut Shell

### Lignocellulose Characterization of Biomass

Groundnut shell and corn cob were characterized for lignocellulose properties. Lignocellulose characterization was done according to the method of Diaz *et al.*, (2013).

**Sample de-fating (extractives):** A 200 g sample was accurately weighed using an analytical balance and transferred into a 1000 mL flat-bottom flask. A sufficient volume of n-hexane was added to completely immerse the sample, followed by vigorous agitation to ensure proper solvent penetration. The flask was sealed with aluminum foil and reinforced with masking tape to minimize solvent loss and contamination. The mixture was allowed to stand for 48 h to achieve exhaustive lipid extraction. Thereafter, the n-hexane containing dissolved oil was carefully decanted, and the defatted sample was air-dried at ambient temperature. The fat content was calculated using Equation (1):

$$\text{Fat \%} = [(\text{Initial wt. of sample} - \text{Final wt. of sample}) / \text{Initial wt. of sample}] \times 100 \quad (1)$$

**Bleaching (lignin removal):** The defatted sample was transferred into a three-neck round-bottom flask, and 500 mL of 7.5% (w/v) aqueous hydrogen peroxide ( $\text{H}_2\text{O}_2$ ) solution was added. A reflux condenser was fitted to the central neck, and the system was heated at 90 °C for 2 h to facilitate lignin removal. Continuous cooling water was circulated through the condenser jacket to prevent solvent loss. After refluxing, the mixture was cooled, filtered under vacuum, and washed thoroughly with hot distilled water to neutralize residual chemicals. The sample was then air-dried. The lignin content was determined using Equation (2):

$$\text{Lignin \%} = [(\text{Initial wt. from lignin removal} - \text{Final wt.}) / \text{Initial wt.}] \times 100 \quad (2)$$

**Sodium hydroxide treatment (hemicellulose removal):** The bleached sample was treated with 500 mL of 18% sodium hydroxide (NaOH) solution in a flat-bottom flask and stirred at room temperature for 30 min. The flask was covered with aluminum foil to prevent contamination. The mixture was subsequently filtered under vacuum and washed with 500 mL of 20% acetic acid solution in hot water to neutralize residual alkali. Further washing with hot distilled water was carried out until a neutral pH was confirmed using a pH meter. The residue was then dried at ambient conditions. Hemicellulose content was determined using Equation (3):

$$\text{Hemicellulose \%} = [(\text{Initial wt.} - \text{Final wt.}) / \text{Initial wt.}] \times 100 \quad (3)$$

**Total ash and cellulose:** A clean, dry porcelain crucible ( $w_1$ ) was weighed, after which 2 g of the sample ( $w_2$ ) was introduced. The crucible was heated in a furnace at 600 °C for 3 h to ensure complete combustion of organic matter. It was then cooled in a desiccator and reweighed ( $w_3$ ). Ash content was calculated using Equation (4), while cellulose content was obtained by difference using Equation (5):

$$\text{Ash \%} = [(\text{Sample weight } w_2 - \text{Weight loss } w_2) / w_2] \times 100 \quad (4)$$

$$\text{Cellulose \%} = 100 - (\text{Fat} + \text{Lignin} + \text{Hemicellulose} + \text{Ash}) \quad (5)$$

### Composite Formulation

Corncob (CC) and groundnut shell (GNS) particulates with an average particle size of 250  $\mu\text{m}$  were used as reinforcing phases, while unsaturated polyester resin served as the matrix material. The required proportions of reinforcement and matrix, as specified in the experimental design (Tab. 1), were measured and mixed thoroughly in a 500 mL beaker to ensure uniform dispersion. Following homogenization, 5 wt.% of methyl ethyl ketone peroxide (MEKP) was added as a curing agent (hardener), and the mixture was further stirred to initiate crosslinking. Composite fabrication was carried out using the hand lay-up technique [2]. The mixture was poured into glass molds and allowed to cure at room temperature ( $\approx 30^\circ\text{C}$ ). The molded composites were left undisturbed in a fume hood for 24 h to ensure complete curing and volatilization of residual compounds. Subsequently, the cured composites were demolded and wrapped in polyethylene bags for storage and further characterization. The process flow diagram of the composite fabrication is presented in Fig. 3.

Tab.1. Composite formulation

| S/N | Groundnut (wt.%) | Corn cob (wt.%) | UPR (wt.%) | MEKP (wt.%) |
|-----|------------------|-----------------|------------|-------------|
| 1   | 25.00            | 0               | 70.00      | 5           |
| 2   | 22.50            | 2.50            | 70.00      | 5           |
| 3   | 20.00            | 5.00            | 70.00      | 5           |
| 4   | 17.50            | 7.50            | 70.00      | 5           |
| 5   | 15.00            | 10.00           | 70.00      | 5           |
| 6   | 12.50            | 12.50           | 70.00      | 5           |
| 7   | 10.00            | 15.00           | 70.00      | 5           |
| 8   | 7.50             | 17.50           | 70.00      | 5           |
| 9   | 5.00             | 20.00           | 70.00      | 5           |
| 10  | 2.50             | 22.50           | 70.00      | 5           |
| 11  | 0.00             | 25.00           | 70.00      | 5           |



Fig. 3. Flowchart of Developed Composite (Groundnut shell and Corncob)

### Water Uptake Test

The composites were cut to a small dimension ( $10 \times 2 \times 0.2$  cm) for the water uptake test. The composite samples were submerged in a beaker holding 1000 mL of distilled water at room temperature for various periods (1 h, 2 h, 3 h, 4 h and 5 h). Samples were removed from the beaker, and the water uptake of the composites was calculated using the initial and final weights. The water uptake was determined by applying Equation (6):

$$\text{Water uptake \%} = [(\text{Final weight} - \text{Initial weight}) / \text{Initial weight}] \times 100 \quad \dots\dots (6)$$

### Characterization of the Composite

The sample was characterized for the presence of functional groups using Fourier Transform Infrared Spectrometry. Surface morphology and elemental analysis was done using scanning electron microscopy and energy dispersive X-ray spectroscopy. Tensile strength, tensile modulus and hardness were analyzed using universal testing machine.

### Hardness Test

The reference standard for this test method is ASTM E92. Hardness of a material is its capacity to resist indentation. This test method is applicable to metals and uses a test force between 1 gf to 120 kgf. For accurate test results, the hardness reading has to be taken on a flat specimen.

To prepare the metal sample for analysis, the surface of the sample is initially polished using diamond paste. The sample is cleaned between stages to prevent contamination.

For the sample testing, the diamond indenter is brought into contact perpendicular to the sample and the force (f) is applied. The time for the initial application of the force to the full test force should not be more than 10 seconds. The full test force should be applied for 10 to 15 seconds. The length of the 2 diagonals of indentation are measured and the mean diagonal length is calculated. Hardness is calculated using Equations (7) and (8):

$$HV = \text{Test Force} / \text{Surface Area} = F(\text{kgf}) / A(\text{mm}^2) \quad \dots\dots\dots (7)$$

$$HV = 1.8544 \times F(\text{kgf}) / d^2(\text{mm}^2) \quad \dots\dots\dots (8)$$

### **Tensile Strength Determination**

Tensile strength testing follows ASTM A370-21 standards for steel products. The sample's longitudinal direction is verified, then cut (~200 mm × 50 mm) and milled to achieve the required gauge length, fillet radius ( $\geq 13$  mm), and gripping sections ( $\geq 50$  mm). Testing is performed using a controlled rate, initially linear per Hooke's law, with stress proportional to strain. Yield strength is determined via the 0.2% offset method, after which the extensometer is removed. Strain hardening and necking occur until failure. Tensile strength is calculated as maximum load divided by cross-sectional area. Elongation and percentage reduction in area quantify ductility.

## **RESULTS AND DISCUSSION**

This section presents the results of the composite material characterization, including Lignocellulose characterization, Water Uptake, Tensile strength, Fourier Transform Infrared Spectroscopy (FTIR), Scanning Electron Microscopy (SEM) and Brunauer-Emmett-Teller (BET) analysis.

### **Lignocellulose Characterization Results**

The lignocellulose characterization results for corncob and groundnut shell are presented in Tab. 2.

Tab.2. Lignocellulose characterization of corncob and groundnut shell

| Sample          | Moisture (%) | Lignin (%) | Hemicellulose (%) | Ash (%) | Oil (%) | Cellulose (%) |
|-----------------|--------------|------------|-------------------|---------|---------|---------------|
| Corn cob        | 3.461        | 19.189     | 36.434            | 1.642   | 8.489   | 30.785        |
| Groundnut shell | 0.954        | 17.926     | 13.602            | 5.292   | 0.689   | 61.537        |

The results presented in Tab. 2 indicate that groundnut shell (GNS) possesses a higher cellulose content (61.537%) compared to corncob (CC) (30.785%), suggesting its potential as a superior reinforcing agent for bio composite materials due to enhanced mechanical strength and stiffness.

Conversely, corncob exhibits a higher hemicellulose content (36.434%) and oil content (8.489%), which may influence its moisture uptake and dimensional stability. These compositional differences provide a basis for tailoring biocomposite properties through hybridization of CC and GNS fibers to achieve a balanced combination of stiffness, flexibility, and stability. The lignocellulosic composition critically affects composite performance. Higher cellulose in GNS contributes to increased rigidity and tensile strength, while elevated hemicellulose in CC may enhance flexibility but also promote moisture absorption, potentially affecting dimensional stability. Lignin content, comparable in both materials, imparts thermal stability, and the biodegradable nature of these fibers enhances environmental sustainability. Understanding the lignocellulose profiles of CC and GNS is therefore essential for designing bio composites with optimized properties for targeted applications. These findings are consistent with previous studies [22, 23, 24].

#### Fibre Water Uptake Analysis

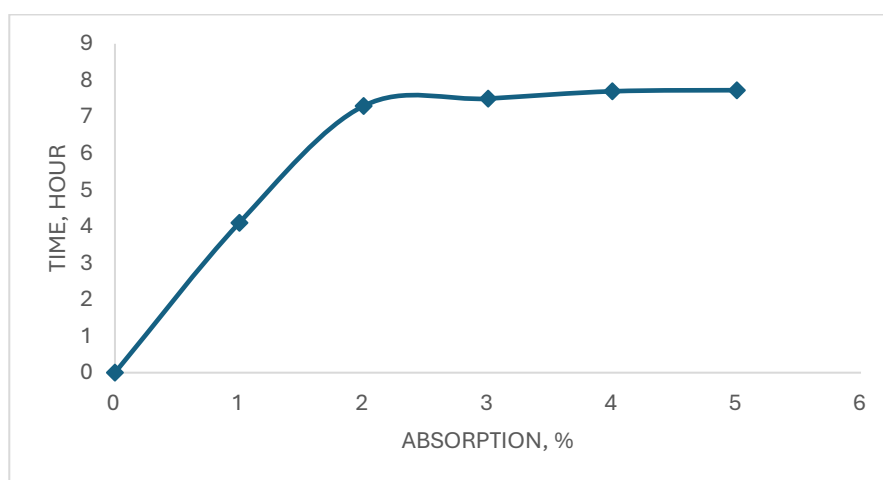


Figure 4. Graph of Groundnut shell vs Water uptake

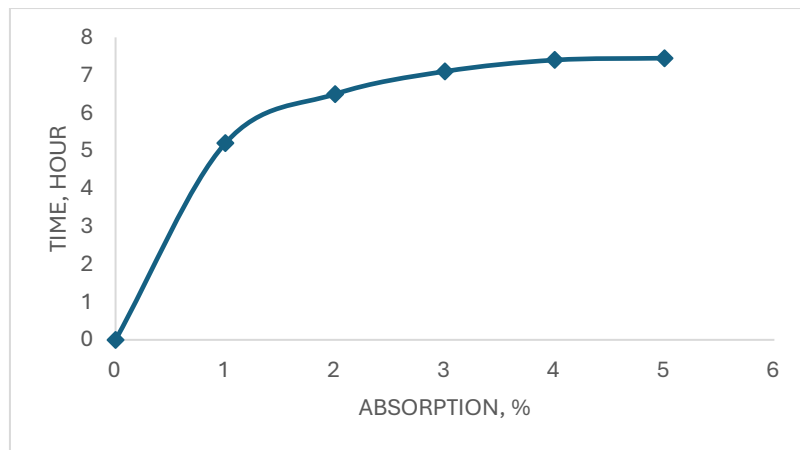


Figure 5. Graph of Corn cob vs Water uptake

The water uptake analysis for groundnut shell and corn cob is shown in Figs. 4 and 5 respectively. Water absorption increased rapidly during the initial immersion period due to capillary penetration of water into fibre lumens and surface pores. As time progressed, the rate of absorption declined and approached equilibrium, indicating saturation of accessible hydroxyl sites and diffusion limitations within the fibre cell wall. This behavior is consistent with Fickian diffusion commonly reported for lignocellulosic fibres, where the absorption curve exhibits an initial linear region followed by a plateau corresponding to equilibrium moisture content. This observation aligns with the findings of Daramola *et al.* [25], Bone *et al.* [26] and Prasad *et al.* [27].

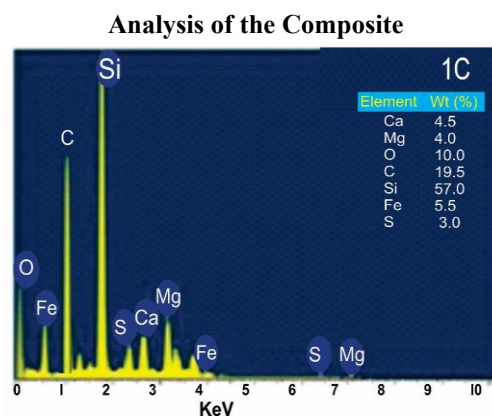


Fig. 6. Groundnut shell / corn cob hybrid composite

Tab. 3 presents the water uptake results for various composite formulations with different ratios of groundnut shell (G. nut) and corncob (C. cob) in an unsaturated polyester resin (UPR) matrix with a fixed amount of METP. Fig. 6 shows the developed hybrid composite.

Tab. 3. Water uptake analysis of the developed hybrid composite

| S/N | G. nut (wt.%) | C. cob (wt.%) | UPR (wt.%) | METP (wt.%) | Water uptake (wt.%) |        |       |       |       |
|-----|---------------|---------------|------------|-------------|---------------------|--------|-------|-------|-------|
|     |               |               |            |             | 1 hr.               | 2 hr.  | 3 hr. | 4 hr. | 5 hr. |
| 1   | 25.00         | 0             | 70.00      | 5           | 0.338               | 0.356  | 0.410 | 0.446 | 0.474 |
| 2   | 22.50         | 2.50          | 70.00      | 5           | 0.379               | 0.437  | 0.573 | 0.673 | 0.744 |
| 3   | 20.00         | 5.00          | 70.00      | 5           | 0.399               | 0.479  | 0.637 | 0.723 | 0.782 |
| 4   | 17.50         | 7.50          | 70.00      | 5           | 0.422               | 0.544  | 0.784 | 0.844 | 0.939 |
| 5   | 15.00         | 10.00         | 70.00      | 5           | 0.617               | 0.788  | 0.913 | 0.897 | 1.094 |
| 6   | 12.50         | 12.50         | 70.00      | 5           | 0.793               | 0.845  | 0.975 | 1.039 | 1.275 |
| 7   | 10.00         | 15.00         | 70.00      | 5           | 0.916               | 0.959  | 1.184 | 1.316 | 1.312 |
| 8   | 7.50          | 17.50         | 70.00      | 5           | 0.979               | 0.992  | 1.202 | 1.420 | 1.599 |
| 9   | 5.00          | 20.00         | 70.00      | 5           | 0.994               | 1.1975 | 1.278 | 1.617 | 1.718 |
| 10  | 2.50          | 22.50         | 70.00      | 5           | 1.073               | 1.383  | 1.544 | 1.755 | 1.833 |
| 11  | 0.00          | 25.00         | 70.00      | 5           | 1.326               | 1.529  | 1.887 | 1.920 | 1.987 |

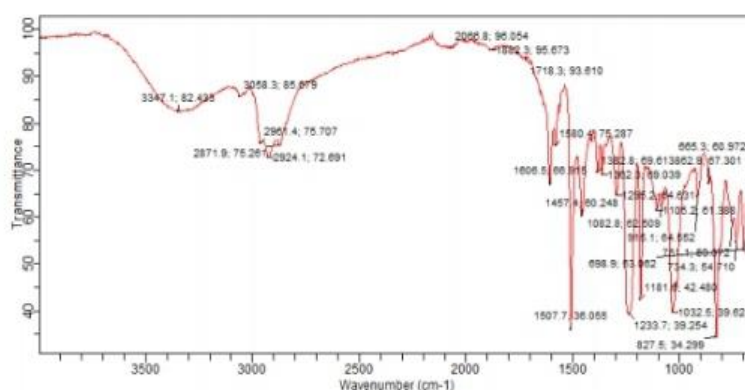


Fig. 7. Graphical Representation of Water Uptake of the Produced Composite

The water absorption behavior of composites comprising varying proportions of groundnut shell and corncob was systematically investigated in Tab. 3. The results, as illustrated in the bar chart in Fig. 7, reveal that water uptake increases progressively with time for all composite samples. Notably, the composite containing 100% corncob exhibited the highest water absorption capacity.

A clear trend of increasing water uptake with increasing corncob content is observed, as indicated by the gradual rise in bar heights for samples with higher corncob proportions. This behavior can be attributed to the higher hemicellulose content and more porous structure of corncob, which enhances hydrophilicity and facilitates moisture diffusion.

In contrast, composites with higher groundnut shell content showed lower water absorption, likely due to their relatively higher cellulose crystallinity and more compact microstructure, which limits water penetration. The significant disparity between the 100% corncob and 100% groundnut shell composites underscores the strong influence of material composition on moisture behavior.

These findings have important implications for practical applications. Composites rich in corncob may be suitable for moisture-absorbing applications such as agriculture, biomedical systems, and water treatment, while groundnut shell-rich composites are better suited for applications requiring dimensional stability and moisture resistance, including packaging and footwear. Overall, this study highlights the potential of agricultural waste-based composites for tailored performance and sustainable material development [28, 29, 30].

### SEM Analysis

At 8000 $\times$  magnification (Fig. 8), the SEM micrograph reveals the surface morphology of the developed composite, clearly showing the distribution of groundnut shell and corncob particles within the matrix.

The image indicates a relatively uniform dispersion of the reinforcing particles, suggesting good interfacial adhesion between the groundnut shell and corncob phases. Such uniformity is essential for effective stress transfer and improved composite performance. The morphological characterization was carried out at magnifications of 8000 $\times$  and 10000 $\times$  (Figs. 8 and 9, respectively). The micrographs generally exhibit a rough and heterogeneous surface with compacted regions, indicative of a relatively dense structure. However, the presence of visible gaps and voids in certain regions suggests localized porosity, which may serve as potential sites for stress concentration and crack initiation. At higher magnification (Fig. 9), the SEM image provides detailed insight into particle morphology, including surface texture, size variation, and the interaction between fibrous and particulate constituents. Overall, the SEM analysis confirms that the composite exhibits a heterogeneous yet reasonably well-bonded microstructure [31, 32, 33].

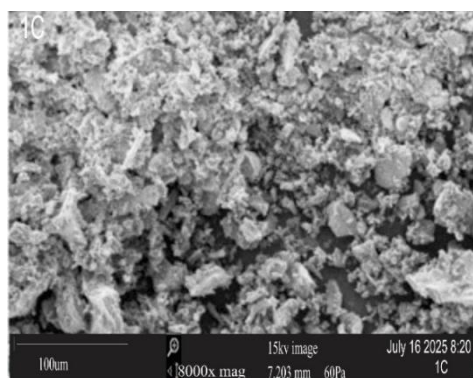


Fig. 8. SEM of the composite (8.000 $\times$ )

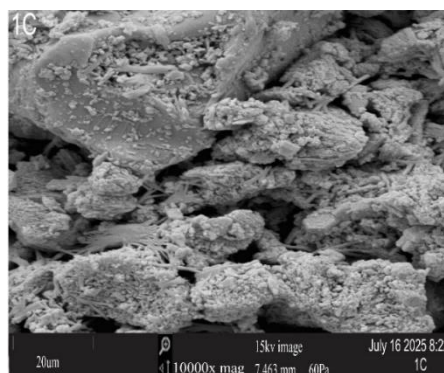


Fig. 9. SEM of the composite (10.000 $\times$ )

### Fibre Water Uptake Analysis Elemental Composition (EDX) Analysis

The energy-dispersive X-ray (EDX) analysis of the composite, as presented in Fig. 10, reveals that the material is predominantly composed of silicon (57.0%), followed by carbon (19.5%) and oxygen (10%). Minor constituents include iron (5.5%), calcium (4.5%), magnesium (4.0%), and sulfur (3.0%). The high silicon content is indicative of enhanced thermal stability, hardness, and durability, which are desirable for structural and high-temperature applications. Carbon contributes to improved mechanical strength, while oxygen is associated with oxide formation and surface functional groups that influence interfacial interactions and chemical reactivity. The interaction and distribution of these elements within the composite matrix play a critical role in determining its mechanical, thermal, and physicochemical properties [34, 35, 36].

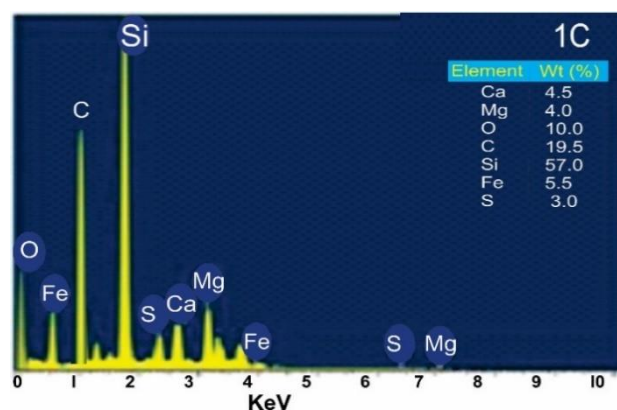


Fig. 10. EDX of the composite

### FTIR Analysis

The Fourier Transform Infrared (FTIR) analysis of the produced composite, as presented in Fig. 11, provides insight into the functional groups responsible for its physicochemical behavior, including its relatively low water uptake characteristics. The identified absorption peaks, summarized in Tab. 4, confirm the presence of key functional groups within the composite matrix. The absorption band at  $665.3\text{ cm}^{-1}$  is attributed to C–H bending or Si–O stretching vibrations, indicating the presence of organic constituents and possible silicate structures. The peak observed at  $1718.3\text{ cm}^{-1}$  corresponds to C=O stretching vibrations, confirming the presence of carbonyl functional groups. The band at  $2871.9\text{ cm}^{-1}$  is associated with C–H stretching of aliphatic (alkyl) groups, reflecting the organic backbone of the composite material. Furthermore, the broad absorption peak at  $3347.1\text{ cm}^{-1}$  is assigned to O–H stretching vibrations, indicating the presence of hydroxyl groups.

Overall, the FTIR results confirm the coexistence of organic and inorganic functional groups within the composite, contributing to its structural integrity and moisture resistance [37, 38].

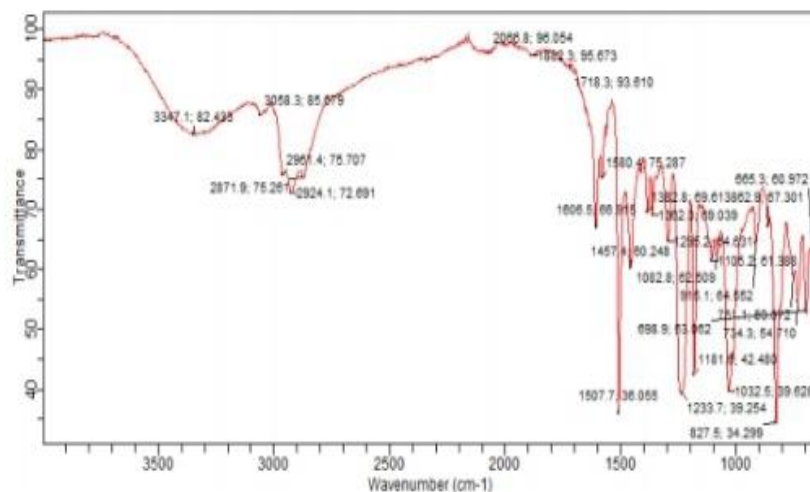


Fig. 11. Image of FTIR Spectra Analysis – see original figure

Tab. 4 Peak Assignments

| Wavenumber (cm <sup>-1</sup> ) | Intensity | Possible Assignment            |
|--------------------------------|-----------|--------------------------------|
| 665.3                          | 60.972    | C-H bending or Si-O stretching |
| 1718.3                         | 93.610    | C=O stretching                 |
| 2871.9                         | 75.261    | C-H stretching                 |
| 3347.1                         | 82.433    | O-H stretching                 |

The presence of relatively hydrophobic functional groups, such as C–H and C=O, contributes significantly to the reduced water uptake observed in the composite. Although hydroxyl (O–H) groups are present and can facilitate some degree of water interaction due to their hydrophilic nature, their overall effect is moderated by the composite's structure and the dominance of less polar functional groups. This controlled water absorption behavior suggests that the composite may be suitable for applications requiring water resistance or reduced moisture sensitivity, such as protective materials, packaging, or structural components exposed to humid environments.

### BET Analysis

The results are presented in Tab. 5 below.

Tab. 5 BET Results

| Parameter                   | Value                     |
|-----------------------------|---------------------------|
| Surface area                | 266.971 m <sup>2</sup> /g |
| Correlation coefficient (r) | 0.99297                   |
| C constant                  | 2.801                     |
| Slope                       | 8.388                     |
| Intercept                   | 4.657                     |

The BET analysis shown in Tab. 5 revealed a high surface area of 266.971 m<sup>2</sup>/g, which can impact its adsorption properties, reactivity, and interactions with its environment.

The correlation coefficient (r) of 0.99297 suggests a strong linear relationship between the data points, providing a valuable insight into the surface area and porosity of the composite material. This finding aligns with the observations of Ravi and Thyagarajan [39], Farghaly *et al.* [40] and Salama *et al.* [41].

### Tensile Strength Analysis

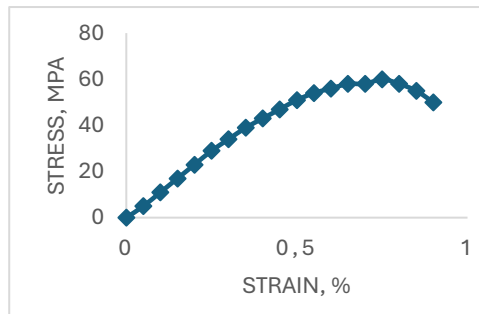


Figure 12. Graphical Representation of Tensile Strength

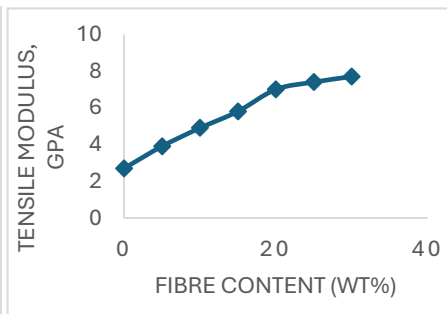


Figure 13. Graphical Representation of Tensile modulus

The tensile stress–strain response of the hybrid composite in Fig. 12 showed a distinct initial linear elastic region, reflecting efficient load transfer between the reinforcing fibres and the polymer matrix and indicating good interfacial bonding at low strain levels. The composite exhibited an ultimate tensile strength of approximately 59 MPa, a strain at break in the range of 0.892%, and a Young's modulus of 7.9 GPa (Fig. 13), confirming a relatively stiff material with limited ductility. As the strain increased, a gradual departure from linearity was observed, attributed to the initiation of matrix microcracks and progressive interfacial debonding between fibre and matrix.

The tensile strength achieved suggests a positive hybridization effect, arising from the complementary mechanical contributions of the different reinforcing phases, while the low elongation at break is consistent with the predominantly brittle fracture mechanism commonly reported for structural polymer composites [42, 43, 44].

The predicted tensile modulus values show a progressive increase with fibre loading, reflecting the increasing contribution of the reinforcing phase to the overall stiffness of the composite. As the reinforcement level increases further, the rate of improvement becomes more gradual. At higher fibre fractions, the predicted modulus approaches a plateau, indicating that additional reinforcement contributes less effectively to stiffness enhancement. This reduction in marginal gain can be attributed to factors such as fibre–fibre interaction, localized agglomeration, and constraints in matrix wetting, all of which reduce the effectiveness of load transfer. Overall, the predicted trend aligns with established composite theory [44, 45].

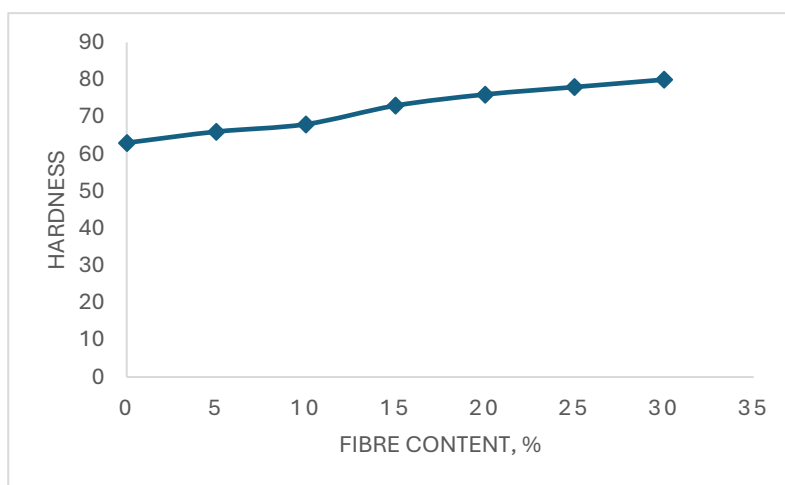


Fig. 14. Graphical Representation of Hardness Test – see original figure

The hardness graph in Fig. 14 shows a steady increase with increasing fibre content, reflecting the growing contribution of the reinforcing phase to the composite's resistance against surface indentation.

At relatively low fibre loadings, the improvement in hardness arises from the restriction of matrix chain mobility and the enhanced resistance to localized plastic deformation under the indenter. At higher loadings, particularly beyond about 25 wt.%, the rate of increase diminishes and approaches a plateau. This trend is commonly observed in fibre-reinforced composites, where excessive reinforcement may lead to fibre agglomeration, reduced matrix continuity, and localized interfacial defects that limit further improvement in surface resistance [46, 47].

## CONCLUSIONS

This study successfully developed and characterized hybrid groundnut shell–corn cob reinforced polyester composites with tailored properties. The results demonstrate that material performance is strongly dependent on filler composition. Groundnut shell, with its high cellulose content, contributed significantly to improved stiffness, reduced water absorption, and enhanced dimensional stability. In contrast, corn cob increased porosity and hydrophilicity, leading to higher water uptake but offering advantages in applications requiring permeability or adsorption. The mechanical properties, including a tensile strength of approximately 59 MPa and modulus of 7.9 GPa, confirm that the hybrid composites possess adequate strength and rigidity for structural applications. SEM analysis revealed good interfacial bonding and uniform dispersion, although some voids were observed, which may influence long-term durability. EDX and FTIR analyses confirmed the presence of functional groups and elements responsible for the composite's mechanical, thermal, and chemical behavior. Additionally, the high BET surface area (266.971 m<sup>2</sup>/g) highlights the material's suitability for adsorption-related applications. Overall, the study establishes that hybridization of agricultural residues can effectively balance mechanical strength, moisture resistance, and functional performance, providing a sustainable alternative to conventional composites. Further studies should optimize the CC/GNS ratio to achieve an ideal balance between mechanical strength and water resistance, particularly for structural applications.

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## PROCENA FIZIČKO-MEHANIČKIH I HEMIJSKIH SVOJSTAVA HIBRIDNOG KOMPOZITA NA BAZI OKLASKA KUKURUZA I LJUSKE KIKIRIKIJA

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**Apstrakt.** Ovaj rad istražuje razvoj i osobine održivih hibridnih biokompozita ojačanih česticama ljuske kikirikija (GNS) i oklaska kukuruza (CC) u matrici od nezasićene poliestarske smole (UPR).

Analiza lignoceluloznog sastava pokazala je da ljuska kikirikija sadrži visok udeo celuloze (61,537%), dok oklasak kukuruza ima veći sadržaj hemiceluloze (36,434%) i ulja (8,489%), što značajno utiče na mehaničku čvrstoću i ponašanje materijala pri apsorpciji vlage.

Ispitivanja upijanja vode pokazala su postepeno povećanje apsorpcije tokom vremena, pri čemu su vrednosti za kompozite sa 100% ljuske kikirikija iznosile od 0,338 do 0,474 mas.%, dok su za kompozite sa 100% oklaska kukuruza dostigle 1,326–1,987 mas.% nakon 5 časova, potvrđujući izraženiju hidrofilnost kompozita sa većim udelom oklaska kukuruza.

Mehanička ispitivanja pokazala su krajnju zateznu čvrstoću od približno 59 MPa, modul elastičnosti pri zatezanju od 7,9 GPa i relativno izduženje pri lomu od 0,892%, što ukazuje na dobru krutost, ali ograničenu duktilnost materijala.

BET analiza pokazala je veliku specifičnu površinu od 266,971 m<sup>2</sup>/g uz visok koeficijent korelacije ( $r = 0,99297$ ), što ukazuje na značajnu poroznost i potencijal za adsorpciju. SEM analiza potvrdila je ravnomernu raspodelu čestica uz prisustvo lokalizovane poroznosti, dok je EDX analiza pokazala dominantan sadržaj silicijuma (57,0%), uz ugljenik (19,5%) i kiseonik (10%). FTIR spektri identifikovali su karakteristične funkcionalne grupe pri talasnim brojevima 665,3, 1718,3, 2871,9 i 3347,1 cm<sup>-1</sup>, što ukazuje na prisustvo silikatnih, karbonilnih, alkilnih i hidroksilnih grupa.

Naučna novina ovog istraživanja ogleda se u hibridizaciji oklaska kukuruza i ljuske kikirikija radi postizanja podesivih svojstava u pogledu apsorpcije vlage i mehaničkih karakteristika.

Dobijeni rezultati potvrđuju značajan potencijal kompozita proizvedenih od poljoprivrednog otpada za održive konstrukcije i funkcionalne primene.

***Ključne reči:*** Oklasak kukuruza, ljuska kikirikija, hibrid, kompozit, upijanje vode.

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