DEVELOPMENT OF A SMART SENSOR SYSTEM FOR REAL-TIME MEAT FRESHNESS MONITORING

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ABSTRACT: Ensuring meat quality is essential for public health, customer satisfaction, and efficiency in the food industry. Good-quality meat lowers the risk of foodborne illnesses by preventing contaminated products from reaching consumers. It also builds consumer trust by offering safe, nutritious, and flavourful food. Maintaining quality helps extend the shelf life of meat, reduce waste, and streamline the supply chain. Following strict quality standards also ensures legal compliance, helping companies avoid costly recalls and penalties. In short, consistent meat quality supports a dependable and sustainable food system that benefits producers, consumers, and the environment. Current monitoring systems rely on physical, chemical, and biological methods to assess meat quality and safety. These include traditional approaches like sensory checks, pH measurements, microbial testing, and modern tools such as gas sensors, colour indicators, and electronic noses. While these newer technologies are more effective at detecting spoilage and contamination, they come with challenges. Many are expensive and require advanced equipment, limiting their use in routine settings. Additionally, most existing systems are not designed for real-time monitoring, which can delay the detection of spoilage. A practical and innovative solution involves developing a non-invasive monitoring system to overcome the existing challenges in evaluating meat quality. This system integrates real-time image analysis with a range of sensor technologies, including temperature, moisture, gas, and pH sensors. This innovative approach leverages the strengths of each sensor to detect environmental factors, volatile organic compounds, and biochemical changes associated with meat spoilage. For visual analysis, an ESP32 camera is used to monitor discoloration and texture changes. Pixel-based image processing is applied to quantify key visual quality parameters like colour and surface texture. By combining sensor data with image analysis, the system delivers a more accurate and reliable assessment of meat freshness. Designed as a compact and user-friendly device, it enables continuous, real-time monitoring throughout the supply chain without damaging the product and provides clear and concise output regarding meat quality.

Key Words : Meat freshness, Sensors, Accuracy, Quality assessment, Real-time monitoring.

1. INTRODUCTION

Meat quality plays a key role in meeting consumer expectations, improving production processes, and staying competitive in the market. In the past, assessing meat quality has mostly relied on sensory evaluations or laboratory tests that often involve damaging the sample. Although these traditional methods can yield valuable data, they tend to be time-consuming, costly, and influenced by human judgment. As a result, there is growing interest in exploring faster, more objective, and non-destructive approaches that can evaluate meat quality more efficiently and consistently.Meat is a staple in diets across the globe and is consumed in various forms, with beef, pork, and poultry being the most common. Among these, poultry and pork are particularly popular due to their affordability and wide availability. However, meat consumption patterns vary significantly between regions, influenced by cultural preferences, dietary traditions, and economic conditions. In recent years, global demand for meat has been steadily increasing, driven primarily by population growth and rising income levels—especially in developing countries where improving living standards are making meat more accessible to a broader segment of the population. *(Chen et al.,2018)*

Numerous factors, ranging from post-slaughter handling to animal genetics, affect the quality of meat. Key attributes that define quality include tenderness, juiciness, flavor, color, texture, and the meat's ability to retain moisture. Pre-slaughter factors such as the animal's breed, age, diet, and stress levels can have a significant impact on these qualities. Similarly, post-slaughter processes—including how the meat is handled, the rate of chilling, and storage conditions—also play a critical role. In addition to physical characteristics, meat quality is assessed through chemical indicators such as fat content, protein levels, and pH value. These elements not only affect the nutritional value and appearance of the meat but also influence its shelf life and how well it is received by consumers.The deterioration of meat quality poses significant concerns not only for food safety and public health but also for the environment. Spoiled meat often exhibits changes in smell, color, texture, and taste, making it both unappealing and potentially hazardous to consume. These changes are typically the result of bacterial growth, oxidation, or improper storage conditions. Consuming spoiled meat can lead to foodborne illnesses such as food poisoning, with symptoms ranging from nausea and vomiting to diarrhea and, in severe cases, hospitalization. Beyond the health implications, spoiled meat also leads to considerable financial losses—especially within the food industry, where large quantities may have to be discarded. Additionally, the disposal of decaying meat contributes to environmental issues, including increased food waste and the release of harmful substances during decomposition. Therefore, maintaining meat quality is essential—not only for safeguarding consumer health but also for promoting sustainability and minimizing environmental impact. *(Almasi et al.,2022)*

Modern techniques for assessing meat quality increasingly rely on a variety of advanced sensors. Gas sensors are used to detect specific compounds associated with spoilage, providing early warning signs of deterioration. pH sensors monitor changes in the meat's acidity levels, which can indicate bacterial activity. Colour sensors are employed to identify visual changes that occur due to oxidation, helping assess freshness. Biosensors, which often utilize enzymes, react with spoilage-related compounds to generate measurable signals, offering a targeted and sensitive approach to quality monitoring. Additionally, technologies such as impedance analysis and spectroscopy-based sensors enable non-destructive detection of internal spoilage, preserving the integrity of the sample. These sensor technologies are also playing a key role in the development of smart packaging systems, which can continuously monitor the quality of meat during storage and transportation, enhancing both food safety and supply chain efficiency.

Meat quality must be maintained to protect customers by avoiding the consumption of dangerous bacterial growth. It also enables food producers and retailers to comply with stringent health and safety regulations. From a business perspective, consistently delivering high-quality meat helps maintain customer satisfaction and reinforces trust in the brand. Moreover, accurate and ongoing quality monitoring contributes to reducing food waste, which has economic benefits and helps mitigate environmental impact. By extending shelf life and minimizing spoilage, these practices support both sustainable food systems and public health objectives. *(Florek et al.,2007)*

A) **Enhanced Precision and Dependability**: Integrating data from diverse sensor sources significantly boosts the precision and dependability of meat quality evaluations.
B) **Comprehensive Analysis:** Sensor fusion enables the simultaneous measurement of various quality parameters, offering a well-rounded and detailed insight into meat freshness and overall condition.
C) **Minimized Subjectivity:** Using objective, technology-driven measurements reduces the influence of human error or bias typically found in sensory evaluations, ensuring greater consistency and repeatability.
D) **Real-time Surveillance:** Many advanced sensor systems support online or in-process monitoring, enabling immediate detection of quality deviations and allowing for proactive adjustments during production
E) **Increased Operational Efficiency:** Automated systems based on sensor fusion decrease the reliance on manual inspection, saving time and reducing labour costs associated with conventional quality control methods.

2. MATERIALS AND METHODOLOGY

A) Raw materials

The raw materials used for this study are Chicken, Mutton, and Beef.

1. Chicken Meat

Chicken is valued for its high protein and versatility and is widely used in food industries, cooking, and nutrition. It's a healthy and adaptable food source, promoting growth and providing essential vitamins and minerals for energy. Proper cold storage is crucial for safety and quality. Raw chicken lasts 1-2 days refrigerated in its original packaging or a sealed container on the bottom shelf. Cooked chicken keeps refrigerated for 3-4 days, within two hours of cooking. For longer storage, freeze chicken in airtight bags or containers, labeled with the date, for up to 9 months (raw) or 2-6 months (cooked). Thaw safely in cold water (changed every 30 minutes) or, ideally, in the refrigerator overnight.

2. Mutton Meat

Mutton is a rich source of high-quality protein for tissue repair and immune function.[1] Its high heme iron content aids red blood cell production and prevents anemia. It's also rich in vitamin B12 for nerve function and DNA synthesis, plus zinc for immunity and wound healing, and other beneficial minerals.[2] However, its saturated fat content warrants moderate consumption. Freezing effectively preserves mutton's flavor, texture, and nutrients by inhibiting spoilage bacteria.[3] Proper freezing in airtight, freezer-safe materials with clear date labeling is crucial to prevent freezer burn and ensure consumption within the recommended timeframe, maintaining a constant freezer temperature of 0°F (-18°C) or below.

3. Mutton Meat

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4. Beef Meat

Beef offers significant nutritional value, being a rich source of high-quality protein vital for muscle development, enzyme production, and tissue repair. It's particularly beneficial for its readily absorbed heme iron, crucial for red blood cell formation and oxygen transport throughout the body. Furthermore, beef contains essential B vitamins, including B12 which supports nerve function and red blood cell synthesis, as well as zinc, important for immune function, wound healing, and cell growth. To promote health, it's advisable to select leaner cuts, manage portion sizes, and be mindful of the saturated fat and cholesterol content. For safe storage and to maintain quality, raw beef steaks, roasts, and chops can be refrigerated for three to five days at or below 40°F (4°C) when properly packaged. For longer preservation, ensure it's wrapped in freezer-safe materials to prevent freezer burn.

B) Fabrication Material

1.ESP 32 CAM

The ESP32-CAM significantly enhances meat quality monitoring by integrating a camera for visual detection of spoilage indicators (color, mold, texture). This enables automated, real-time analysis, catching issues early. Its Wi-Fi and Bluetooth facilitate remote monitoring across the supply chain, ensuring consistent oversight. The device's small size and low power consumption are ideal for portable, battery-powered systems. Its dual-core CPU allows for onboard image processing and the fusion of data from additional sensors (pH, gas, temperature) for a more holistic quality assessment. The ESP32-CAM's versatility and ease of development make it a crucial component for building effective and scalable meat quality monitoring systems, ultimately ensuring higher food safety standards.

2. Battery

A battery is crucial for a continuous and reliable meat quality monitoring system, especially during power outages, ensuring food safety and legal compliance by preventing oversight that could lead to spoilage and health risks. Battery power enhances system portability, enabling monitoring across the entire supply chain, including remote areas and during transportation. It prevents data loss by maintaining continuous data logging and transmission of quality measurements. Additionally, it supports energy-efficient sensor and component designs, reducing operational costs. The battery's dependability, portability, and efficiency are essential for a comprehensive meat quality monitoring system, safeguarding consumer health and product integrity in diverse situations.

3. Gas Sensor

A gas sensor is vital for meat quality monitoring as it detects VOCs (like ammonia and hydrogen sulfide) released by spoilage, providing real-time data on freshness and safety. Its sensitivity allows for early detection of spoilage by accurately measuring these markers. Integrating gas sensors with pH and temperature sensors creates a more precise and comprehensive monitoring system, ensuring timely identification and correction of quality issues to maintain high food safety standards.

Fig 1 Gas Sensor

(Adapted from Crowley K, et al.,2005)

4. Temperature Sensor

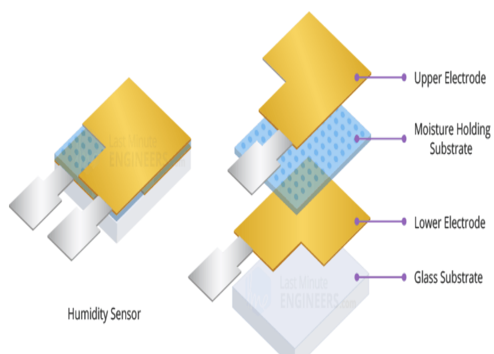


Fig 2. Humidity Sensor

(Adapted from Corradini M.G, et al., 2018)

Temperature sensors are crucial for meat quality monitoring because they ensure proper storage, preventing spoilage and ensuring food safety. Real-time temperature monitoring maintains quality, extends shelf life, and triggers alerts if conditions become unsafe. Combining temperature sensors with other sensors provides a more complete picture of meat quality. Inside the DHT11, there is a humidity sensing component along with a Thermistor.

Humidity sensors use a moisture-sensitive material between two electrodes. As the material absorbs moisture, its conductivity changes, which alters the resistance between the electrodes. This resistance change is measured to determine relative humidity. More moisture means lower resistance, and less moisture means higher resistance.

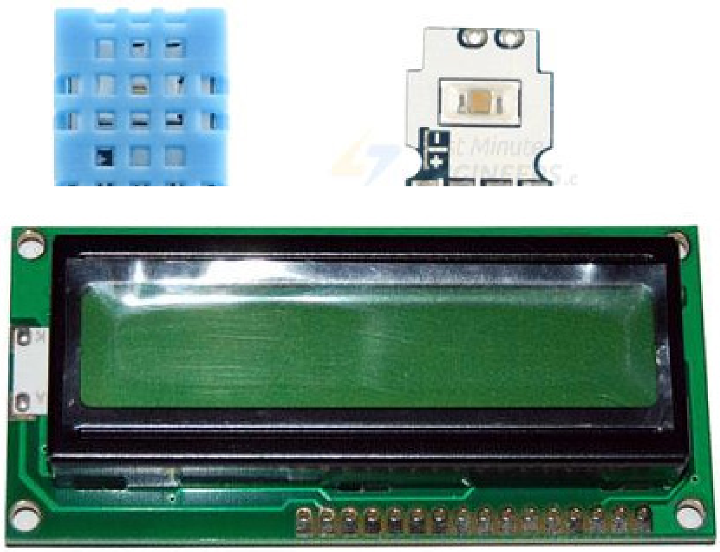


Fig 3. Temperature Sensor

(Adapted from Jean-Louis Damez, et al., 2011)

The DHT11 sensor measures temperature using a thermistor, a resistor whose resistance changes with temperature. Specifically, it uses an NTC thermistor, meaning its resistance decreases as tempera ture increases.

5.Ph Sensor

A pH sensor is highly valuable in meat quality monitoring as it measures acidity/alkalinity, a key indicator of freshness and spoilage. Changes in pH signal microbial growth and biochemical activity. Continuous pH monitoring allows early detection of deterioration, ensuring meat safety and enabling timely action to maintain quality. Integrating pH sensors with gas and temperature sensors creates a comprehensive system for accurate and reliable assessments. This early detection reduces food waste and enhances food safety by preventing the distribution of contaminated products. Overall, pH sensors are crucial for preserving meat safety and quality throughout the supply chain.

6.LIQUID CRYSTAL DISPLAY (LCD)

A Liquid Crystal Display (LCD) is a flat panel display technology commonly used in electronic devices. It consists of liquid crystals sandwiched between two glass panels, with transparent electrodes controlling the alignment of these crystals. LCDs are energy-efficient, making them suitable for battery-powered devices. They function by manipulating light transmission: when no electric field is applied, the crystals align to allow light to pass through, creating a transparent appearance. When a voltage is applied, the crystals realign, scattering the light and creating a visible image. This process enables the display of alphanumeric characters and other visual information.

Fig 4. Liquid Crystal Display (LCD)

(Adapted from Zhuang Q, et al., 2022)

C) PROCESS DESCRIPTION

The Meat Freshness Monitoring System combines image processing and sensor data analysis to assess the quality of stored meat. The methodology begins with capturing real-time images of the meat using an ESP32-CAM, which are processed using Python libraries such as OpenCV and machine learning models to analyze visual features like color and texture that indicate freshness. Simultaneously, environmental factors such as temperature, pH, and gas levels (e.g., ammonia or CO2) are monitored using sensors like DHT11, pH sensors, and MQ-series gas sensors interfaced with a NodeMCU microcontroller. The sensor data and image analysis results are integrated and sent to a cloud platform or a laptop for combined processing and analysis. A web or mobile application displays the analyzed data, providing real-time feedback on meat freshness, issuing alerts for spoilage, and ensuring optimal storage conditions. This approach enhances food safety by leveraging IoT and AI technologies for accurate and efficient monitoring.

D) MODULE DESCRIPTION

Module 1: Image Acquisition and Processing

Objective: To capture real-time images of meat and analyze visual characteristics for freshness.

Components: ESP32-CAM module, Python-based image processing algorithms.

Tasks:

Capture high-quality images of meat using ESP32-CAM.

Process the images to extract features like color, texture, and patterns using OpenCV.

Use a trained machine learning model to classify meat freshness based on the extracted features.

Module 2: Data Monitoring

Objective: To measure the Meat parameters affecting meat freshness.

Components: NodeMCU, DHT11 (temperature and humidity), MQ-series gas sensor (e.g., MQ3 or MQ135 for ammonia/CO2), pH sensor.

Tasks:

Collect temperature, humidity, gas concentration, and pH values using respective sensors.

Transmit sensor data to the NodeMCU for processing and forwarding to a central system.

Establish thresholds for freshness based on sensor readings (e.g., high ammonia concentration indicating spoilage).

Module 3: Data Integration and Analysis

Objective: To integrate and analyze data from the image processing and sensors for accurate freshness prediction.

Components: Laptop/PC, cloud storage, Python for combined analysis.

Tasks:

Receive image and sensor data on a central device (laptop or cloud platform).

Analyze combined data using machine learning models to determine freshness levels.

Generate actionable insights and display results in a user-friendly app.

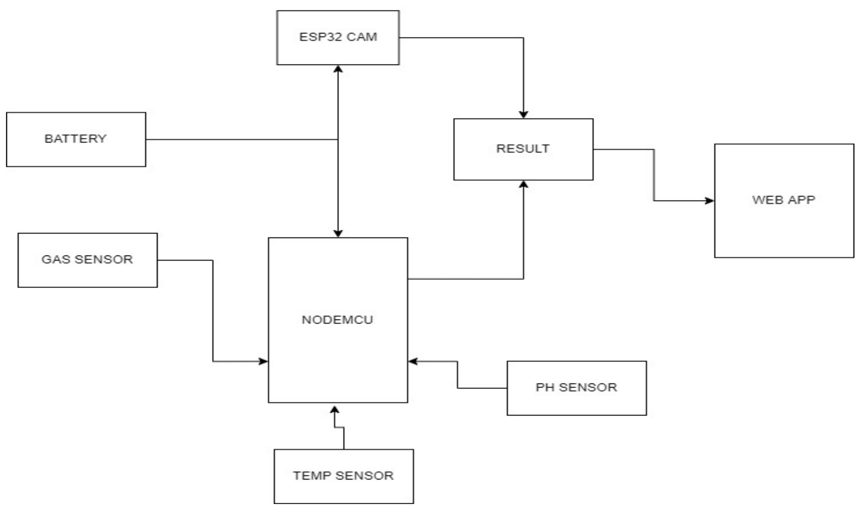


Fig 5. Block Diagram

The sensor involved in monitoring meat freshness are ESP32 camera, gas sensor, Temperature, pH sensor and a battery are connected together to the WENODMCU.

III. RESULTS AND DISCUSSION

The developed system successfully demonstrated non-destructive meat freshness monitoring under various environmental conditions. Trials were conducted using different meat samples, including chicken, mutton, and beef. The system captures real-time images using an ESP32-CAM to assess freshness based on appearance, texture, and colour. The dataset includes over 10,000 high-resolution images to enhance fault detection. Wireless communication between the ESP32-CAM and NodeMCU enabled efficient data transfer to the software application. In addition to image analysis, the system monitors key parameters such as pH, colour, gas emissions, and temperature, which serve as reliable indicators of freshness. Fresh beef typically displays a bright red colour with a slightly acidic pH, mutton appears darker red with moderate fat content, and poultry exhibits a pale pink colour with a lower pH. As spoilage progresses, pH levels rise, colour fades or darkens, and gas emissions increase. Sensor data is compared against known freshness standards to evaluate accuracy and practical applicability. The results from both image processing and sensor measurements are integrated to generate a final freshness assessment, which is displayed through the software. Overall, the integration of imaging and sensor technologies resulted in a smart, user-friendly meat quality monitoring system, offering a reliable solution to prevent meat spoilage.

A) DATA SET

The dataset used for meat freshness classification consists of 6,672 images, representing both fresh and spoiled meat samples. In addition to the visual data, the dataset records essential storage conditions, including pH levels, temperature, moisture content, and humidity, to support a more comprehensive and accurate analysis. A camera system captures real-time images of meat samples, which are then compared against the pre-recorded dataset to assess the freshness status. This approach enables a systematic evaluation by combining visual inspection with environmental parameters, improving the reliability of freshness detection.

B) **DATA SET FOR ESP 32-CAMEA MACHINE LEARNING**

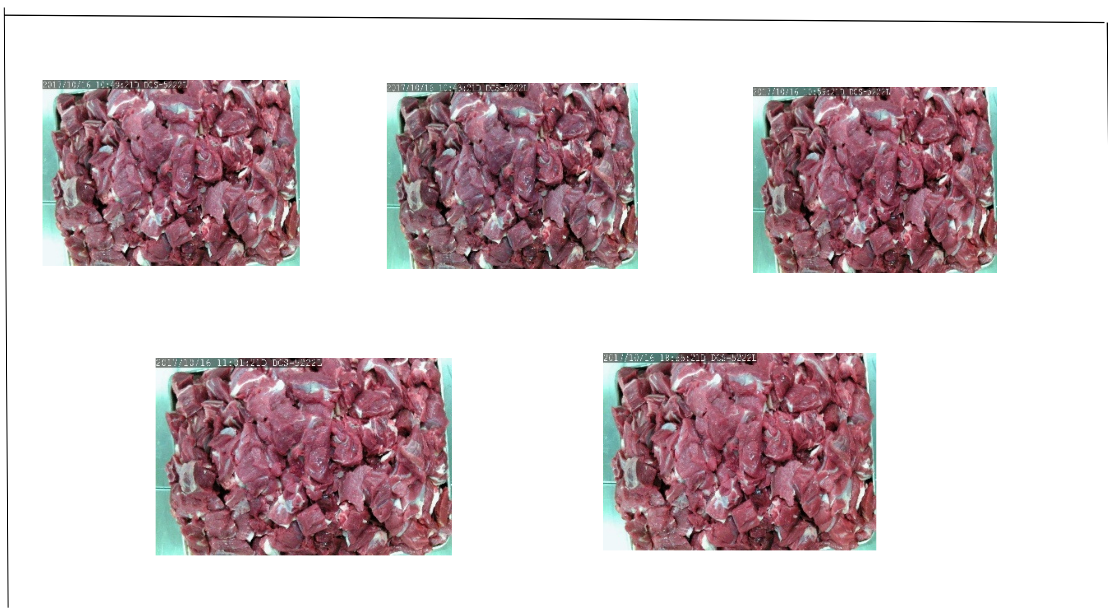


Figure 6. Data sets for the Fresh Meat Samples

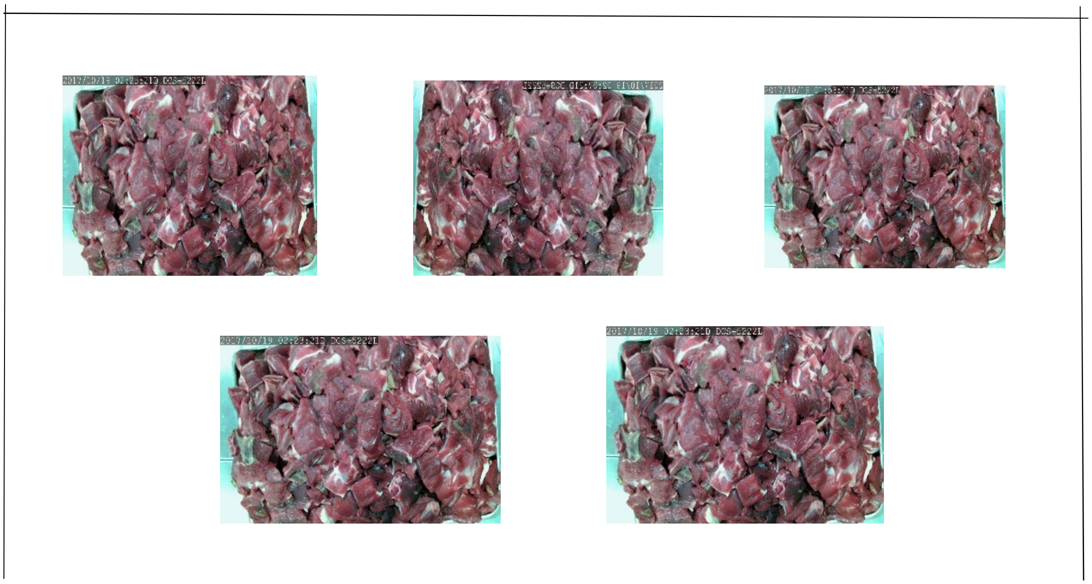


Figure 7. Data sets for the Spoiled Meat Samples

C) DATA SET FOR OBTAINING SOFTWARE RESULT

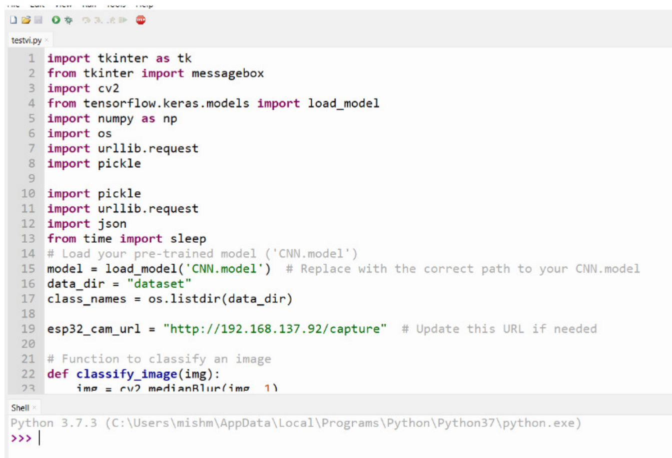
Temperatu	Humidity	pH	Moisture	Gas_MQ13	Quality
21.32	43.06	6.04	64.97	470.48	Spoiled
28.38	53.89	7.24	75.43	302.64	Fresh
4.99	55.64	6.22	67.4	752.13	Spoiled
11.35	59.81	6.28	67.25	775.75	Spoiled
34.27	82.68	6.52	78.01	376.12	Spoiled
29.81	76.19	7.21	69.67	205.29	Fresh
15.64	40.1	6.88	79.88	458.36	Spoiled
26.38	86.77	7.09	77.94	414.71	Spoiled
13.88	40.42	6.43	68.63	724.32	Spoiled
39.97	50.08	7.48	69.24	272.16	Spoiled
26.04	58.05	7.08	60.65	630.04	Spoiled
6.57	72.87	5.98	67.82	460.44	Spoiled
26.78	50.34	5.73	76.57	296.68	Spoiled
29.86	67.77	7.44	65.87	263.12	Fresh
33.48	86.46	6.58	76.5	274.56	Spoiled
26.72	84.22	5.92	71.17	750.54	Spoiled
36.64	82.09	5.64	63.6	321.06	Spoiled
3.89	58.91	7.22	75.2	371.24	Spoiled
1.17	45.15	5.81	66.65	572.9	Spoiled
32	80.37	7.38	62.16	705.08	Spoiled
12.35	72.2	5.86	62.38	280.4	Spoiled
38.34	71.69	5.97	65.94	530.89	Moderate
7.41	43.6	5.61	70.9	464.01	Spoiled
27.61	64.8	7.27	79.77	731.49	Spoiled
12.87	72.94	5.78	68.32	261.96	Spoiled
17.61	65.5	7.43	60.64	378.91	Spoiled

A	B	C	D	E	F	G
10.38	64.14	6.19	66.77	229.59	Spoiled	
20.92	56.18	6.26	65.56	510.74	Spoiled	
4.07	73.83	7.09	77.78	358.22	Spoiled	
14.56	46.63	6.78	62.64	304.8	Spoiled	
1.41	89.19	6.73	66.12	700.21	Spoiled	
2.79	67.74	6.32	73.78	688.06	Spoiled	
34.14	40.64	6.64	67.48	445.02	Spoiled	
21.1	74.49	7.14	73.63	519.39	Spoiled	
21.1	44.92	7.14	66.94	283.33	Spoiled	
23.14	54.15	7.37	70.93	748.18	Spoiled	
34.38	45.76	6.96	67.63	436.18	Spoiled	
21.05	84.08	6.23	74.76	723.96	Spoiled	
11.78	41.07	5.61	77.64	448.13	Spoiled	
27.37	70.72	7.12	61.63	776.42	Spoiled	
27.6	68.34	7.5	68.14	656.92	Spoiled	
38.58	44.38	6.48	75.8	689.77	Moderate	
35.12	67.32	6.64	70.06	289.4	Spoiled	
5.32	71.07	6.46	72.19	357.78	Spoiled	
29.91	44.88	7.41	61.58	313.95	Fresh	
25.06	68.45	5.65	78.67	633.53	Spoiled	
10.92	44.16	6.83	79.84	203.85	Spoiled	
4.92	55.7	5.74	73.1	367.51	Spoiled	
32.15	62.06	6.5	67.93	316.07	Spoiled	
34.9	59.02	5.79	73.31	471.83	Moderate	
5.56	77.04	7.34	72.94	496.5	Spoiled	
22.19	87.96	5.88	65.63	775.77	Spoiled	
33.12	46.85	5.56	72.28	276.18	Spoiled	

Figure 8. Data sets that include suitable readings for the parameters analysed(pH,Temperature,Humdity,moisture and gas)

D). IMAGE PROCESSING

Image processing involves capturing and analysing digital images to extract meaningful information. In this system, a camera module (ESP32-CAM) captures real-time images of meat samples, which are then processed to enhance features like texture, colour, and surface appearance. By comparing these features with a pre-existing dataset, the system can accurately assess the freshness of the meat. This non-destructive method enables fast and reliable monitoring without manual inspection, making it ideal for real-time quality control.



```
import tkinter as tk
from tkinter import messagebox
import cv2
from tensorflow.keras.models import load_model
import numpy as np
import os
import urllib.request
import pickle

import pickle
import urllib.request
import json
from time import sleep
# Load your pre-trained model ('CNN.model')
model = load_model('CNN.model')  # Replace with the correct path to your CNN.model
data_dir = "dataset"
class_names = os.listdir(data_dir)

esp32_cam_url = "http://192.168.137.92/capture"  # Update this URL if needed

# Function to classify an image
def classify_image(img):
    img = cv2.medianBlur(img, 1)
```

```
Python 3.7.3 (C:\Users\mishm\AppData\Local\Programs\Python\Python37\python.exe)
>>>
```

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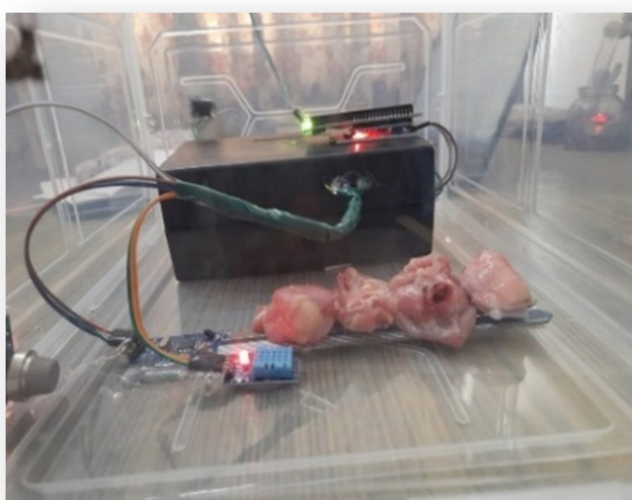
Figure 10. Algorithm used for image processing for ESP 32 CAM

E) QUALITY ASSESSMENT OF VARIOUS MEAT SAMPLES

SAMPLE 1 – CHICKEN MEAT



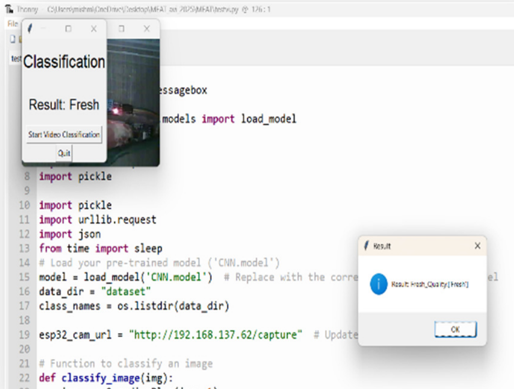


Figure 11. Placing of the meat sample (Chicken) on the sensors for determining the parameters (pH, Gas, Temperature, Humidity and moisture

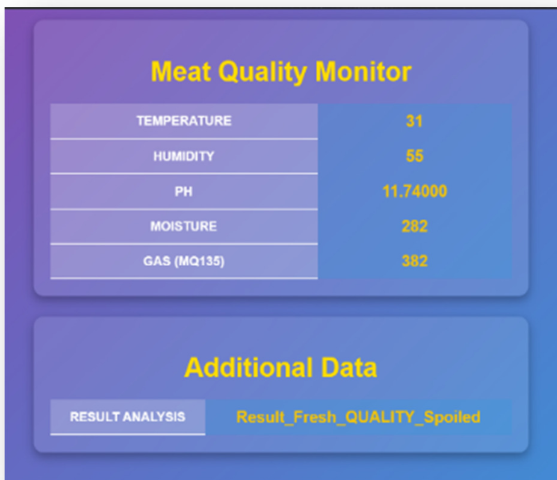
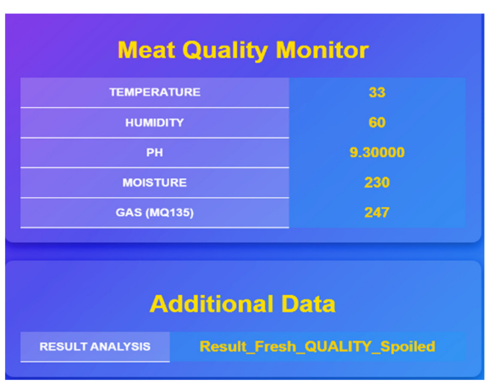


Figure 12. Combining sensor readings and camera results to obtain the final resU



SAMPLE 2 – MUTTON MEAT

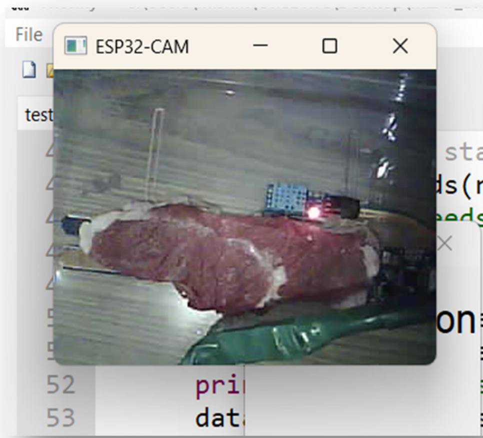


Figure 14. Placing of the meat sample (Mutton) on the sensors for determining the parameters (pH, Gas, Temperature, Humidity and moisture

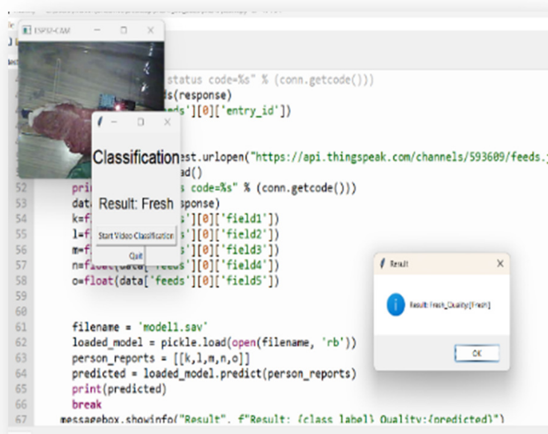


Figure 15. Capturing images of the meat sample using ESP 32-CAM

Figure 16. Combining sensor readings and camera results to obtain the final result

SAMPLE 3 - BEEF MEAT

Figure 18. Placing of the meat sample (beef) on the sensors for determining the parameters (pH, Gas, Temperature, Humidity and moisture

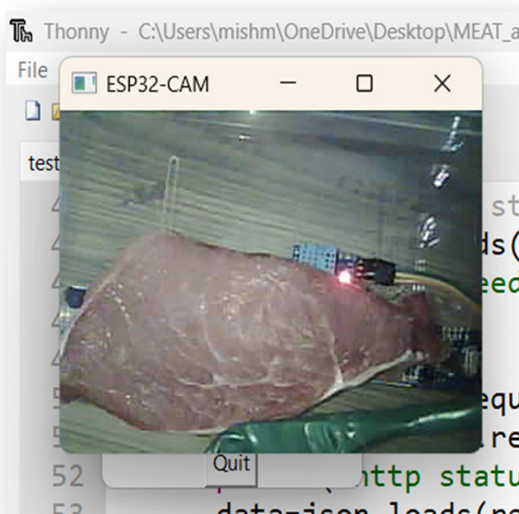


Figure 19. Capturing images of the meat sample using ESP 32-CAM

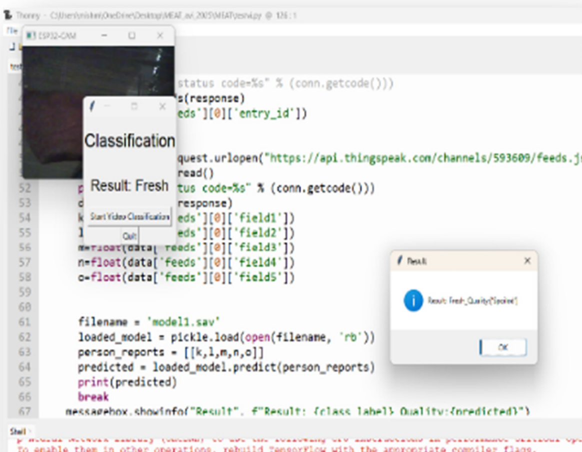


Figure 20. Combining sensor readings and camera results to obtain the final result

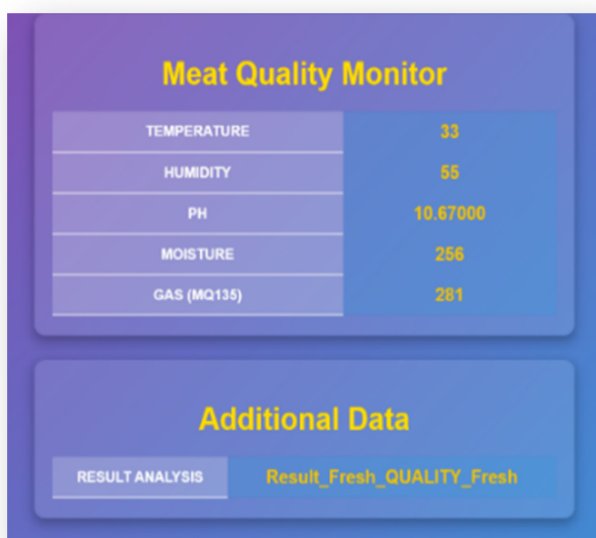


TABLE 1

TRIAL RESULTS COMBINING BOTH THE CAMERA RESULTS AND SENSOR READINGS OBTAINED FROM THE SOFTWARE

S.NO	Varieties	Time (Hr)	Temp (F)	pH	Humidity (%)	Moisture (%)	Gas Level	Overall Result
1	Chicken	0hrs	30	6.2	50	180	120	Fresh Fresh
		1hr	31	6.5	52	185	150	Moderate
		2hr	32	6.9	54	190	180	Not Okay
		3 hr	33	7.5	57	200	210	Not Okay
		4hr	34	8.2	60	245	245	Spoiled
		5hr	35	8.9	62	290	290	Spolied
		6hr	36	9.3	65	320	320	
2	Beef	0hrs	29	5.8	46	168	100	Fresh Fresh
		1hr	30	6.2	48	180	130	Moderate
		2hr	30.5	6.7	50	190	160	Not Okay
		3 hr	31.5	7.5	52	208	210	Spoiled
		4hr	32	8.6	54	228	260	Spolied
		5hr	33	9.7	54	245	295	Highly
		6hr	33	10.48	54	256	317	Spoiled
3	Mutton	0hrs	30	6.1	48	175	115	Fresh Fresh
		1hr	30.5	6.4	50	182	140	Moderate
		2hr	31	6.9	53	190	175	Not Okay
		3 hr	32	7.8	56	205	225	Spoiled
		4hr	33	8.6	59	225	270	Spoiled
		5hr	34	9.8	62	250	320	Highly
		6hr	34.5	11.7	65	282	382	Spoiled

4.4 TRIAL ANALYSIS

The developed meat quality monitoring system is engineered for non-destructive, real-time analysis to improve the accuracy and scalability of quality assessment processes in the food industry. Its primary objective is to provide a consistent and objective evaluation of meat freshness, reducing the reliance on manual inspection, which can be subjective and time-consuming. To evaluate the system's performance, experiments were conducted using chicken, beef, and mutton samples over 48 hours under controlled environmental conditions. During the initial phase of the study, measurements were taken at one-hour intervals for the first six hours. These frequent assessments allowed for a detailed observation of early spoilage indicators. The data collected across this duration served as the basis for analyzing and comparing the degradation patterns unique to each type of meat.

The system utilizes a combination of advanced sensors and imaging technology to monitor multiple spoilage parameters. Specifically, it captures temperature variations, gas emissions (such as ammonia and sulfur compounds), and color changes in the meat samples. At the beginning of the monitoring period, fresh chicken exhibited a pale pink hue, beef appeared bright red, and mutton showed a deeper red coloration. As time progressed and spoilage set in, these visual characteristics shifted noticeably; chicken turned grayish, beef darkened, and mutton lost its natural vibrancy, while gas emission levels increased correspondingly.

The system demonstrated a high level of precision in detecting these quality changes, with an accuracy rate ranging between 75% and 85% when benchmarked against traditional manual inspection methods. Moreover, each test cycle was completed within approximately 6 to 7 minutes, highlighting the system's efficiency in operational settings. Overall, the study confirmed the system's potential as a reliable and rapid solution for monitoring meat freshness, with promising implications for widespread adoption in commercial food processing and distribution environments.

IV. CONCLUSION

This research developed and validated a non-invasive, IoT-based meat freshness monitoring system using an ESP32-CAM and multiple environmental sensors (gas, pH, temperature, humidity, and moisture). Designed for chicken, mutton, and beef, the system integrates real-time image processing with sensor data to assess spoilage indicators like discoloration, VOC emissions, and pH rise. A rule-based algorithm enables freshness classification with 75–85% accuracy under varying conditions. Compact, energy-efficient, and Wi-Fi-enabled, the system is scalable across the meat supply chain, offering a cost-effective, automated alternative to traditional meat quality assessments. Future enhancements include machine learning integration and cloud-based monitoring.

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