Monitoring stagnated droplets for orchard management using flexible, and printed sensors

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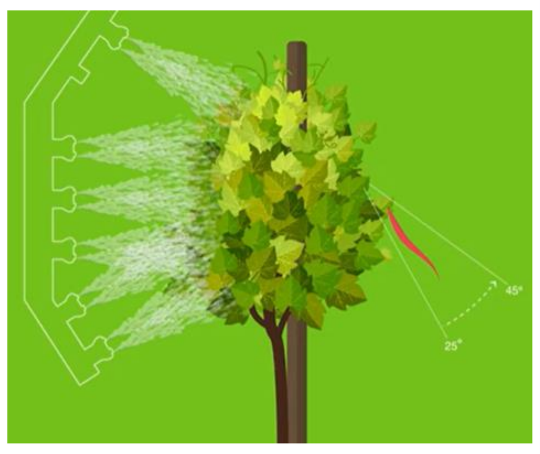
Introduction

- Droplet stagnation on crops leads to fungal diseases, reduce pesticide efficiency, and significant yield loss [1].
- Existing sensors lack precision, sensitivity, and have low resolution towards different droplets types.
- Flexible and printed capacitive sensor offer a sustainable and low cost alternative.
- This work present a comparison between fractal and interdigitated electrode (IDE) based capacitive sensor for droplets monitoring, fabricated via screen printing on flexible substrate. The fractal geometry enhances electric field strength and sensitivity compared to IDE designs.



Methodology

The step-by-step methodology for performing this work is shown below

Step 1
- Material Selection & Fractal Design
  - Selection of Substrate/Encapsulant Materials → PI, TPU, PET, Paper, Parylene
  - Selection of Electrode Materials → Conductive carbon Ink, Silver Ink
  - FEM Simulation of Fractal Geometry

Step 2
- Fabrication
  - Screen Printing
  - Coating
  - Testing

Step 3
- Characterisation & Droplet Monitoring
  - Microscopy (Optical, SEM)
  - Electrical & Environmental Testing
  - Droplet Detection

Step 4
- Validation
  - Laboratory
  - Field Testing

Fabrication

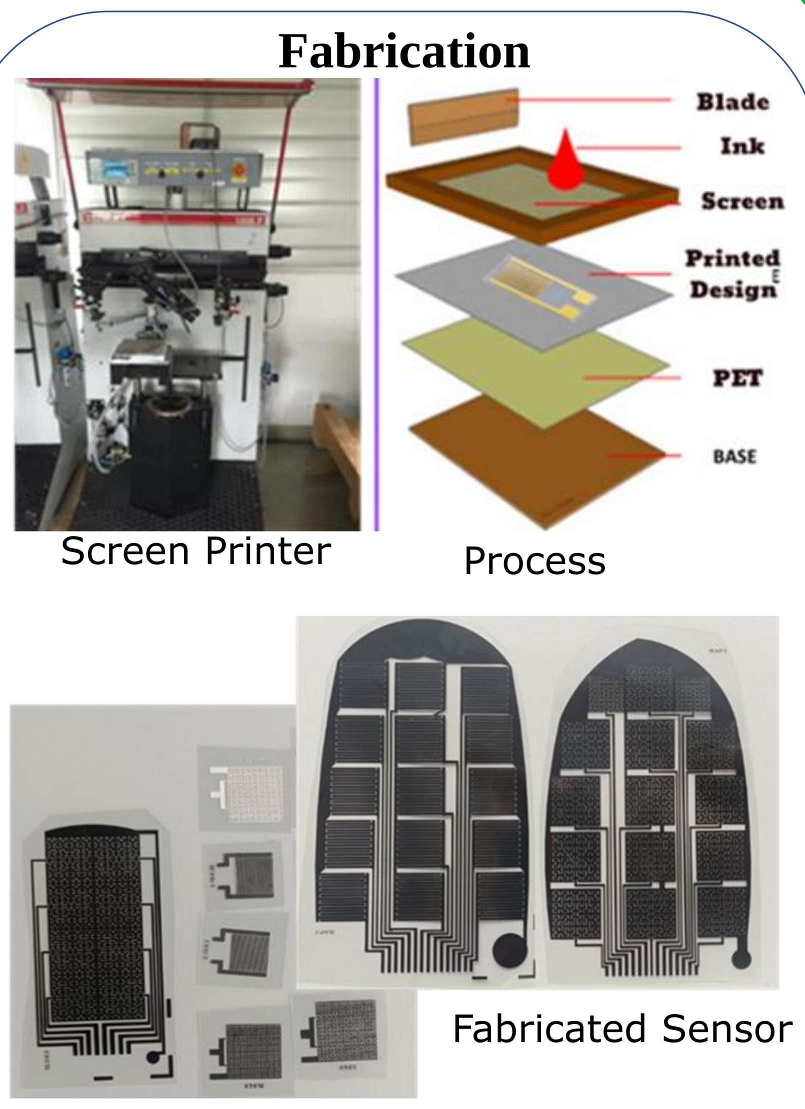


Fig 1. Screen printing process and fabricated flexible sensor array on PET substrates [2].

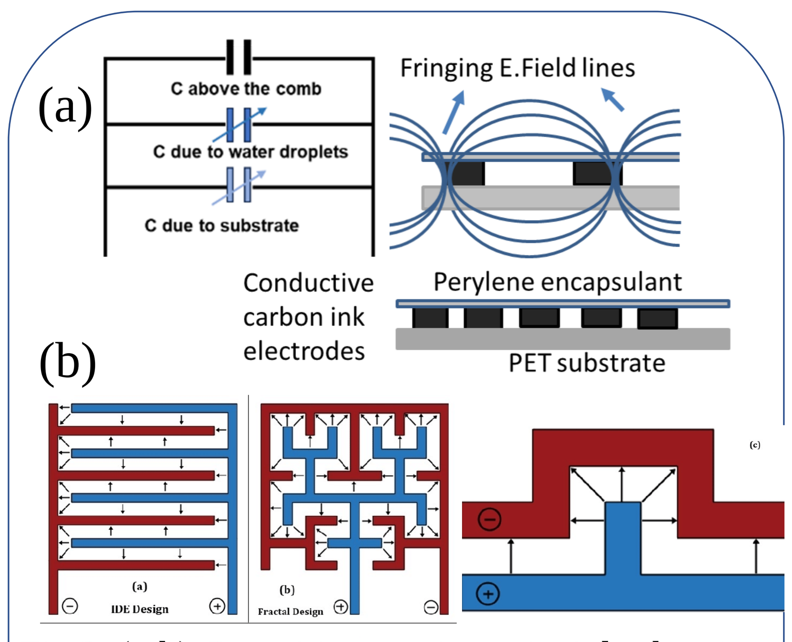


Fig 2. (a-b) Capacitive sensing principle showing contribution for field generation (b) IDE and Fractal layouts with stronger field concentration in the fractal design [3].

Results & Discussion

- FEM simulation were performed for two different design (IDE and Fractal). The results confirmed higher electric field intensity for fractal electrodes (~10881 V/m) compared to IDE (~6682 V/m).
- Sensor were simulated for both with and without droplets.
- Experimental validation demonstrated superior capacitance response of the fractal sensor for multiple droplets.

Generally for capacitive based sensor we have

$$C=\varepsilon_{\circ}\varepsilon_r Ad \quad (1)$$

$$Ct=Ca+Cb+Ci \quad (2)$$

$$C_a + C_b = \varepsilon_0\left(\frac{\varepsilon+\varepsilon_2}{2}\right)\frac{K\left(\sqrt{(1-(G/W)^2}\right.}{K\,(G/W)} \quad (3)$$

$$C_i = \varepsilon_0\varepsilon_1\frac{h}{G} \quad (4)$$

- Eq. 1 represent capacitance relation with the dielectric constant. Here '$\varepsilon_{\circ}$' is the dielectric constant of the vacuum, 'ε_r' is the relative permittivity of the material, 'A' is the area, and 'd' represents the distance in between the comb of sensor.
- Eq 2. represent total capacitance (Ct) which is caused by Ca, Cb, and Ci , capacitance above, below and in-between the electrode.
- In Eq 3. 'G' represents the gap between the sensor electrodes, and 'W' is the width of the one-unit cell. And In Eq 4. '*h*' represent the thickness of electrode.
- The parylene coating improved surface stability, enabling consistent response and recovery cycle during dispensing and aspiration.

Lab Test

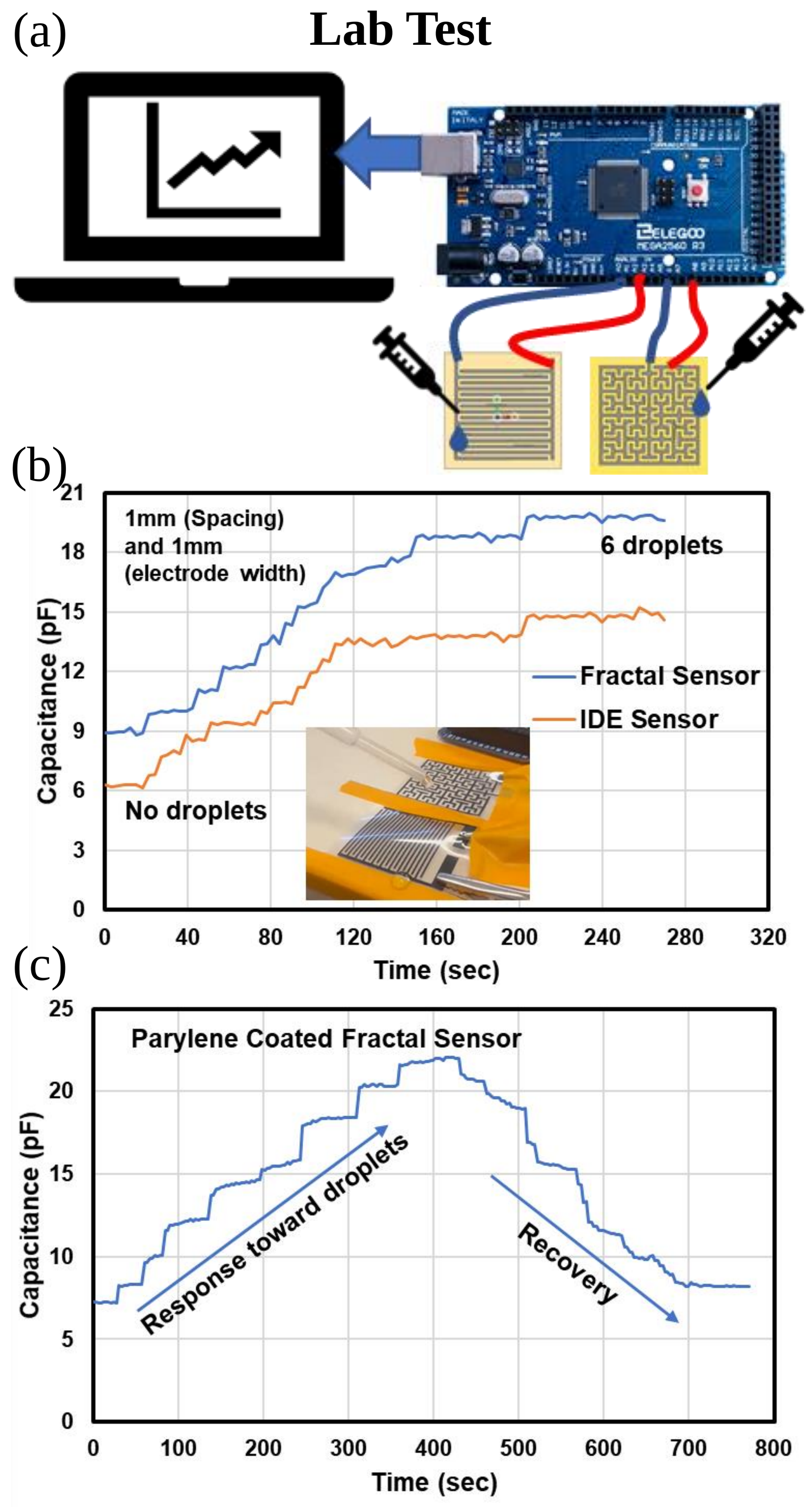


Fig 4. (a) Arduino based setup for IDE and fractal sensor capacitance measurement. (b) Droplets test was performed for both IDE and fractal using pipette to dispense droplets, enhanced droplet sensitivity observed in the fractal design for the same number of droplets as for IDE. (c) Parylene coated fractal sensor was further characterized for response and recovery by dispensing and aspirating droplets using a pipette.

Simulation Results

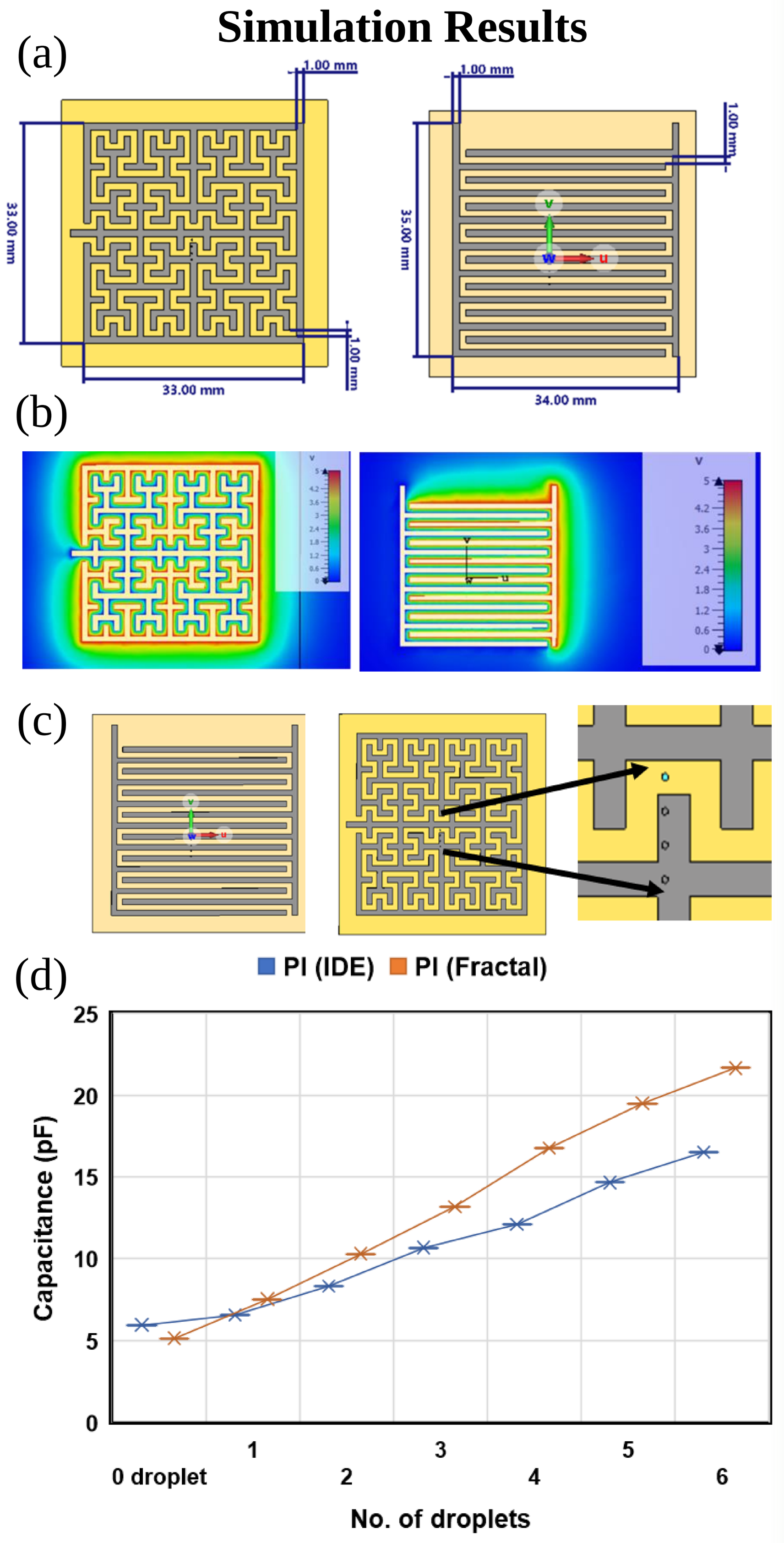


Fig 3. Design, simulation, and performance of fractal and IDE sensor. (a-b) Fractal and IDE (~33*33mm) sensors layouts with 1mm electrode width and 1mm spacing, and their simulated potential map. (c) Sensors characterization for multiple droplets (d) Simulated response of both fractal and IDE sensor in terms of capacitance.

Table.1 Summary of the simulation

S.NO	Substrate	Capacitance without droplets	Capacitance with droplets
1	No Substrate (IDE)	3.05 pF	11.55pF
	No Substrate (Fractal)	2.48 pF	13.67 pF
2	PI (IDE)	5.96 pF	15.56 pF
	PI (Fractal)	5.14 pF	17.48 pF
3	PET (IDE)	7.84 pF	16.23 pF
	PET (Fractal)	6.56 pF	21.57 pF

Fig (5) Future direction for sensor implementation in real field

Conclusion

- Successfully design a flexible, printed, fractal and IDE based capacitive sensor for droplet monitoring.
- Simulation demonstrated high sensitivity for fractal geometry and resolution across ~250 µm droplet.
- Both IDE and Fractal geometry sensor were printed and tested for initial proof of concept.
- The fractal geometry provided enhanced field distribution and improved sensitivity compared to IDE design electrode.
- The response was tested for both fractal and IDE sensor using Arduino mega, and the response was recorded in terms of capacitance for multiple droplets, dispensing through pipette.
- The parylene coated fractal sensor were also tested for multiple droplets impact.
- The sensor design demonstrates strong potential for precision agriculture, enabling early detection of stagnated droplets to reduce disease risk and chemical waste.

Future Direction

- Develop array-based multiplexed systems for high-resolution droplet mapping.
- Integrate with IoT and wireless monitoring platforms for real-time monitoring and data transmission.
- Further characterization such as temperature, humidity, moisture, UV effects.
- Characterization for different droplets impact (using real spray nozzle used in the field).
- Expand applications to biomedical (mist/inhaler monitoring) and environmental (air quality microdroplet detection) sectors.

References

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[3] Waheed, Syed et. al. (2021). IEEE Access. PP. 1-1. 10.1109/ACCESS.2021.3128320.