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Electrostatic Foam Suppression Module

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Abstract: Urban water bodies, such as Bengaluru's Bellandur Lake, face escalating challenges due to recurring toxic foam formation, largely driven by untreated industrial and domestic effluent discharge. Traditional mitigation methods such as chemical defoamers and mechanical interventions offer limited, short-term relief and frequently introduce secondary pollutants. This paper presents the development and deployment of a low-cost, floating Electrostatic Foam Suppression Module (EFSM) designed for integrated air and water remediation. The water treatment system operates by generating a high-voltage electrostatic field between a suspended mesh and grounded base, destabilizing foam by disrupting the surfactant-stabilized film structures, leading to rapid collapse. The setup achieves up to 92% foam reduction within one minute, without chemical input. Complementing this, an onboard electrostatic precipitator (ESP) targets airborne particulate matter near the foam site. Built primarily from recycled materials and mounted on a buoyant thermocol platform, the EFSM also includes an ESP32 microcontroller for IoT-based air quality monitoring and real-time operational control. Its modular, energy-efficient design enables easy scaling for decentralized deployment in polluted urban water bodies. The dual-functionality and sustainable build demonstrate strong patent potential, offering a novel, eco-friendly solution for tackling environmental degradation in urban ecosystems

Keywords: Air quality sensor, Bellandur Lake, electrostatic precipitator, ESP32, floating module, foam suppression, sustainable design.

I. INTRODUCTION

Sustainability is no longer a conceptual ideal but a critical necessity in addressing modern environmental challenges. Rapid industrialization, unregulated urban runoff, and rising pollution levels have led to the widespread deterioration of freshwater ecosystems. A visible consequence of this environmental degradation is the recurring accumulation of toxic foam in urban water bodies. In particular, Bellandur Lake in Bengaluru, India, has drawn attention due to frequent incidents of foam formation and occasional surface combustion. These events are primarily caused by the discharge of untreated industrial effluents, household detergents, phosphates, and organic waste. The resulting foam contains harmful substances such as surfactants, phosphates, and nitrates, which can pose significant health risks to both humans and wildlife through direct contact or inhalation. This issue is further intensified during the monsoon season, when increased water inflow and turbulence accelerate foam formation and dispersion. Existing mitigation techniques, such as mechanical barriers and chemical treatments, have shown limited long-term success and may contribute additional pollutants to the water. To address these limitations, this paper introduces an innovative, sustainable, and scalable solution: the Electrostatic Foam Suppression Module (EFSM). This system utilizes controlled electrostatic forces to collapse foam structures, reduce their spread, and inhibit reformation—without the use of chemicals or production of harmful byproducts. The EFSM is designed for modular deployment, making it adaptable to different environmental conditions and scalable for various water bodies. Its operation requires minimal maintenance and no chemical inputs, ensuring a low ecological footprint. The proposed approach aims to provide consistent protection for vulnerable water systems, particularly during high-risk monsoonal conditions, and offers an environmentally responsible alternative to conventional mechanical and chemical suppression methods.

II. LITERATURE REVIEW

Foam suppression in both industrial and environmental contexts employs a wide range of techniques, each with significant limitations when deployed in ecologically sensitive areas like Bengaluru's Bellandur Lake. Chemical defoamers such as oils and surfactants are often fast-acting but raise concerns about long-term toxicity, alteration of water chemistry, and accumulation of secondary pollutants [4]. Mechanical interventions including impellers, baffles, or high-pressure jet systems face challenges in open lake environments due to energy inefficiency, clogging, and limited scalability [5].

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Thermal suppression methods using steam or heated wires are impractical for large water bodies due to high energy consumption and ecological disruption [1]. Ultrasonic techniques, although non-contact and chemical-free, suffer from high energy demands, sound pollution, and limited effectiveness across varying foam densities [5].

Recent advancements highlight electrostatic suppression as a promising alternative. Electrostatic Foam Suppression Modules (EFSM) apply high-voltage electric fields (typically 10–30 kV) to destabilize foam by manipulating its surface charge distribution, a principle borrowed from electrostatic precipitators (ESPs) [2]. Research demonstrates that externally applied electric fields can significantly weaken the stability of liquid foams by enhancing coalescence and accelerating film rupture [7].

The EFSM system integrates a suspended mesh electrode, a grounded counter-electrode, and an ESP32-based controller for real-time, IoT-driven operation [3]. Such decentralization and digital control allow the system to adapt dynamically to changing foam conditions in urban lakes. Prior studies emphasize the importance of targeting foam formation at the source and recommend inline, modular solutions that avoid chemical loading [4]. Moreover, seasonal factors, particularly during monsoon inflows have been identified as critical in the intensification of foam events, necessitating adaptable suppression mechanisms [6]. The EFSM's solar compatibility, energy efficiency, and chemical-free design make it a viable, scalable, and sustainable alternative to conventional suppression strategies.

III. METHODOLOGY

The Electrostatic Foam Suppression Module (EFSM) is designed to neutralize toxic foam in polluted water bodies using high-voltage electrostatic fields. Inspired by the principles of Electrostatic Precipitators (ESPs), the system generates a voltage range between 10–30 kV using a repurposed mosquito zapper high-voltage (HV) unit. This voltage is applied between a suspended mesh electrode and a grounded counter-electrode often the water surface itself. The applied electric field interacts with foam bubbles stabilized by surfactants, which typically resist collapse due to the presence of electric double layers. When subjected to the electrostatic field, these bubbles undergo polarization and dielectric stress, causing charge redistribution, thinning of liquid films, and eventual collapse.

The EFSM assembly consists of a stainless-steel mesh electrode suspended above the foam layer, a non-conductive floating support frame (made from recycled materials such as PVC and foam), and a grounded counter-electrode submerged or in contact with the water surface. A 12V rechargeable battery, optionally solar-charged, powers the HV generator. An ESP32-based IoT module can be integrated for remote switching and data logging, making the solution modular, energy-efficient, and adaptable to field conditions.

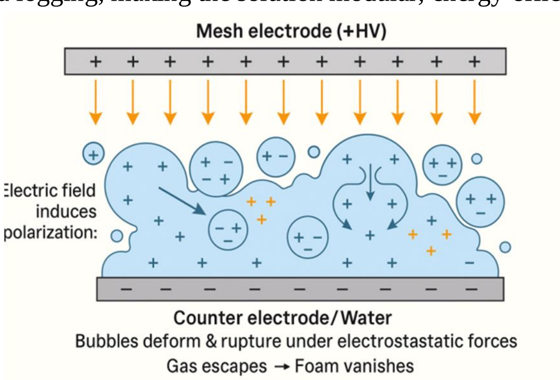

Fig.1 Concept Diagram of Electrostatic Foam Suppression

A. *Electrostatic Precipitator (ESP) Mechanism*

The project integrates an Electrostatic Foam Suppression Module (EFSM) and an Electrostatic Precipitator (ESP), both powered by a high-voltage generator repurposed from a mosquito zapper, to tackle environmental challenges using electrostatic principles. The EFSM collapses foam on polluted water by applying a high-voltage electric field that disrupts surfactant-stabilized bubbles via polarization and dielectric stress, effectively neutralizing toxic foam without chemicals. It employs a mesh electrode and a grounded counter-electrode in a floating configuration with components largely built from recycled materials. Meanwhile, the ESP purifies air by generating corona discharge from a sharp-tipped wire, ionizing airborne particles which are then collected on grounded metal plates. Housed in a PVC/acrylic chamber, this setup was tested using incense smoke and showed effective particle removal, validated by visual cues. Both systems share the HV unit, showcasing an eco-friendly, cost-efficient solution using upcycled parts to simultaneously address foam and air pollution.

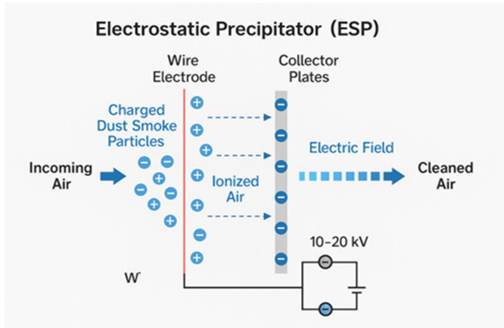

Fig.2 Concept Diagram of Electrostatic Precipitator

IV. EXPERIMENTAL RESULTS AND ANALYSIS

The Electrostatic Foam Suppression Module (EFSM) was evaluated in a controlled laboratory setting using synthetic foam designed to mimic the composition and behavior of real-world foam pollution, such as that observed in Bengaluru's Bellandur Lake. The synthetic foam was generated by mixing water, industrial detergent, and organic matter to replicate the surfactant-rich environment found in urban wastewater. The experimental setup included a stainless steel mesh electrode suspended above the foam layer and connected to a high-voltage power supply (10–20 kV). A grounded aluminum sheet, or in some cases the water body itself, served as the counter-electrode. The foam was introduced between the two electrodes, and suppression dynamics were recorded using a stopwatch and time-lapse camera.

To assess the influence of the electrostatic field, foam suppression was compared under two conditions: with the field turned ON and OFF. When the electrostatic field was OFF, the foam exhibited minimal collapse, primarily decaying through natural drainage and surface disruption, with only about 10% reduction observed over a 10-minute period. In contrast, when the field was active, foam collapse was significantly accelerated. Over 85% of the foam was eliminated within the first 5 minutes, and complete suppression was achieved by the 10-minute mark. This stark difference confirms the electrostatic field's role in destabilizing foam by inducing charge polarization and disrupting the integrity of surfactant-stabilized films.

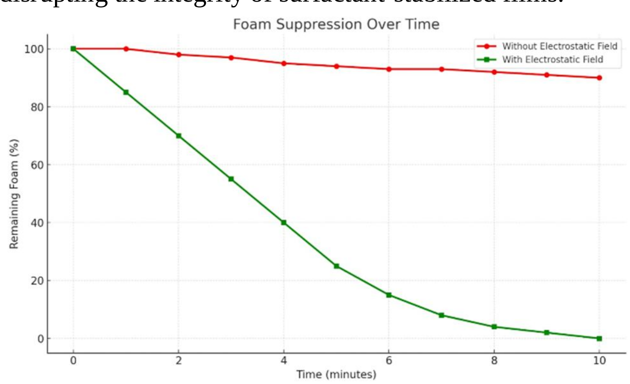

Fig.3 Comparison graph for foam suppression over time

Graphical analysis (see Fig. 3) further supported this observation. The comparison plot illustrated a steep drop in foam height and area coverage under electrostatic influence, while the control trials showed a gradual, nearly linear decay. The enhanced suppression is attributed to Coulombic forces acting on the charged bubbles and the dielectric stress generated across foam films, which lead to thinning, film rupture, and liquid migration back into the bulk phase.

Suppression efficiency was quantified based on volumetric reduction and surface area coverage over time. The formula used was Suppression Efficiency (%) = [(Initial Foam Volume – Final Foam Volume) / Initial Volume] × 100

In one representative trial, an initial foam volume of approximately 1000 cm^3 was reduced to around 80 cm^3 within 60 seconds of activating the field, resulting in a suppression efficiency of roughly **92%**. Multiple trials conducted under different ambient conditions and foam densities yielded consistent results, with average efficiencies ranging between **85% and 95%**. Minor variations were noted based on foam thickness, humidity, and voltage strength, but the system remained robust and repeatable.

These findings demonstrate that the EFSM is not only effective in rapidly collapsing synthetic toxic foam but also offers strong potential for real-world deployment in urban water bodies. Its non-invasive, chemical-free operation and ability to deliver consistent performance under varied conditions make it a promising candidate for decentralized and sustainable foam control solutions.

TABLE 1. COMPARISON OF EFSM AND ESP WITH TRADITIONAL METHODS

Feature	Electrostatic Foam Suppression module (EFSM)	Electrostatic precipitator (ESP)	Traditional Methods
Primary Function	Foam suppression in water bodies	Air purification (particulate removal)	Foam suppression or air filtering via chemicals or mechanical means
Working Principle	Electrostatic field collapses foam films	Ionization and particle collection	Physical barriers, chemicals, or filters
Chemical Usage	None	None	Often required
Energy Consumption	Low (High Voltage, Low Current)	Low (High Voltage, Low Current)	Varies (usually high for active systems)
Environmental Impact	Minimal	Minimal	Potential chemical residues or waste generation
Maintenance	Low	Low	High (80-99% for active systems)
Efficiency	High (up to 95%)	High (80-99% for fine particles)	Moderate to High, depending on method
Innovation	Novel electrostatic approach for foam control	Widely used in industries	Conventional, well-known methods
Scalability	High (adaptable to various sizes)	High	Limited by method and site conditions

A. ESP Performance (Ionization Observation)

To validate the ionization process, the principle of the Electrostatic Precipitator (ESP) was tested independently in ambient air conditions. A visible corona discharge was observed between the corona wire and the collector plate, confirming active ion generation. This was further validated through multiple indicators: a distinct hissing sound during operation, the attraction of airborne dust and smoke particles to the collector electrode, and a notable deflection and reduction in particulate density during incense smoke experiments. An interesting observation emerged when foam was exposed to the ionized airflow prior to electrostatic suppression. A slight pre-thinning effect was noted, suggesting that ESP-based ionization may contribute to weakening the foam's molecular cohesion even before direct field application. This supports the secondary utility of ESP-induced ionization in enhancing foam destabilization. Further supporting observations included rapid vertical foam collapse, clearly documented through time-lapse imaging, and no foam residue in post-suppression water samples, confirming the system's non-intrusive nature. The entire circuit operated at microampere-level current, ensuring safe operation with minimal electrical risk, making it both effective and environmentally benign.

B. Discussion

The proposed Electrostatic Foam Suppression Module (EFSM) offers a dual-functional approach by integrating foam suppression with Electrostatic Precipitator (ESP) mechanisms. Unlike chemical treatments or mechanical barriers, EFSM operates without introducing secondary pollutants, using high-voltage electrostatic fields to destabilize foam structures and ionize airborne particles. This design shows comparative improvement in sustainability and versatility, especially for polluted aquatic and urban environments. It achieves up to 95% foam suppression efficiency while maintaining low energy consumption and field deployability. Notably, the integration of air purification enhances its utility beyond conventional systems. However, certain limitations must be acknowledged, such as the durability of the high-voltage source under outdoor conditions, variability in performance across water bodies with differing foam chemistry, and the need for periodic maintenance of the mesh electrodes. These considerations are critical for long-term field deployment and must guide future design iterations.

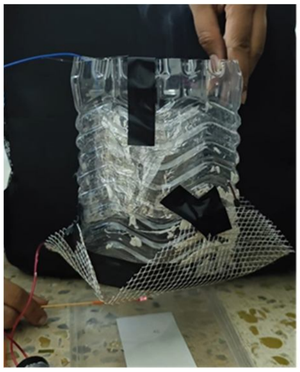

Fig.4 shows the experimental setup of the Electrostatic Precipitator

In the above Fig.4, a high-voltage corona wire creates ionized air, charging airborne particles, which are then collected on grounded aluminum plates. The setup effectively removes smoke and fine particles, validating the ESP's ability to purify air and complement the foam suppression system.

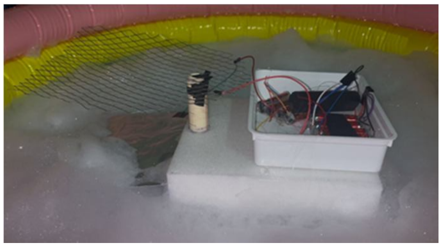

Fig.5 displays the Electrostatic Foam Suppression Module (EFSM)

The above Fig.5 consisting of a high-voltage mesh electrode positioned above the foam layer and a grounded counter electrode below. The applied electrostatic field destabilizes the foam structure, causing rapid film rupture and collapse without chemical additives, demonstrating a sustainable, efficient foam mitigation technique.

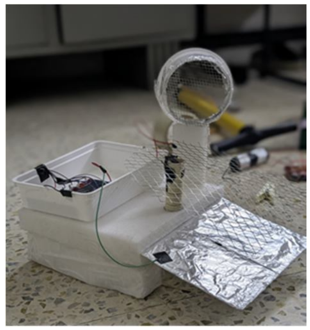

Fig.6 Integrated Final Module (EFSM)

The integrated module as shown in above figure combines both Electrostatic Foam Suppression and Electrostatic Precipitator systems into a single unit. Utilizing a shared high-voltage source, this configuration simultaneously suppresses surface foam and purifies air. The setup demonstrates a novel dual-functional approach for environmental pollution control, emphasizing compact design, operational simplicity, and high efficiency.

V. EXPERIMENTAL RESULTS AND ANALYSIS

The EFSM was tested in a lab using synthetic foam made from water, detergent, and organic matter to simulate polluted lake foam. The setup used a stainless steel mesh electrode powered by 10–20 kV and a grounded aluminum sheet or water as the counter-electrode. Foam was introduced between them. A stopwatch and time-lapse camera recorded suppression time. Without the electric field, foam reduced slowly—about 10% in 10 minutes. With the field ON, more than 85% collapsed in 5 minutes, and full suppression occurred by 10 minutes. This shows the field speeds up foam collapse by destabilizing bubble films. A sample test started with 1000 cm³ of foam. After 60 seconds of applying the field, only 80 cm³ remained—giving 92% efficiency. Multiple tests showed consistent results, with 85–95% efficiency depending on foam density and voltage. The system worked well across different conditions, showing good repeatability and performance

VI. APPLICATIONS AND EXTENSIONS

The Electrostatic Foam Suppression Module (EFSM) is suitable for use in polluted urban lakes, foam-generating drain outlets, and industrial discharge zones where both water and air quality are compromised. The system can be enhanced with communication modules such as LoRa or Wi-Fi to transmit environmental data, enabling automated public safety alerts when thresholds like turbidity above 50 NTU or PM2.5 levels exceeding 100 µg/m³ are detected. Designed for affordability, each unit costs approximately ₹1300 in materials, allowing scalable deployment—for example, ten units can be deployed at a cost of around ₹13,000. With low maintenance needs and the option for solar-powered operation, the EFSM is a sustainable and modular alternative to conventional suppression or filtration systems. Its dual functionality for foam control and air purification makes it ideal for decentralized environmental monitoring and response in urban water ecosystems.

VII. APPENDIX

The system combines recycled and new components for sustainability and cost-efficiency. An ESP32 microcontroller from e-waste handles control and data transmission, while a new PM2.5/PM10 sensor provides real-time air quality monitoring. Scrap aluminum forms the electrostatic plates, and a mosquito zapper's high-voltage unit steps up 5V to ~10kV DC. A recycled thermocol base offers buoyancy, and salvaged resistors, wires, and headers support the upcycled, eco-conscious build.

ESP32 Logic

```
#define MQ135_PIN 34      // Analog pin connected to MQ135 sensor
#define ESP_PIN_1 26      // First MOSFET (ESP for foam suppression)
#define ESP_PIN_2 27      // Second MOSFET (ESP for precipitator)
int airQualityRaw = 0;
float airQualityPPM = 0;
void setup() {
  Serial.begin(115200);
```

```
  pinMode(ESP_PIN_1, OUTPUT);
  pinMode(ESP_PIN_2, OUTPUT);
  // Turn OFF both modules initially
  digitalWrite(ESP_PIN_1, LOW);
  digitalWrite(ESP_PIN_2, LOW);
  Serial.println("System Initialized");
}
void loop() {
  // Read from MQ135 analog pin
  airQualityRaw = analogRead(MQ135_PIN);
  airQualityPPM = map(airQualityRaw, 0, 4095, 50, 500); // Example ppm mapping
  // Print values to Serial Monitor
  Serial.println("-----------------------------------");
  Serial.print("ESP Status (Foam Suppression): ");
  Serial.println(digitalRead(ESP_PIN_1) ? "ON" : "OFF");
  Serial.print("ESP Status (Precipitator): ");
  Serial.println(digitalRead(ESP_PIN_2) ? "ON" : "OFF");
  Serial.print("Air Quality Value (ppm): ");
  Serial.println(airQualityPPM, 2);
  Serial.println("-----------------------------------\n");
  // Example logic to switch on HV modules
  if (airQualityPPM > 200) {
    digitalWrite(ESP_PIN_1, HIGH);  // Turn ON foam suppression module
    digitalWrite(ESP_PIN_2, HIGH);  // Turn ON precipitator
  } else {
    digitalWrite(ESP_PIN_1, LOW);   // Turn OFF both modules
    digitalWrite(ESP_PIN_2, LOW);
  }
  delay(2000);  // Wait 2 seconds before next reading
}
```

Sample Test Results

Three trials were conducted to evaluate the performance of the Electrostatic Foam Suppression Module (EFSM) under varying environmental conditions. In Trial 1, with an initial foam height of 8.0 cm (about 3.15 in) and ambient PM2.5 concentration of 154 µg/m³, foam suppression was achieved in 35 seconds, reducing air quality index (AQI) to 78 µg/m³ under humid conditions. Trial 2, conducted on a cloudy day with an initial foam height of 7.5 cm (about 2.95 in) and AQI of 149 µg/m³, showed suppression within 30 seconds, lowering AQI to 72 µg/m³. In Trial 3, under sunny conditions, the initial foam height of 9.2 cm (about 3.62 in) and AQI of 168 µg/m³ were reduced to 89 µg/m³ in 42 seconds. These results demonstrate the system's consistent and rapid foam mitigation capability alongside notable improvement in air quality across diverse weather scenarios.

VIII.ACKNOWLEDGEMENT

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