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Biopolymeric Hydrogel Platforms Integrated with Colorimetric Indicators for Sustainable Intelligent Packaging

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INTRODUCTION & AIM

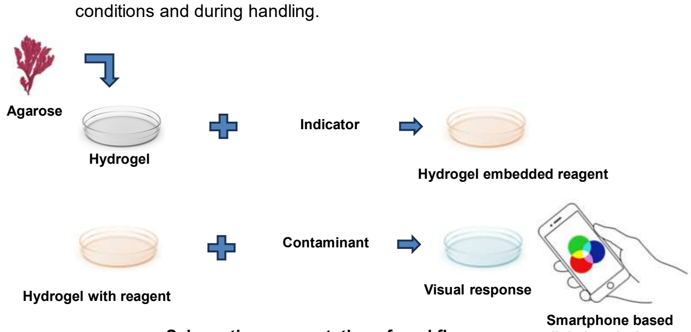
- Food safety and quality monitoring are central to reducing **spoilage and waste** across the supply chain.
- Many existing intelligent packaging indicators still rely on **petroleum-derived, non-biodegradable materials**.
- There is a growing need for **bio-based, environmentally benign sensing platforms**.

➢ To develop and optimize an **agarose biopolymer hydrogel platform** integrated with an **embedded colorimetric indicator system**, and to evaluate its potential for **smartphone-assisted intelligent packaging**.

METHOD

Preparation

- **Choice of matrix:** Agarose chosen as a **biopolymeric hydrogel** due to its renewability, optical clarity, and potential food-contact compatibility.
- **Formulation optimization:**
  - Agarose concentration varied to tune **mechanical strength**, **porosity**, and **transparency**.
  - Conditions identified where hydrogels remained structurally stable in wet conditions and during handling.



Schematic representation of workflow

Integration

- A **pre-formulated colorimetric reagent mixture** was used as the indicator system.
- The reagent mixture was **blended with warm agarose solution** prior to gelation.
- Hydrogels were cast as **discs or thin films** with controlled thickness to ensure reproducible optical paths.
- The indicator-embedded hydrogels were stored under conditions that preserved **indicator stability and responsiveness**.

Interaction studies

- **Model phenolic solutions** were prepared at different concentrations to simulate food-related phenolic levels.
- Hydrogel discs/films were brought into contact with phenolic solutions under **controlled pH, temperature, and contact time**.
- Experiments were designed to mimic **food-relevant conditions** and typical interactions within a packaging environment.
- Color development was allowed to proceed until a **visually stable response** was observed

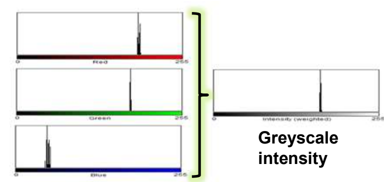
Optimized Hydrogel Properties

- **High transparency**, permitting clear visual inspection and reliable image capture.
- **Adequate mechanical integrity** for handling, storage, and repeated measurements.
- **Minimal indicator leaching**, ensuring stable and reproducible color signals.

RESULTS & DISCUSSION

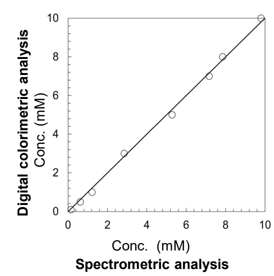
Smart phone based digital analysis

- Color changes were documented using a **smartphone camera**
- Digital images were processed to extract **RGB channel values** from defined regions of interest on the hydrogel surface, and **converted to greyscale intensity**



Smartphone Imaging vs. Spectrophotometric Trends

- When the smartphone-derived greyscale responses were compared with reference spectrophotometric data, a **strong agreement** in trends was observed.
- Both methods reflected similar changes in signal with increasing phenolic levels, indicating that **digital image colorimetry can closely track a conventional optical method**.
- Thus **smartphones** have potential to serve as practical readout devices in **intelligent packaging systems.**



Operational Performance and Practical Considerations

- The hydrogel sensors exhibited a **rapid visual response** following contact with phenolic solutions, suitable for near real-time quality monitoring.
- Indicator-embedded hydrogels **maintained functional stability** during storage and handling, indicating robustness for potential application in the supply chain.
- Overall, the combination of **biopolymeric hydrogel matrix** and **embedded colorimetric indicator** demonstrates a **user-friendly and low-cost** solution.

Sustainability and Application Potential

- The use of **biopolymeric agarose** and **benign colorimetric chemistry** aligns with principles of **green and sustainable packaging**.
- Such hydrogel sensors can be configured as **labels, patches, or thin films** integrated into packaging formats.
- The approach supports **waste minimization and circular economy goals.**

CONCLUSION

- An **agarose-based biopolymeric hydrogel platform** with an embedded **colorimetric indicator system** for **intelligent packaging application.**
- Optimized hydrogel provided **transparency, stability** and **indicator retention**.
- **Smartphone-based digital image analysis (RGB → greyscale)** yielded response trends in strong qualitative agreement with **reference spectrophotometers**.
- System was tested up to 1µM phenolic concentration and exhibited clear concentration dependent response with good reproducibility.
- The integration of **eco-friendly materials** with simple optical readout underlines the **practical feasibility** of biopolymeric hydrogel–colorimetric platforms.

FUTURE WORK / REFERENCES

- **Validation in real food matrices:** evaluation performance of sensors in **actual food based applications**
- **Extension to additional analytes:** adaption of the hydrogel platform in defection of several **markers** related to quality and safety of food using suitable colorimetric chemistries.
- **Advanced data analysis:** exploring **image processing** and **machine leaning based** tools and techniques for accounting variations in data capturing and processing using smartphones.
- **Regulatory and lifecycle considerations:** investigation of **food-safety** and **regulator compliance** backed by the **life cycle assessment** and **cost benefit analysis** over conventional indicators.