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Chapter 1: INTRODUCTION

1.1 Introduction

The Population is growing at an exponentially pace, and the world need for food supplies is growing rapidly. In response to this issue, food production has expanded by more than three times during the last fifty years [1]. The incineration of the waste generates a substantial amount of greenhouse gases, pollutants and particulate matter [1]. Because of the burning of the wastes greenhouse gas, pollutant & particulate matter have been produced in large amount [2]. In preservation of both human health and plant's ecosystem, adopting the sustainable practice in order to manage agriculture and food waste are vital. Because agriculture and food wastes possess enriched qualities, these beneficial materials must be removed and valorized [3]. Among them, Pectin is a one of the valuable biowaste and biopolymer which is comprised of α-1,4-linked D-galacturonic acid, these are partly methyl esterized, & side chain comprises

numerous neutral sugars, such as L-rhamnose, L-arabinose, and D-galactose [4]. The chemical significance across all domains like food, pharmaceutical, cosmetics etc. Can be explained by its natural, safe, easy and moldable nature [5, 6].

Jackfruit (Artocarpus heterophyllus) is a common and ubiquitous fruit in the Indian market, especially throughout the summer months. It is therefore generated in large quantities. Agricultural waste has therefore been produced. The peel represents about 59 per cent of the weight of a ripe fruit and has been discarding so far. The peel contains vital substances such dietary fiber, Polysaccharides, and polyphenolic chemicals [7, 8]. Using this process is possible to extract the pectin from jackfruit peel, which is one of the most heteropolysaccharides components (7.5-15%

on dry weight basis) in the peel. If the process is optimized, the yield may be higher, to about 28-38%, depending on the acids and optimization method used [16, 17]. As the pectin molecule was plentiful in carboxyl groups, so the carboxyl groups combined or coordinated with the Ca^{2+} when using the in-situ Ca^{2+} crosslinking method. Then the egg-box conformation was created. And this structure of Pectin-Ca^{2+} was stable due to ionic and hydrogen bonding [18]. The shell calcination to obtain this crosslinking. Too much money (and thus resources) in terms of the minerals: Protein, calcium carbonate (limestone), magnesium, etc. was wasted due to careless disposal. Calcium is recovered from the egg shell as CaO, $CaCO_3$, $Ca(OH)_2$, calcium phosphate, or hydroxyl apatite, in contrast to the other natural calcium sources. Egg shell calcium oxide (CaO) was over calcined, Efficient waste management preserve natural resources, lowers global warming, and promotes the development of environmentally friendly products [15].

The need for sustainable, edible, or biodegradable materials has grown as a result of the sharp shift towards agricultural and food waste-associated biopolymers due to concerns about the effects of synthetic plastic on the environment and human health. The anionic polysaccharide pectin follows the capacity of polysaccharides, a class of carbohydrates, to bond with water molecules to create an inexpensive, biodegradable film and offer improved capabilities once they were homogenized in water as gel. Building on this Ca^{2+}-crosslinked matrix, the design allows for control over polyphenol-matrix interactions and polysaccharide network fine-tuning while maintaining bioactivity. This allows the crosslinked network and polyphenols to cooperate and stabilizes sensitive anthocyanins. Plant anthocyanins facilitate the development of the stable and intelligent polymer [18,19]. This flower of Alcea rosea (holly hock flower, Gul Khaira) is an upright, relatively short-lived biennial or perennial herb, capable of reaching a height of 3m and it possesses anthocyanins. All 5 of the papery crinkled petals, ranging from a pink to a strong crimson, spread out from the central column of stamens [20]. Water soluble flavonoids give the flower a purple or

deep red color pigment in an acidic solution, it is made up of glycosylated polyphenolic chemicals. The pigmented anthocyanins are derived from the glycosylides of flavylium ions. There are six forms of flavylium ions with a sugar molecule attached. The six types are, cyanidin, dephinidin, malvidin, peonidin, pelargonidin and petunidin. Cyanidin and dephinidin among these ensure anti-inflammatory effects of plants [19, 23]. Because of its superior biological activity and environmental safety, anthocyanin is a common natural pigment. Its stability is jeopardized since it will deteriorate over time due to its susceptibility to light, heat, and oxygen, Divalent metals species such as calcium (Ca^{2+}) have been investigated for use as cross-linkers to improve the stability or strength of the resultant polymer matrix [21, 22].

7 The objective of this thesis is to extract pectin from agriculture or food waste through a simple environment friendly method and synthesize their HG/bio film to understand structure property relationship. In this study, pectin was isolated from jackfruit peel by using mild acidic environment. The effect on the synthesis of HG when anthocyanin is present, as well as release characteristics, will also be investigated. This method develops the neutral HG [9]. The possible formation of HG by using chemical crosslinker egg shell, study the function of anthocyanin incorporation to the HG/bio film formation. Gul Khaira (Alcea rosea) produces the purple color pigment by the reaction of ethanoic acid into distilled water. Extracting purple color Anthocyanin in the presence of ethanoic acid, blocking blue-green and UV, caring cells from excessive light stress (Photoinhibition) [9]. Another is to explore ability of anthocyanin to coordinate with metal ion such as Ca^{2+} (divalent) and form stable complexes, if there is possibility then check its swelling and structural modifications [1313].

1.2 Literature Survey

1.2.1 Pectin: Sources, Extraction, and Properties

Pectin has been long researched as a natural polysaccharide as of the advantage such as a biocompatible, biodegradable, tunable gelling property. It has been used in food, drug, biomedical applications [5]. The amount and quality of the pectin obtained is highly dependent on the extraction conditions such as the concentration of the acid, temperature and pH of the solution [4, 6]. Under such circumstances, the readily available jack fruit (Artocarpus heterophyllus) peel waste is considered as the waste material that is mostly wasted waste [10]. Yield from the range of 7.5 to 38% has been obtained on extraction and purity of biopolymers obtained is enough for using for the direct formulation of HG [7, 8].

1.2.2 HG(HG) Synthesis and Crosslinking Mechanisms

HG are 3D crosslinked polymeric networks effective in absorbing huge volumes of water without structural disintegration, making them suitable for controlled release, wound healing, and agricultural applications [24]. Ionic crosslinking with Ca^{2+} is particularly favored for polysaccharide-based HG due to its simplicity and low toxicity. A Ca^{2+} cross links through the 'egg-box mechanism' between the carboxylate groups of adjacent pectin chains (Figure3a), a complex gel networks [25]. That Ca^{2+} -crosslinked pectin matrices effectively stabilize anthocyanin pigments, which is directly relevant to the present study [18]. Studies concerning carboxymethyl tamarind kernel gum HG [26, 27, 28] set up a great milestone in biopolymer HG on controlled release of nutrients for agricultural uses.

1.2.3 Anthocyanin: Extraction, stability, and Encapsulation

Anthocyanins are pigments derived from plants and are accountable for red, purple and blue shades of plants and fruits. These contain confirmed antioxidative and anti-inflammatory

outcomes [20]. Their practical application is constrained by susceptibility to heat, oxidation, and pH fluctuations. Coordination with divalent metal ions such as Ca^{2+} has been shown to significantly improve anthocyanin stability and color retention [13]. Encapsulation within pectin-based matrices has proven equally effective, as demonstrated by who successfully incorporated anthocyanins into bioactive films for food freshness monitoring [19, 21]. These results further support our current hypothesis and approach regarding the pectin-Ca^{2+} complex formation method for stabilization and controlled release of anthocyanin.

1.2.4 Calcium Oxide from Eggshell Waste

Eggshells are mostly Calcium carbonate (~94% of composition and were considered for this purpose a high-volume product for Food Industry Waste having a considerable amount of calcium is available to recover. Calcination of eggshell at high temperatures results in the formation of highly reactive CaO that can function as an ionic crosslinking agent within the polymer [15]. By utilizing eggshell-derived CaO as a Ca^{2+} source in this study for in-situ pectin crosslinking, this work accomplishes both the independent use of non-synthetic agents such as $CaCl_2$, and the two stream wastes from agriculture-jackfruit peel and eggshell-are valorise in this green framework in one time.

1.2.5 Swelling Behavior and Release Kinetics of HG

Understanding how a HG swells is key to knowing how it behaves, especially regarding how it releases the molecules trapped inside. We looked into this by establishing a clear way to measure the swelling properties of superabsorbent HG. Our work showed that for these polysaccharide systems, the release of molecules is primarily driven by the swelling process itself [29, 30]. To analyze these release patterns, the Korsmeyer-Peppas equation is frequently used to distinguish between simple diffusion and other types of release. As Siepmann and Peppas have noted, choosing the right model depends on the shape of the material and how much it swells [31]. In

the present work, the Korsmeyer-Peppas model will be applied to elucidate the anthocyanin release mechanism from the Pectin-Ca^{2+} HG Matrix.

Chapter 2

MATERIAL AND SYNTHESIS

2.1 Materials

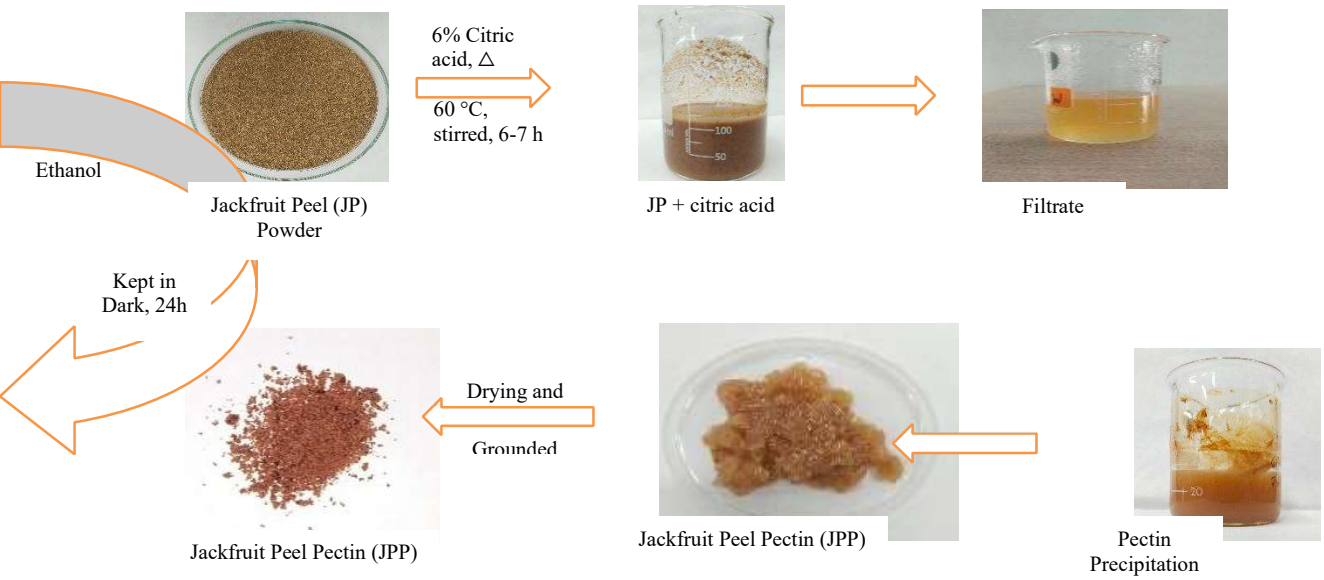
Jackfruit Peel (JP) and Eggshell (ES) were collected from the vegetable market and kitchen waste, respectively. Gul Khaira flower petals (Alcea rosea) were collected from the campus of Delhi Technological University, Delhi, India. Citric acid (10%), sodium hydroxide (NaOH, 98%), & hydrochloric acid (HCl, 36%) bought from Thermo Fisher Scientific (Delhi, India). Ethanoic acid (glacial acetic acid) was used as the extraction solvent for anthocyanin. All chemicals were used as received without further purification. All solutions were prepared using deionized (DI) water.

2.2 Extraction of Pectin from Jackfruit Peel

The jackfruit peel was collected fresh, washed thoroughly with deionized water to remove surface impurities, and chopped into small pieces. The peel was first blanched in hot distilled water at 80°C for 15 minutes to inactivate pectinase enzymes and then dried in a hot air oven at 60°C for 24 hours. The dried peel was ground into a fine powder using a mechanical grinder and passed through a 60-mesh sieve to obtain fine and uniform particle size.

For pectin extraction, five grams of purified bio-waste were treated with 6% citric acid for five to six hours at 60°C. After cooling to room temperature and beginning the separation process using Whatman filter paper, the collected supernatant liquid was heated to 60°C for to 15 to 20 minutes to make it more concentrated, then cooled to room temperature, after that 90% ethanol were added. The mixture were then kept into dark for 24 hr. the precipitated pectin were filtered, washed with ethanol to remove impurities and dried at 50°C for 24 hr. The dried pectin was

grounded by motar and pestle and stored in an airtight polythene at room temperature for further use. According to estimates, the amount of pectin extracted from jackfruit peel was roughly 13%, 12% and 10% of their dry weights, respectively. The fig.1. shows extraction process.



sFigure 1*:* Extraction mechanism of Jackfruit Peel Pectin by environmentally friendly method

2.3 Preparation of Calcium Oxide (CaO) from Eggshell

Eggshells were collected from kitchen waste, washed with deionized water to remove egg white residues and other biological matter, and air dried for about 24 hours. The cleaned and dried eggshells were crushed into small fragments and then calcined in a muffle furnace at 600°C for 2 hours which convert calcium carbonate ($CaCO_3$) of eggshell to more reactive form i.e. calcium oxide (CaO) according to the thermal decomposition reaction:

$$CaCO_3 \xrightarrow[600°C]{\text{Calcination}} CaO + CO_2$$

$$CaO + H_2O \longrightarrow Ca(OH)_2 \quad \text{and} \quad Ca(OH)_2 \longrightarrow Ca^{2+} + 2OH^-$$

The resulting white color eggshell powder (CaO) were obtained and cooled in a desiccator and stored in an airtight container to prevent from moisture. The calcined eggshell was used as the crosslinking agent for the HG synthesis.

2.4 Extraction of Anthocyanin from Alcea rosea (Gul Khaira)

Flower of Alcea rosea (Gul Khaira) were collected from the DTU campus then their petal were washed gently with distilled water. From this 5 g of fresh petals were macerated in 100 mL of ethanoic acid solution (1% v/v in distilled water) for 3 hours at 50°C-60°C in the beaker. The resulting petals imparted their deep purple-colored pigment into the solution were this extract were filtered through Whatman No. 1 filter paper to remove plant debris. The filtrate, containing the anthocyanin pigment in the ethanoic acid medium, was collected and stored at room temperature in dark place to prevent from photoreduction. The ethanoic acid medium maintains an acidic pH that stabilizes the flavylium cation form of anthocyanin, which exhibits the characteristic purple-to-wine red coloration. The maximum absorbance (λ_{max}) of the anthocyanin extract was measured by UV-Vis spectroscopy to confirm the pigment identity and estimate concentration. Can be understand by the below equation:

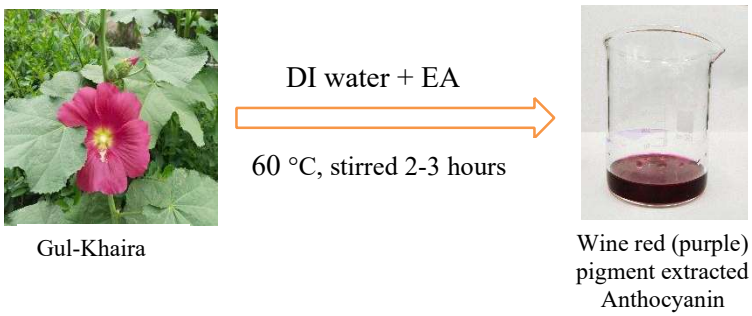


Figure 2: Extraction of anthocyanin

2.5 Fabrication of Pectin-Eggshell (ES) HG

The Pectin-ES HG was prepared by dissolving 40 mg of the extracted jackfruit peel pectin (JPP) in 10 mL of deionized water under continuous stirring at 60°C until a clear, viscous solution was obtained. To this pectin solution, 2 mL of the eggshell solution (40% w/v, prepared were added dropwise with constant stirring. The immediate formation of viscous HG due to the eggshell (CaO)

cross linking with the free carboxylate ($–COO^-$) groups in the pectin chain to form ionic crosslinks (Pectin-Ca^{2+}), producing a characteristic egg-box conformation. The final HG obtained was placed in a small beaker to obtain gel discs which were then air dried for 24 hours at room temperature. Then it was dried for 48 hours at 50°C and the dried HG disks collected and stored in sealed polythene until further characterization and swelling experiment was carried out.

2.6 Fabrication of Anthocyanin-Incorporated Pectin-ES HG

The procedure for the preparation of anthocyanin-loaded Pectin-Eggshell (ES) HG: A solution of jackfruit peel pectin (40mg) was prepared by dissolving the pectin in 10mL deionized water at room temperature. Then add in 2 ml (2g) the fresh and dried Alcea rosea anthocyanin extracted powder into make a consistent pectin-anthocyanin solution. After adding the anthocyanin, the solution's colour is a dark purple solution. After that, the Eggshell (ES) solution (40%w/v) (2mL) was added dropwise into the mixture solution and continued stirred for in-situ ionic crosslinking. In addition to the Ca^{2+} ions (from Eggshell, CaO) which cross-linked neighbouring pectin chains, also served to coordinate with the OH and carbonyl group of the anthocyanin to stabilize them into the HG matrix.

Chapter 3

EXPERIMENTAL ANALYSIS

3.1 Swelling Studies

The swelling behaviour of all synthesized Pectin HG was seen based on gravimetric analysis. The accurately weighed dried HG (W_D) were immersed in DW. At certain time intervals, the swollen HG were removed from the DW , & extra water on the HG disc was blotted off with the help of filter paper and weighed again (W_S) [22]. The equilibrium swelling ratio was determined for all synthesized HG at equilibrium (maximum swelling) by using the given formula [23].

$$\text{Equilibrium Swelling Ratio} = \frac{W_{SG} - W_{DG}}{W_{DG}} \quad \text{.....(1)}$$

Similarly, the swelling analysis for the Ca^{2+} incorporated Pectin-Anthocyanin HG was carried out in distilled water [5].

3.2 Release analysis of anthocyanin in water

The in-vitro release of anthocyanin from the Pectin-ES-Anthocyanin HG was studied in DW at room temperature (25 ± 1°C). A pre-weighed, dried anthocyanin-loaded HG disc was immersed in 10 mL of distilled water in a small beaker. At certain time intervals (0.5, 1, 2, 4, 6, 8, 12, 24, 48, and 72 hours), an aliquot of 3 mL was withdrawn from the release medium and to make sure that volume is steady throughout the experiment, an equal vol. of fresh DW was poured into the beaker.

The anthocyanin concentration in the withdrawn aliquots was determined by UV-Vis spectrophotometry at the characteristic maximum wavelength (λmax) of the anthocyanin extract (approximately 200–500 nm) for cyanidin-based anthocyanins in acidic conditions). A

calibration curve was constructed using known concentrations of the anthocyanin extract to quantify the cumulative anthocyanin released over time. The cumulative percentage release was calculated and plotted as a function of time. Experiments were done in triplicate & mean values with std. errors were reported.

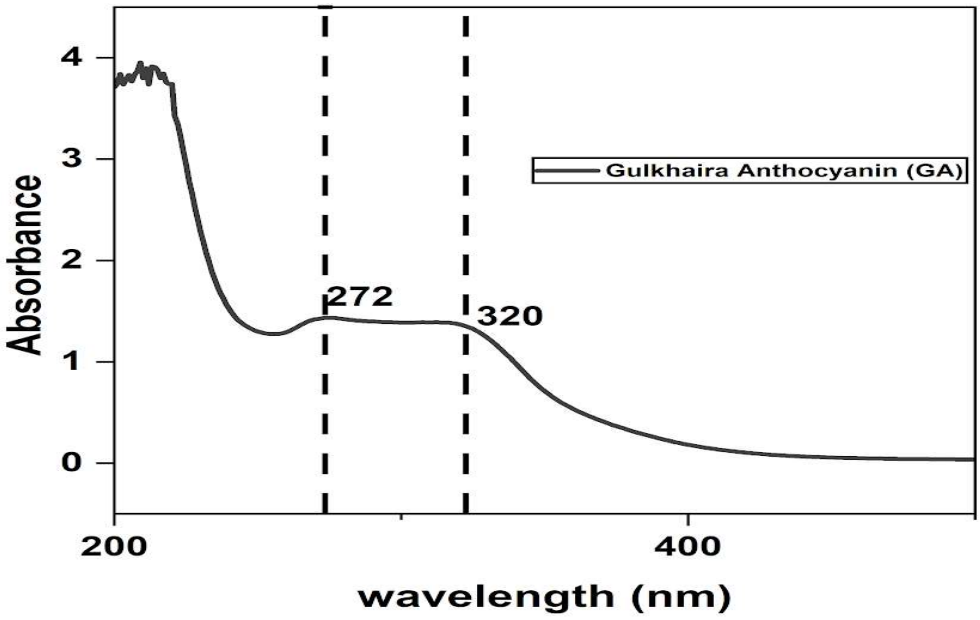


***Figure 3 : Uv-Vis spectra of* Gul Khaira Anthocyanin (GA)**

3.4 Characterization

The FTIR Spectra of Jackfruit Peel Pectin (JPP), Eggshell (ES), Gulphaira anthocyanin (GA), JPP-ES HG and Anthocyanin-loaded JPP-ES HG were obtained using the ATR-FTIR Nicolet iS50 FTIR Tri detector spectrometer within a wavenumber range of 4000-450 cm^{-1}. The DSC

(Differential Scanning Colorimetry) was taken for Jackfruit Peel Pectin (JPP), Eggshell (ES), Gulphaira anthocyanin (GA), JPP-ES HG and Anthocyanin-loaded JPP-ES HG using Hitachi NEXTA DSC 200/600 within a temperature range of 30-300°C at a uniform heating rate of 10°C/min. FESEM EDS was performed for Jackfruit Peel Pectin (JPP), Eggshell (ES), Gulphaira anthocyanin (GA), JPP-ES HG and Anthocyanin-loaded JPP-ES HG using FESEM: Gemini SEM 500 mode with Energy-Dispersive X-ray Spectroscopy (EDS)detector for elemental analysis and mapping. UV-Vis spectroscopy was carried out for anthocyanin released data.

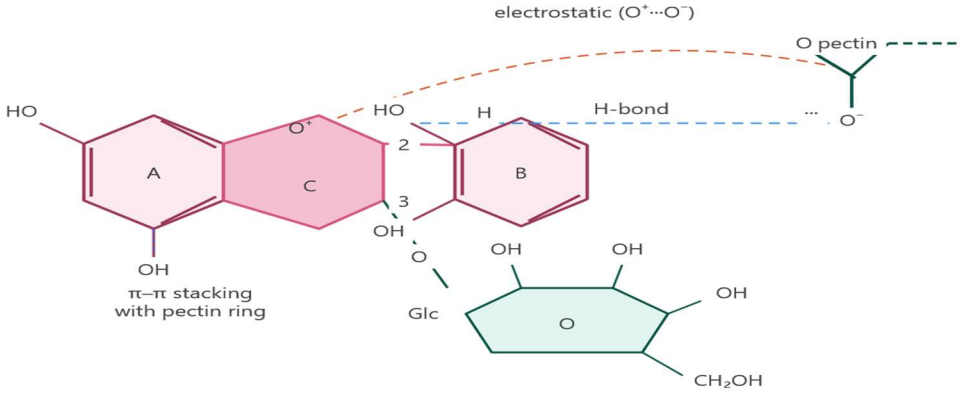
Chapter 4

RESULT AND DISCUSSION

4.1 Mechanism of synthesis of Jackfruit Peel Pectin and eggshell HG

Prior to this section we understand about the structural and chemical properties of pectin, now in this section we will study about the presence of esters and other molecules in the pectin matrix which tell us its gelation and structural properties. Through its degree of esterification, we will understand the mechanism of pectin gelation. Through Ionic gelation mechanism the multivalent species, such as divalent Ca^{2+} from the activated CaO major component of Eggshell (ES) takes part in crosslinking with JPP and the stabilization of the Pectin-crosslinked ES HG through this Ionotropic mechanism. Gul-Khaira Anthocyanin (GA) plays critical role in stabilization of gel formation between Pectin of jackfruit peel and ions of eggshell providing the additional influence of gel formation. Additionally, anthocyanin form hydrogen bonding with water molecule resulting the restricted motion of free water thus influencing the concentration of polymeric environment by leading gelation.

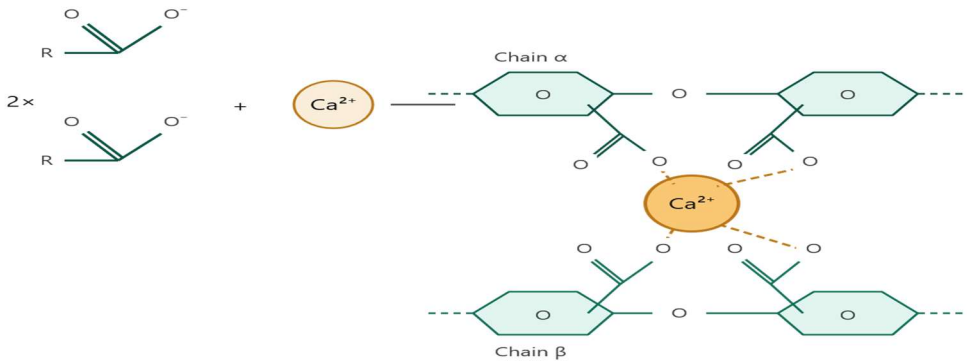
Anthocyanin (cyanidin-3-glucoside) — pectin encapsulation interactions



Hydrogen bond Electrostatic interaction π–π stacking

Flavylium C^+ (ring C) + free –OH (rings A,B) → electrostatic + H-bond entrapment in Ca^{2+}–pectin mesh
Glucoside –OH groups form additional H-bonds with pectin backbone · pigment remains pH-active

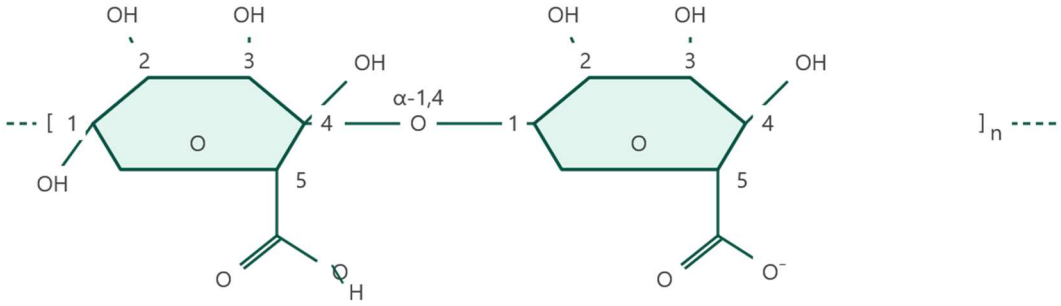
Egg-box junction zone — Ca^{2+} chelation of pectin $–COO^-$ groups



Coordinate bond (O → Ca^{2+})

$2\,(–COO^-) + Ca^{2+} \rightarrow (–COO)_2Ca$ $\Delta G < 0$, spontaneous · immediate gelation

Pectin (JPP) — poly-α-D-galacturonic acid backbone

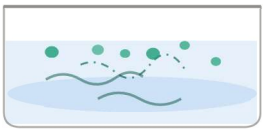


Free –COOH (pKa ≈ 3.5) ionises to $–COO^-$ at neutral pH → available for Ca^{2+} chelation
Haworth projection · α-D-galacturonic acid · degree of esterification = 0% (free acid form)

Pectin hydrogel (JPP) — formation mechanism

23

Step 1 — Pectin (JPP) dispersion in water

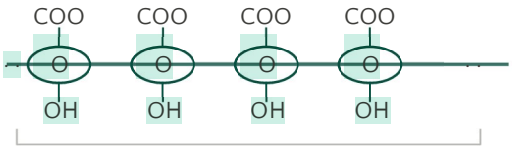


0.4 g JPP + 10 mL H_2O

150–200 rpm

Hydrated pectin solution

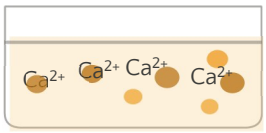
Pectin chain — galacturonic acid units



Free carboxylate ($-COO^-$) groups available for crosslinking

Step 2A — Calcined eggshell ($CaO/CaCO_3$) suspension added (40%)

Dissolution in aqueous medium



Eggshell suspension (40%)

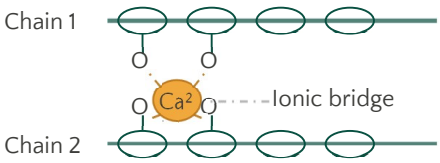
CaO / $CaCO_3$ particles

$CaO + H_2O \rightarrow Ca(OH)_2$

$Ca(OH)_2 \rightarrow Ca^{2+} + 2\ OH^-$

Immediate gel formation

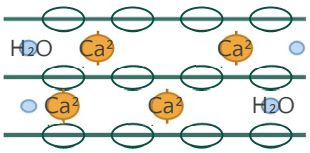
Ca^{2+} crosslinks $-COO^-$



Reaction: $2\ R{-}COO^- + Ca^{2+} \rightarrow (R{-}COO)_2Ca$ (egg-box junction zone)

Step 3 — Egg-box 3D hydrogel network formed

Egg-box junction zone network



Water entrapped in mesh

Egg-box junction zone model

Chain α ——COO^- · · · Ca^{2+} · · · ^-OOC—— Chain β

Chelation

$-COO^-$ groups fold around Ca^{2+} like egg in box

Multiple junction zones → rigid 3D gel matrix

High water retention ≈ hydrogel character

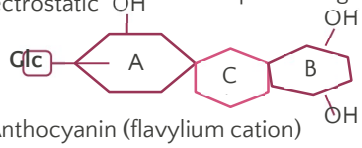
Immediate gelation on Ca^{2+} contact

Gel strength ∝ Ca^{2+} concentration

Step 2B — Anthocyanin pigment added (40%) into JPP gel then ES

H-bond + electrostatic OH

entrapment in gel matrix



Anthocyanin (flavylium cation)

Anthocyanin encapsulation

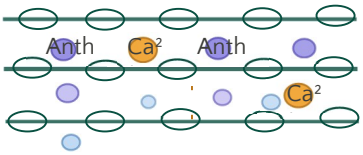
$-OH$ of anthocyanin ⇌ H-bond ⇌ $-OH/-COO^-$ of pectin

Electrostatic: flavylium $C^+ \leftrightarrow -COO^-$

Anthocyanin trapped in egg-box mesh cavities

Pigment colour preserved; pH indicator function retained

Step 4 — Anthocyanin-loaded hydrogel — 3D porous network



3D porous anthocyanin-loaded hydrogel

Matrix composition

- Pectin (JPP) backbone chains
- Ca^{2+} ionic crosslink (eggshell)
- Anthocyanin (encapsulated pigment)
- Trapped water molecules

Step 5 — Drying: air-dry 24 h → oven-dry 50 °C / 24 h

H_2O ↑

Air drying (24 h, RT)

Surface water evaporates

Pores begin to collapse

Soft gel → semi-dry

50 °C heat ↑

Oven drying (50 °C, 24 h)

Residual water removed

H-bonds in matrix densify

Final dry hydrogel film

ES crosslinked JPP hydrogel and Anthocyanin incorporated JPP+ES hydrogel





The gel formation is majorly influenced by three factors:

1. Degree of acetylation (DA)
2. Degree of methoxylation (DM)
3. Degree of esterification (DE)

The constituents of Eggshell help in creation of "egg-box" structure by the presence of free carboxylate ions(-COO^-) and sulfate ion in the heteropolymer, significantly strengthen the polymeric chain formation or intercalation. The acetyl group typically attach to galacturanic acid by the -OH group in pectin chain. The degree of acetylation alters the gel formation, high DA make it difficult to form gel while at low DA it influencing the gelling it also influencing gel formation at low pH with the high degree of acetylation as carboxylate ions more actively participated in crosslinking to form HG, with this neutral sugar will also take part and help in the formation of Pectin HG [25].

4.2. Swelling studies

The swelling characteristics of the HG fabricated were tested in distilled water for its water absorption capacity and the induced mechanical stress on the polymer network [18]. Figure 4.2 The time-dependent percentage swelling ratio shows the comparison between the eggshell crosslinker and addition of Gulphaira anthocyanin pigment.

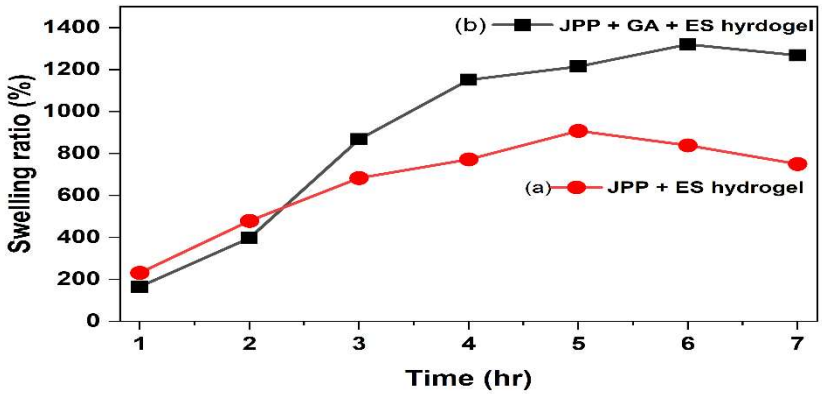


Fig. 4.2. Swelling ratio (%) of synthesized HG by (a)JPP with ES and (b) by the incorporation of Gulphaira anthocyanin with Jackfruit Peel Pectin (JPP) crosslinked by Eggshell (ES).

From the swelling curves, the initial rate of water absorption for both pure (a) JPP + ES HG and

anthocyanin-contained (b) JPP + GA + ES composite showed the fast rate of water absorption. This initial phase is characteristic of hydrophilic polymeric networks, driven by the rapid hydration of the matrix via hydrogen bonding. The swelling ratio of JPP-crosslinked ES HG and anthocyanin composite HG showed the highest to 839.12 ± 156% and 1360 ± 52% after immersing 5 hrs and 6 hrs into distilled water respectively. Beyond this peak, the swelling ratio stabilized and exhibited a slight decline, marking the onset of initial polymeric chain degradation and partial network erosion.

Mechanistically, these swelling and stabilization processes are strongly dependent on the ionic interactions in the matrix. Activated CaO, in which calcined eggshell is a valuable resource, readily gives up its divalent Ca2+ ions to the aqueous system. Such ions facilitate excessive crosslinking of the polymer network because they can coordinate with plenty functional group of carboxylate (-COO-) and hydroxyl (-OH) existed on pectin chain. This targeted chelation are the ones which build up the characteristic "egg-box" junction zones, which form the basic structural unit of the HG network [18, 25].

Also, the use of anthocyanin affects significantly the swelling kinetics because it has extra phenolic hydroxyl binding sites which can bind with the free Ca2+ ions available from eggshell. The introduction of this additional chelation resulted in a very stable and highly linked semi-interpenetrating network structure. Consequently, the anthocyanin not only modulates the water uptake capacity—allowing the matrix to accommodate a significantly larger volume of solvent before reaching osmotic equilibrium—but also enhances the overall mechanical integrity of the HG matrix, delaying premature structural degradation [19].

4.3 FTIR

The Fig. 4.3 (a) to (e) illustrates the FTIR spectra of Jackfruit Peel Pectin (JPP), Eggshell (ES), Gulphaira anthocyanin (GA), JPP-ES HG and Anthocyanin-loaded JPP-ES HG respectively. In the FTIR spectrum of JPP (in Fig. 4.3.a), the peaks observed at 3224 cm^{-1}, 2920 cm^{-1}, 1730 cm^{-1},1614 cm^{-1}, 1100 cm^{-1} and 1014 cm^{-1} correspond to O-H stretching vibration, C-H stretching

vibration, C=O stretching vibration, and peaks COO^- stretching vibration and other two corresponding peaks shows presence of polysaccharides groups such C-O-H and C-O-C respectively [32].

FTIR spectrum of eggshell (ES) has been shown in the figure 4.3(b). The O-H stretching vibration was associated with a peak in FTIR spectrum of ES at 3735 cm^{-1} which represents water content or surface hydroxyl groups. Additionally, the absorbance peaks at 2982 cm^{-1} and 1200 cm^{-1} can be attributed to the C-H stretching vibration and the C-O stretching vibration of organic components of eggshell like remaining proteins and lipids [15] respectively. Also, the sharp and broad peak found at 1400 cm^{-1} is the result of the asymmetric C-O stretching vibration of carbonate ion, Although the 2545 cm^{-1} or so band is an overtone to the main carbonate vibrations. In addition to, sharp absorptions peaks at 872 cm^{-1}, and 713 cm^{-1}, the characteristic frequencies of the out-of-plane bending mode and in-plane bending mode for carbonate ion, which confirms more particularly the dominance of a mineral nature in the composition of the eggshell with the calcium carbonate calcite allotrope [16].

FTIR spectrum of the HG consisting of jackfruit peel pectin and eggshell (JPP+ES) can be observed in the fig.4.3(c). In JPP+ES spectrum, the broad peak centered at 3328 cm^{-1} is the O-H stretching vibration involved with intermolecular hydrogen bonding, the peak at 2980 cm^{-1} is attributed to the C-H stretching vibration of galacturonic acid ring. Additional peak at 1740 cm^{-1} indicates the C=O stretching vibration of the esterified carboxyl groups which is present in pectin, with 1570 cm^{-1} assigned to the asymmetric stretching of the carboxylate (COO^-)ion [18]. The big absorption peak at 1400cm also represents the symmetric stretching of COO^- group. Simultaneously overlapping with the strong carbonate ion (CO) stretching band originating from the eggshell moiety [16]. The intense peak around 1068 cm^{-1} is the stretching vibration of C-O-C of pyranose ring from the main backbone of pectin polysaccharide [18].

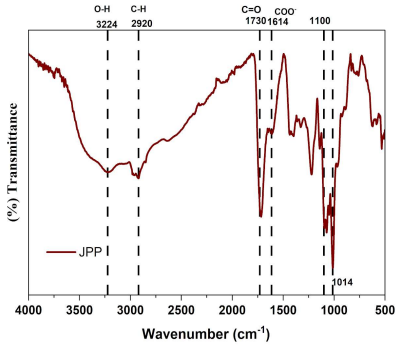
Fig. 4.3(d) below represents the FTIR spectrum of the anthocyanin extract. Among the bands in the FTIR spectrum, the absorption peak in 3300 cm^{-1} is a strong and broad absorption peak

which represents the O-H stretching vibration, shows presence of phenolic hydroxyl groups and inter-molecular H-bonding. In addition, the bands at 2982 cm^{-1} and 2888 cm^{-1} can be assigned as C-H stretching of aliphatic and aromatic group. Next, peak at 2127 cm^{-1} is CC stretching. The intensity of the peak is quite strong at 1617 cm^{-1}, peak corresponds to C=C stretching vibration, the aromatic systems which constitute the anthocyanin structure are very characteristic.

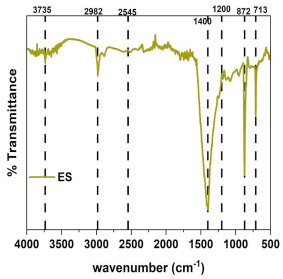
Another unique peak that occurs at 1270 cm^{-1} may be attributed to the stretching vibration of the C-O bond in phenols or flavonoid ethers. Last the following bands around 1385 cm^{-1}, 1035 cm^{-1} and 840 cm^{-1} are due to different C-H bending, stretching and out-of-plane vibration of skeleton of anthocyanins molecule [14].

FTIR spectrum of JPP+Antho+ES composite HG loaded with anthocyanins is shown in the fig.4.3(e). O-H stretching vibration of pectin that existed in spectrum of composite HG produced broad peak at 3280 cm^{-1} was attributed to the presence of a strong intermolecular hydrogen bonding between pectin, anthocyanins and the matrix of eggshell. Peak at around 2982 cm^{-1} arose from C-H stretching vibrations.

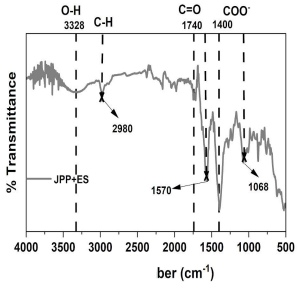
Secondly, the individual absorption at 1743 cm^{-1} corresponds to the C=O stretching of the esterified carboxyl groups belonging to the backbone of pectin [18]. The peak at 1565 cm^{-1} arises from overlapping asymmetric stretching of the carboxylate (COO -) ion of pectin and C=C aromatic ring stretching of added anthocyanins [23]. Finally, the wideband in 1393 cm^{-1} is interpreted as the symmetric COO^- stretching, overlapped with strong stretching of carbonate ion (CO) from eggshell [16]. The cm^{-1} vibration band is a stretching vibration band for the C-O linkage characteristic of phenolic compounds in anthocyanin compounds [14] and the steep vibration band at 870 cm^{-1} indicates the bending mode of out of the plane for the carbonate ion of calcite [16]. Thus, the all three species were incorporated into the HG matrix.



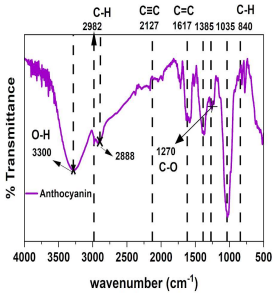
(a)



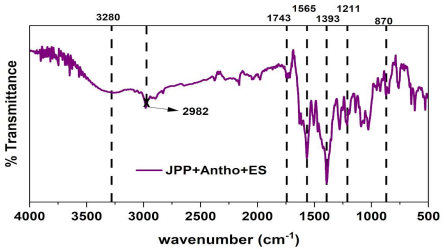
(b)



(c)



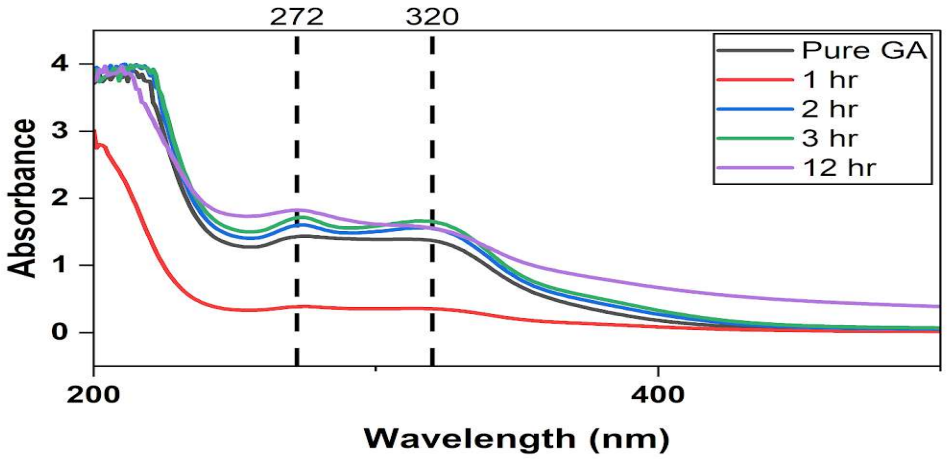
(d)



(e)

Fig. 4.3. FTIR Spectra of (a) Jackfruit Peel Pectin (JPP), (b) Egg Shell (ES), (c) Jackfruit Peel Pectin crosslinked by Egg shell (ES), (d) Gulphaira Anthocyanin (GA) and (e) Gulphaira Anthocyanin incorporated Jackfruit Peel Pectin-Egg Shell hydrogel (JPP+GA+ES)

4.4 Anthocyanin Release Study



The Gul Khaira anthocyanin's release kinetics and structural stability from the pectin-ES HG in deionized water was analysed with the time-resolved UV-Visible spectroscopy. A gradual increase in the value of the maximum intensity of the typical visible absorption band (max = 272 and 320 nm) during the measurement process has shown the diffusion of the pigment from polymer matrix during all the time, and no hypochromic or bathochromic effects prove that the structural integrity of the flavylium cation was preserved during transferring into aqueous solution [35, 36]. A steady progression of the increase in the typical visible absorption band during the study indicated that diffusion of pigment from the polymer remained throughout the experimental time; furthermore, no hypochromic or bathochromic shifts observed shows no change in the integrity of the flavylium cation in passing into aqueous solution [35, 36]. The primary observed UV range, at 272 nm, was attributed to the aromatic ring system of the aglycone moiety the basic flavanoid structural element. Meanwhile, unique shoulder at 320 nm corresponds to aromatic acylation in glycosidic unit that reflects esterification by such as hydroxyl cinnamic acid derivatives [35, 37]. This stability for the specific UV-Vis spectral profiles of the release suggests that these chemical features remained protected in the pectin-ES matrix and that hydrolysis of acylated anthocyanin complexes was largely prevented during release.

4.5 Thermal Analysis

DSC (Differential Scanning Calorimetry):

Fig. 4.5 (i) to (v) shows the DSC thermograms for the thermal stability studies of JPP, ES, JPP+ES, GA, and JPP+GA+ES composite HG. DSC thermogram of raw JPP presented a pronounced endothermic peak at about 205°C that attributed to the thermal degradation and depolymerization of the backbone of galacturonic acid of pectin [17]. The thermogram of ES shows a very stable thermal profile up to 300 °C without significant degradation peaks, which is typical for the strong inorganic calcium carbonate matrix [15]. For the extracted GA, a strong endothermic peak is found at around 145–150, corresponds to the melting point and structural disintegration of the anthocyanin molecules [13]. In JPP+ES, the pectin degradation sharp peak vanishes and the broad endothermic band appear around 115 °C after ionic crosslinking, confirming that the thermal stability is improved due to the successful coordination between the free carboxylate groups of pectin and the calcium ions from the eggshell. Finally, the different thermal degradation peaks of the separate components are entirely veiled in the JPP+GA+ES composite HG. Instead, a broad endothermic peak is detected at around 120 °C which corresponds to the evaporation of highly hydrogen-bonded and physically entrapped water molecules. This significant shift indicates that anthocyanin loaded HG network has been well entrapped and formed good crosslinking structures with sound thermal stability [19, 22].

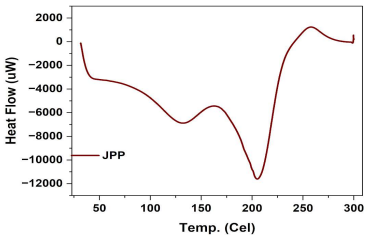


Fig. (i) DSC of Jackfruit Peel Pectin (JPP)

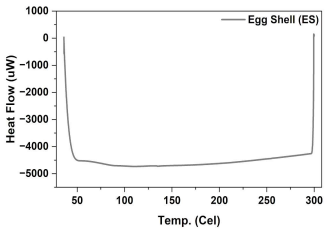


Fig. (ii) DSC of Egg Shell (ES)

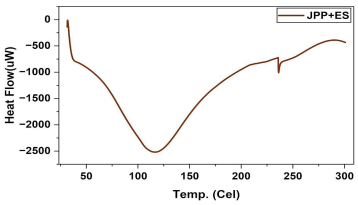


Fig. (iii) DSC of Jackfruit Peel Pectin and Egg Shell (JPP+ES)

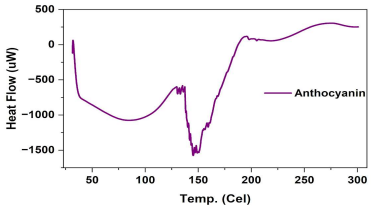


Fig. (iv) DSC of Gulphaira Anthocyanin (GA)

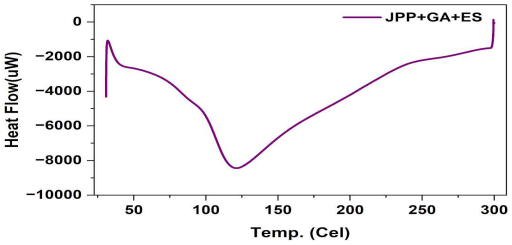


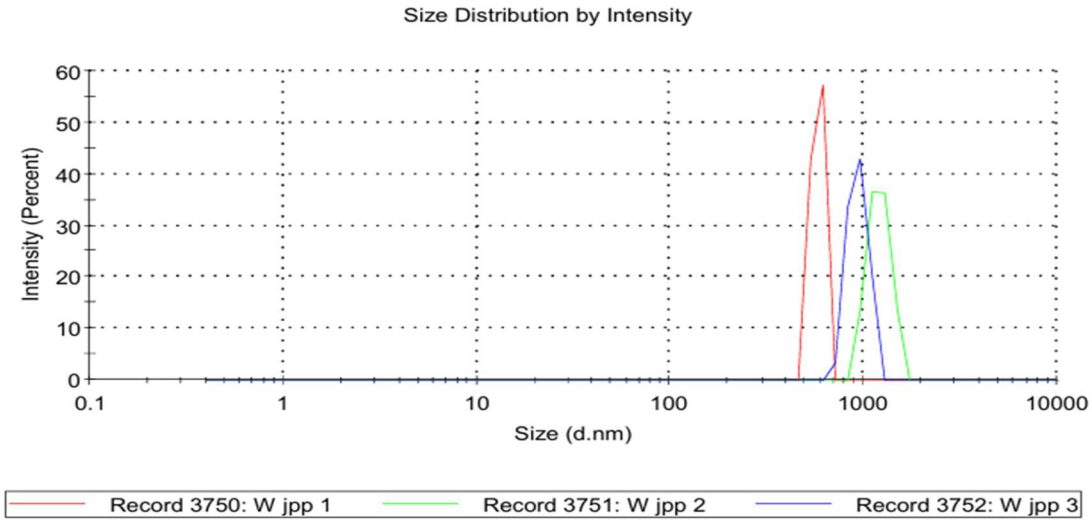
Fig. (v) DSC of Gulphaira Anthocyanin incorporated Jackfruit Peel Pectin crosslinked by egg shell hydrogel (JPP+GA+ES)

Fig. 4.5. DSC Plot of (i) Jackfruit Peel Pectin (JPP), (ii) Egg Shell (ES), (iii) Jackfruit Peel Pectin crosslinked by Egg shell (ES), (iv) Gulphaira Anthocyanin (GA) and (v) Gulphaira Anthocyanin incorporated Jackfruit Peel Pectin-Egg Shell hydrogel (JPP+GA+ES)

4.6 Zeta potential & Particle size

The properties of the particle size & surface charge of JPP were analyzed by DLS and zeta potential. The intensity size distribution indicates that a narrow monodisperse colloidal system is formed in water as is shown by the very low PDI of 0.065. The zeta potential is also shown to be unimodal with an average value of 12.5 mV. The

overall Z-average size is 1645 nm. In addition, the zeta potential analysis shows a unimodal distribution with an average value of −12.5 mV. This negative surface charge is largely believed to result from the deprotonation of the free carboxylate groups of the galacturonic acid (−COO) in the extracted pectin polymer chains [18]. Zeta potential of −12.5 mV shows pre-incipient colloidal instability by solely electrostatic repulsive force, But, the long ch ca bo ar re m



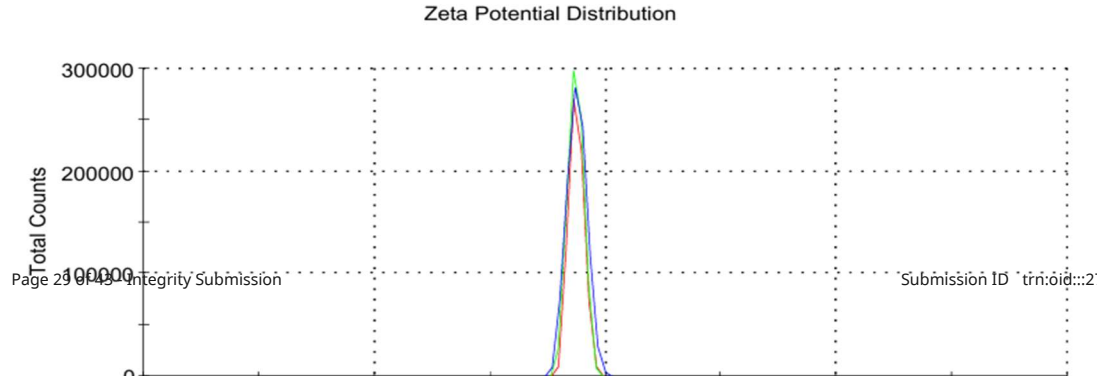


Fig.4.6 shows the particle size and zeta potential of the extracted jackfruit peel pectin (JPP) respectively

4.7 Rheological Measurements

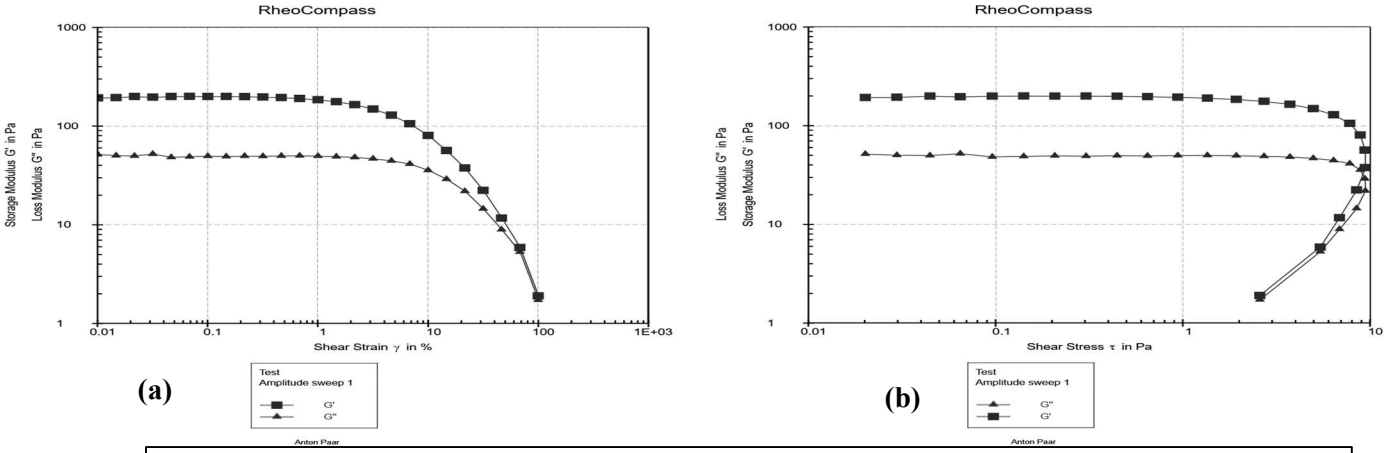


Fig. 4.7(a, b) Rheological amplitude sweep plot for the anthocyanin composite JPP—ES hydrogel.

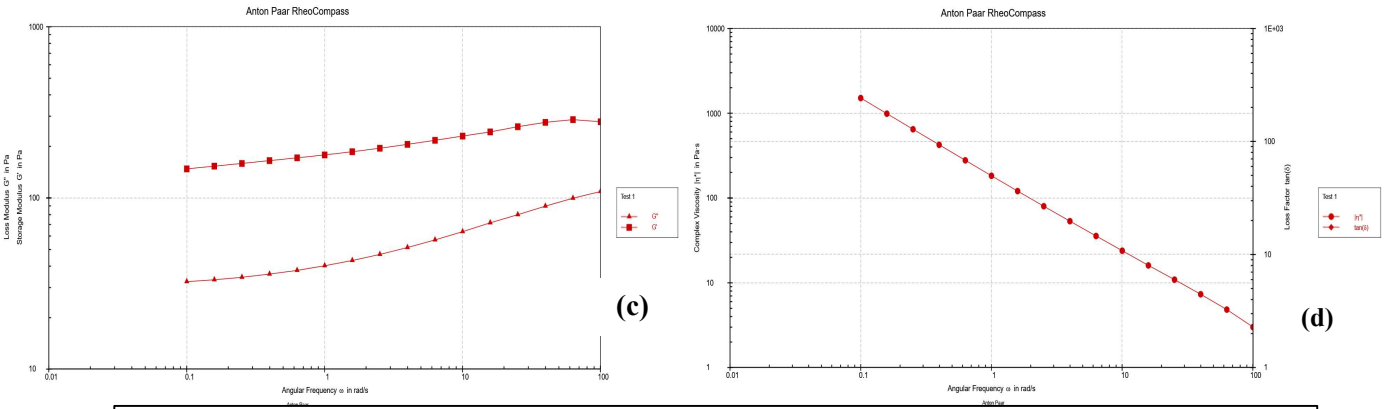


Fig. 4.7(c, d) Rheological frequency sweep plot for the anthocyanin composite JPP—ES hydrogel.

Viscoelastic properties of the developed HG were studied by oscillatory rheological tests. Amplitude sweep measurement as a function of shear strain (Fig. 4.7a) shows that both the

storage modulus (G′) and loss modulus (G″) have been maintained at plateau stability during LVR for small strain values (around 0.01-3%) with G′ (~200 Pa) having higher value compared to G″ (~50 Pa). This predominance of the elastic property over the viscous one is indicative of a good cross-linking process of the jelly-like network, indicating the formation of a stable three-dimensional HG matrix through ionotropic Ca^{2+}-egg box cross-links in the pectin gel matrix [25, 26]. In addition to the critical strain (~5–10%), there was an evident crossover of G' and G" that reflects network breakdown and gel-to-sol transformation due to large deformation, which is analogous to the strain-dependent yield behaviour of physically cross-linked pectin gels [12, 25]. Amplitude sweep data versus shear stress (4.7b) again shows results compatible with the other techniques since an elastic Plateau (at the very minimum shear stresses) declines, before suddenly diving under a certain shear stress limit (typically 2 - 5 Pa).

The shear stress at which G′ = G″ corresponds to the yield stress of the HG, beyond which irreversible structural breakdown initiates [34]. This well-defined yield point is consistent with the cohesive network architecture arising from Ca^{2+} coordination across galacturonate residues of pectin chains, forming the characteristic egg-box supramolecular assembly [18, 25].

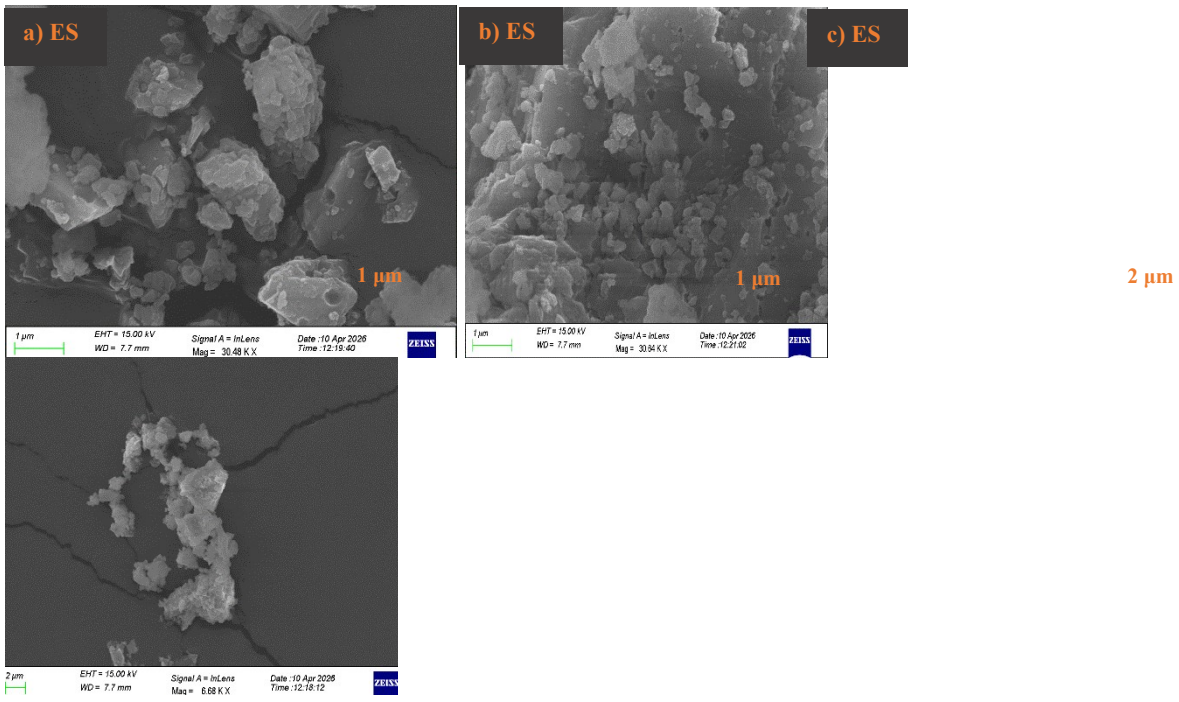
The frequency sweep (Fig.4.7c) demonstrated a monotonic increase in both G′ and G″ over the angular frequency range of 0.1–100 rad/s, with G′ maintaining predominance over G″ across the entire frequency window. The absence of any crossover or terminal flow behaviour within this frequency range confirms the predominantly elastic, solid-like character of the HG network and suggests a stable, entangled crosslink density without significant chain relaxation at the timescales probed [12, 26]. Such frequency-dependent stiffening is a hallmark of Ca^{2+}-crosslinked pectin HG and reflects restricted chain mobility imposed by the multivalent ionic coordination junctions [25].

The complex viscosity(η*) plot (Fig.4.7d) displayed a standard power-law drop in with increase in angular frequency with linear log-log response - denoting shear-thinning

viscoelastic behaviour. This decline in η* with frequency, combined with the maintained gel-like moduli, reflects the frequency-dependent disentanglement of the crosslinked network under oscillatory shear, consistent with a loss tangent (tan δ = G″/G′) less than unity across the frequency range [34]. The shear-thinning behaviour proves useful for potential injectability or flow processing approaches and post-shear structural recovery indicated the ability for the network to be reformed due to the physical crosslinking [26, 30]. In conjunction, rheological characterization confirms that the pectin-anthocyanin-eggshell composite HG had a well-structured and elastic-predominating viscoelastic network with distinct yield stress and shear-thinning behaviour of flowing which should originate from the ionic egg-box mechanism of crosslinking and it also in agreement with our earlier works on ionotropically crosslinked pectin-based HG system [12, 18, 25].

4.8 FESEM

FESEM images were used for investigating the surface morphology of eggshell particles, JPP and its HG (Fig.4.8).



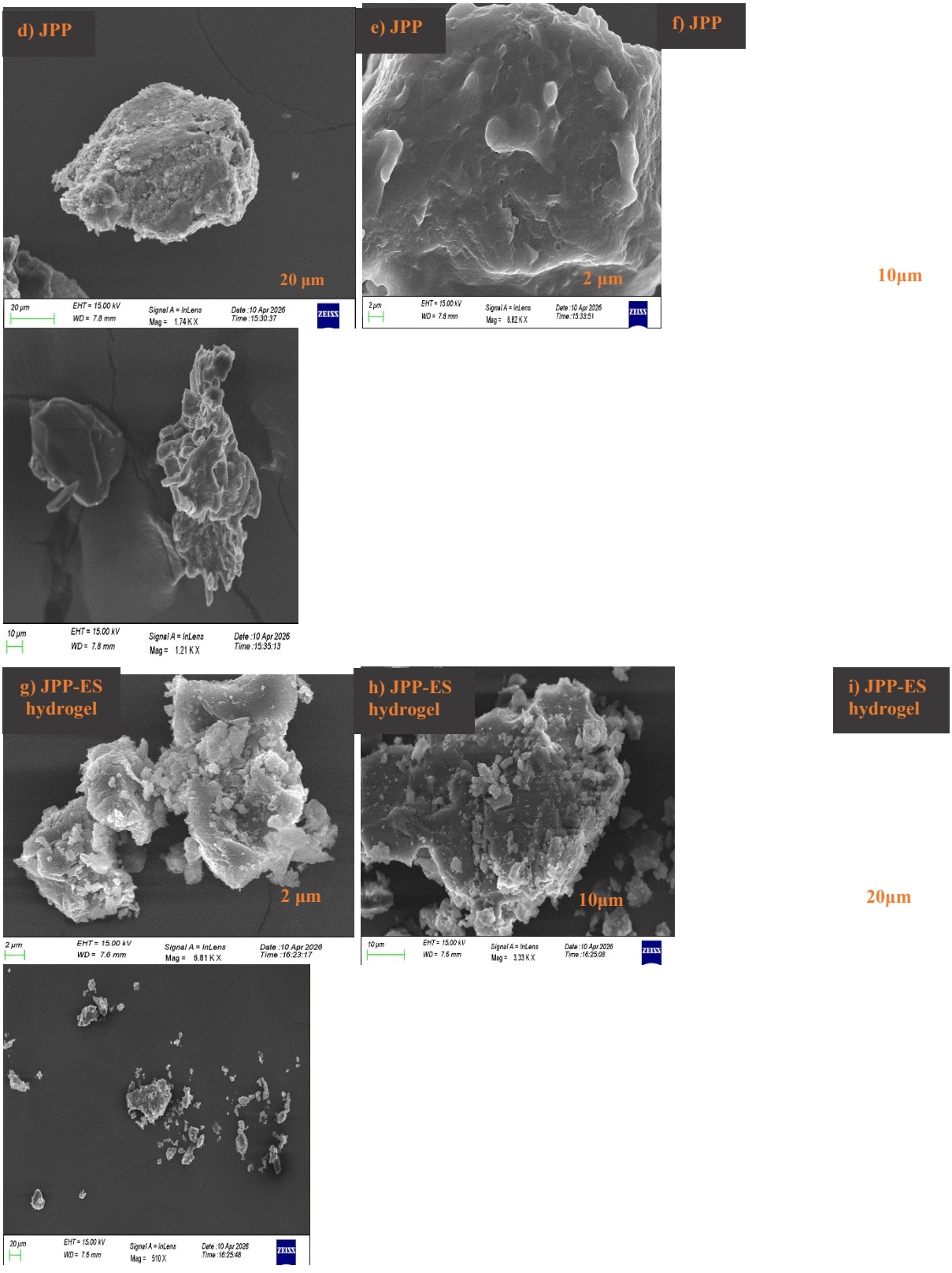


Fig.4.8. FESEM images of Eggshell (ES), Pectin derived from jackfruit peel (JPP), and there synthesized HG.

Eggshell (ES) consists of irregular, angular, and blocky granular aggregates (Fig.4.8a, c).

Particles display distinctly rigid, fractured geometric features that are highly characteristic of crystalline mineral phases (typically calcium carbonate). At 1µm (Fig.4.8b), the surface topography reveals a rough, heavily textured, and compact structure. This hard, granular micro structure together with its gradient distribution of particle size can maintain structural integrity, having adequate interface area for use as a bio-reinforcing filler or active adsorbent.

Whereas that pectin particles are aggregated into irregular, heterogeneous clumps, suggests that lack uniform crystalline geometry, asymmetrical agglomerates (Fig.4.8d, f). The diameter ranging from 50 to 80 µm are highly heterogeneous. At 2 µm highly corrugated, wrinkled, and porous topologies are visible (Fig.4.8e). These surfaces are deeply folded, indented, and completely amorphous in shape. Because of this rugged and discontinuous surface microstructure, the specific surface area of the pectin is maximized, which allows for convenient structural gaps and surface area for rapid hydration and effective matrix entrapment during gelation.

FESEM images of pectin-ES composite HG shows that the HG particles are distributed in widely dispersed, irregular clusters at 20 µm (fig.4.8i) . Implies that HG formation and subsequently drying caused fragmentation and separation of the composite to separate, broken down agglomerates rather than a complete monolith.The diameter ranging from approximately 10 to 80 µm, a dense granular composites and flake-like shapes are visible in the pectin-ES HG matrix (Fig.4.8g, h). These composite blocks are highly textured, rigid, and distinctly uneven in shape. Due to incorporation of the eggshell (ES) into the HG, the smooth amorphous structures of the base pectin were completely disrupted, and heavily coated, granular structures were observed across the composite surfaces. Furthermore, significant discontinuities, fractured planes, and microscopic gaps between the granular structures were observed throughout the pectin-ES HG, presenting a highly heterogeneous, interlocking, and rough surface morphology.

Elemental analysis

Energy dispersive X-ray spectroscopy (EDX) was utilized for elemental analysis & pure determination of eggshell, JPP & produced HG. The analysis demonstrated that carbon and oxygen were the primary constituents across the mapped samples. Traces of structural and trace elements such as calcium, potassium, aluminium and phosphorus, were found in varying amounts. The separation that these additional components (in particular, Ca and P) present themselves as, are also a feature to be anticipated from a precursor like eggshells, within an inorganic mineral matrix. List the atomic percent composition (as calculated by Sum Spectrum): is given in Table 1.

Table 1: Elemental composition of eggshell, pectin, and its HG.

Atomic (%)	C	O	Ca	P	K	Al	F	Zn	Fe	Cu	Mg
Eggshell (ES)	50.86	30.17	1.35	6.87	-	4.03	-	0.70	0.40	0.29	-
Jackfruit peel pectin (JPP)	50.83	48.21	0.38	-	0.51	-	-	-	0.04	-	0.02
JPP-ES HG	40.01	47.66	5.13	0.77	3.76	0.17	1.27	0.26	0.21	0.32	0.24

Chapter 5

CONCLUSION

5.1 CONCLUSION

This investigation successfully establishes a broad, green-chemistry framework for fabrication of a fully bio-derived, functionalized HG matrix. This approach of extracting pectin using mild conditions and using a citric acid catalyst from abundant agricultural waste material – Artocarpus heterophyllus peel to a value-added biopolymer – appears a very practical method. Moreover, we demonstrated the calcium oxide obtained from calcinating waste eggshells works as an effective green ionic crosslinking agent. This approach helped the establishment of a sturdy three-dimensional polymeric matrix exhibiting typical 'egg-box' structural configuration resulting into a dual-waste valorization paradigm. Anthocyanin derived from Alcea rosea (Gul Khaira) petals through ethanoic acid was successfully incorporated in HG to obtain a very stable photophysical active pigment. Spectroscopic examination such as UV-Vis, gave a range of highest absorbance at between 520-540 nm range. The structural integrity and chemical coordination of this composite were extensively corroborated through FTIR and FESEM analyses. The FTIR spectra showed that the interaction between the carboxylate groups of the pectin and the calcium cations had occurred and that the anthocyanin molecules had been incorporated into the system without disturbing the bulk material. Morphologically, the composite exhibited a highly porous, interconnected architecture, which was subtly modified by the presence of the botanical pigment. Thermal and kinetic studies have further confirmed the

material's stability and viability. Thermal Analysis (DSC) revealed that Eggshell-mediated crosslinking dramatically elevated the thermal stability of the matrix. In comparison to the incorporation of anthocyanin, the introduction of pigment resulted in particular degradation effects specifically tied to the anthocyanin pigment. Overall, the thermal stability of the HG was not negatively affected. Swelling kinetics demonstrated a highly tunable water-absorption capacity, dictated directly by the crosslinker concentration, allowing for precise control over network density. Ultimately, this work delivers a cost effective, easily scalable biopolymeric system with substantial potential for active compound delivery.

5.2 FUTURE SCOPE

The foundational methodologies and empirical outcomes established in this study provide a versatile platform for several advanced technological and industrial applications. A primary avenue for immediate exploration lies in the realm of intelligent packaging systems. As anthocyanins have clear predictable colorimetric transitions in response to pH changes, the prepared HG can be used to construct a visual indicator smart film. Films like that might display real-time shelf life of things like milk, poultry and seafood through some visual indication of the change in pH caused by bacterial spoilage. Other than packaging, there is high potential to utilize matrix in the field of agro-chemicals, and biomedical. The developed pectin-calcium based matrix is biocompatible and can be

functionalized with a range of plant derived antimicrobials, essential oil or targeted nutraceuticals. From an agronomic point of view, such expansion dynamics of the HG could be interesting to conceive superabsorbent and controlled-release matrixial materials for agriculture. Adding important trace minerals like iron, copper, or zinc to the polymer, or growth hormones, would make it a vehicle that releases nutrients over time to promote fertile soil conditions and also provide a useful tool in areas of the world where drought conditions are most challenging.

5.3 SOCIAL IMPACT

The impact of this research goes beyond that, contributing immensely to the fields of environment and community betterment. Such endeavours are crucial as they facilitate the creation of a bio-circular economy through the elimination of not just one, but two waste streams-jackfruit peel (which creates a seasonal disposal problem in India) and eggshells. Provides a practical, scalable approach to the municipal solid waste problem that is currently being addressed by this project, and produces state-of-the-art materials. This fits the development agenda strongly into creating a more remote, circular, economy around the rural areas which represent the core of agricultural waste production. This synthesis of a biodegradable and plant-derived option will, additionally combat the growing issue of petro-chemical plastic contamination, and thus offer a non-toxic, alternative to plastic wrap which could pose long-term risks. Used as the cheapest

water conservation and soil-conditioning water storing devices on farms this could help resource-poor farming operations. The technology can help to strengthen regional food security by promoting water conservation and enhancing the resistance of crops to drought and climate stress. Finally, research on the topic really calls for to leave poisonous man-made colors as well as transition to well-being natural colors as well as is in line with public outcry to “clean” up honor mark that implies non-toxic food. From an educational standpoint, affordable, locally sourced plant waste and basic laboratory procedures also present this technology as an excellent candidate for the classroom: an easily replicated low-cost experiment in hands of tomorrow’s community volunteers or the next generation of researchers can really foster the environment around green chemistry and scientific literacy.

REFERENCES

1. Gayen T.K., Ali, M.A. & Warkar, S.G. (2026) Mustard stalk-derived cellulose bio-HG for soil amendment and plant nutrients carriers. J Indian Chem Soc 103:102528. https://doi.org/10.1016/j.jics.2026.102528
2. Gayen T.K., Ali, M.A. & Warkar, S.G. (2026) Agricultural Waste-Derived Lignin and Chitosan Blend Bio HG for Controlled Release of Muriate of Potash for Sustainable Agricultural Applications. Ind Eng Chem Res. https://doi.org/10.1021/acs.iecr.5c05055

3. Gayen T.K., Ali, M.A. & Warkar, S.G. Agricultural and food wastes derived cellulose HG for water reservoirs and dye sorption. Polym. Bull. 83, 319 (2026). https://doi.org/10.1007/s00289-026-06386-6
4. X. Wang, Q. Chen, X. Lu, Pectin extracted from apple pomace and citrus peel by subcritical water, Food Hydrocoll. 38 (2014) 129–137. https://doi.org/10.1016/j.foodhyd.2013.12.003
5. Pectin: An overview of sources, extraction and applications in food products, biomedical, pharmaceutical and environmental issues. https://doi.org/10.1016/j.focha.2023.100192
6. Canteri, Maria & Fertonani, Heloísa & Waszczynskyj, Nina & Wosiacki, Gilvan. (2005). Extraction of pectin from apple pomace. Brazilian Archives of Biology and Technology. 48.259-266.10.1590/S1516-89132005000200013. https://www.researchgate.net/publication/247851083
7. Sundarraj, a. Allwyn & thottiam vasudevan, ranganathan. (2018). Extraction and functional properties of cellulose from jackfruit (artocarpus integer) waste. International Journal of Pharmaceutical Sciences and Research. 9. 4309-4317. 10.13040/IJPSR.0975-8232.9(10).4309-17. https://www.researchgate.net/publication/328138778
8. Rangina Brahma, Subhajit Ray, Optimization of extraction conditions for cellulose from jackfruit peel using RSM, its characterization and comparative studies to commercial cellulose,Measurement: Food,Volume 13,2024,100130, ISSN 2772-2759.https://doi.org/10.1016/j.meafoo.2023.100130
9. Ahmed MS, Maniruzzaman M, Al-Mamun MR et al (2023) Jute Stick-Derived Cellulose-Based HG: Synthesis, Characterization, and Methylene Blue Removal from Aqueous Solution. ACS Omega 8.https://doi.org/10.1021/acsomega.3c06349
10. He Q, Shen Y, Wang M, Huang M, Yang R, Zhu S, Wang L, Xu Y, Wu R. Natural variation in petal color in Lycoris longituba revealed by anthocyanin components. PLoS One. 2011 Aug 4;6(8):e22098. https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0022098
11. Xiaoming Guo, Tao Zhang, Hecheng Meng, Shujuan Yu, Ethanol precipitation of sugar beet pectins as affected by electrostatic interactions between counter ions and pectin chains, Food Hydrocolloids, Volume 65, 2017, Pages 187-197, ISSN 0268-005X, https://doi.org/10.1016/j.foodhyd.2016.11.010.
12. Sourbh Thakur, Jyoti Chaudhary, Vinod Kumar, Vijay Kumar Thakur, Progress in pectin-based HG for water purification: Trends and challenges, Journal of Environmental Management,Volume 238, 2019, Pages 210-223, ISSN 0301-4797, https://doi.org/10.1016/j.jenvman.2019.03.002.
13. Zaker Bahreini, Mohammad Abedi, Alireza Ashori, Ali Parach, Extraction and characterization of anthocyanin pigments from Iris flowers and metal complex formation, Heliyon,Volume 10, Issue 11, 2024, e31795, ISSN 2405-8440, https://doi.org/10.1016/j.heliyon.2024.e31795.
14. Maxwell T Hincke, Yves Nys, Joel Gautron, Karlheinz Mann, Alejandro B Rodriguez-Navarro, Marc D McKee. The eggshell: structure, composition and mineralization. *Front. Biosci. (Landmark Ed)* 2012, 17(4), 1266-1280. https://doi.org/10.2741/3985

15. Tangboriboon, N., Kunanuruksapong, R. & Sirivat, A. Preparation and properties of calcium oxide from eggshells via calcination. *Mater Sci-Pol* **30**, 313–322 (2012). https://doi.org/10.2478/s13536-012-0055-7
16. Sundarraj, A. Allwyn. (2017). Physicochemical characterization of Jackfruit (Artocarpus integer (Thumb.).) Peel. Research Journal of Pharmaceutical, Biological and Chemical Sciences. 8. 2285 - 2295. https://www.researchgate.net/publication/321170588
17. Antony Allwyn Sundarraj, Ranganathan Thottiam Vasudevan, Gobikrishnan Sriramulu, Optimized extraction and characterization of pectin from jackfruit (Artocarpus integer) wastes using response surface methodology, International Journal of Biological Macromolecules, Volume 106, 2018, Pages 698-703, ISSN 0141-8130, https://doi.org/10.1016/j.ijbiomac.2017.08.065
18. Renata Dobrucka, Marcin Szymański, Structure–function relationships of in situ Ca2+-crosslinked pectin/karaya gum films containing Scutellaria baicalensis extract and their effect on blueberry anthocyanin stability, Food Hydrocolloids, Volume 179, 2026, 112732, ISSN 0268-005X, https://doi.org/10.1016/j.foodhyd.2026.112732.
19. Thi-Hong-No Nguyen, Cong-Binh Tran, Thi-Kieu-Oanh Vu, Van-Khoa Nguyen, Minh-Ty Nguyen, Thanh-Chi Mai, Chi-Hien Dang, Dinh-Tri Mai, Huu-Trung Nguyen, Thanh-Danh Nguyen, Anthocyanin incorporated pectin/sericin biofilms for food packaging and shrimp freshness monitoring, International Journal of Biological Macromolecules, Volume 341, Part 1, 2026, 150250, ISSN 0141-8130, https://doi.org/10.1016/j.ijbiomac.2026.150250.
20. Akbar Ali N, Momin Arsalaan, Mujahid Ali Khan, Mujawar Sahil. The Cottage Rose (Alcea rosea): A Phytochemical and Pharmacological Review. Asian Journal of Research in Pharmaceutical Sciences. 2025; 15(4):428-8. doi: 10.52711/2231-5659.2025.00063
21. Liu Yang, Sheng Chen, Zhipeng Jiang, Xue Ding, Wenwen Chen, Ning Ma, Shengyu Xu, Hongyuan Zhang, Application of sodium alginate-pectin active intelligent film containing anthocyanins from Aronia melanocarpa and tea polyphenols in pork preservation and freshness monitoring, Meat Science, Volume 230, 2025, 109931, ISSN 0309-1740, https://doi.org/10.1016/j.meatsci.2025.109931.
22. Chang Liu, Ning Li, Xinyu An, Xu Li, Zhiming Liu, Pectin/zinc alginate films containing anthocyanins from dragon fruit peel as intelligent pH indicators for shrimp freshness monitor, International Journal of Biological Macromolecules, Volume 285, 2025, 138317, ISSN 0141-8130, https://doi.org/10.1016/j.ijbiomac.2024.138317.
23. Shubham Sharma, Kalpani Y. Perera, Amit K. Jaiswal, Swarna Jaiswal, Chapter 8 - Natural antimicrobials from fruits and plant extract for food packaging and preservation, Editor(s): Amit K. Jaiswal, Shiv Shankar Food Packaging and Preservation, Academic Press, 2024, Pages 133-152, ISBN 9780323900447, https://doi.org/10.1016/B978-0-323-90044-7.00008-2.
24. Guilherme, M. R., Reis, A. V., Paulino, A. T., Moia, T. A., Mattoso, L. H. C., & Tambourgi, E. B. (2010). Pectin-based polymer HG as a carrier for release of agricultural nutrients and removal of

heavy metals from wastewater. Journal of Applied Polymer Science, 117(6), 3146–3154. https://doi.org/10.1002/app.32123.

25. Said, N. S., Olawuyi, I. F., & Lee, W. Y. (2023). Pectin HG: Gel-Forming Behaviors, Mechanisms, and Food Applications. Gels, 9(9), 732. https://doi.org/10.3390/gels9090732
26. Malik, R., Warkar, S. G., & Saxena, R. (2023). Carboxy-methyl tamarind kernel gum based bio-HG for sustainable agronomy. Materials Today Communications, 35, 105473. https://doi.org/10.1016/j.mtcomm.2023.105473
27. Khushbu, Warkar, S. G., & Kumar, A. (2019). Synthesis and assessment of carboxymethyl tamarind kernel gum based novel superabsorbent HG for agricultural applications. Polymer, 182, 121823. https://doi.org/10.1016/j.polymer.2019.121823
28. Khushbu, Warkar, S. G., & Thombare, N. (2021). Zinc micronutrient-loaded carboxymethyl tamarind kernel gum-based superabsorbent HG: controlled release and kinetics studies for agricultural applications. Colloid and Polymer Science, 299, 1103–1111. https://doi.org/10.1007/s00396-021-04831-8
29. Yadav, E., Pandey, K., Khushbu, Rani, I., & Warkar, S. G. (2024). Synthesis and application of zinc-loaded carboxymethyl tamarind kernel gum and xanthan gum-based superabsorbent HG to investigate the effect on sesame plant growth. Polymer Bulletin, 81, 9009–9030. https://doi.org/10.1007/s00289-024-05150-y
30. Ganguly, S., Wulff, D., Phan, C. M., Jones, L. W., & Tang, X. S. (2024). Injectable and 3D Extrusion Printable Hydrophilic Silicone-Based HG for Controlled Ocular Delivery of Ophthalmic Drugs. ACS Applied Bio Materials, 7(9), 6286–6296. https://doi.org/10.1021/acsabm.4c00901
31. Siepmann, J., & Peppas, N. A. (2011). Higuchi equation: Derivation, applications, use and misuse. International Journal of Pharmaceutics,418(1),6–12. https://doi.org/10.1016/j.ijpharm.2011.03.051.
32. Yue Han, Xiaolin Jin, Ziyan Zhang, Qingshen Sun, Characterization of pectin with different structural features and its effects on Yogurt quality, LWT, Volume 229, 2025, 118236, ISSN 0023-6438, https://doi.org/10.1016/j.lwt.2025.118236.
33. Xingfa Ma, Mehdi Habibi, Leonard M.C. Sagis, Particle size and morphological features of lupin protein-pectin complexes affect the oil-water interfacial properties and emulsion stabilization, Food Hydrocolloids, Volume 168, 2025, 111497, ISSN 0268-005X, https://doi.org/10.1016/j.foodhyd.2025.111497.
34. H. Hezaveh, I.I. Muhamad, Modification and swelling kinetic study of kappa carrageenan-based HG for controlled release study, J Taiwan Inst Chem Eng 44 (2013) 182-191. https://doi.org/10.1016/j.jtice.2012.10.011.
35. Saha, S., Singh, J., Paul, A., Sarkar, R., Khan, Z., & Banerjee, K. (2019). Anthocyanin Profiling Using UV-Vis Spectroscopy and Liquid Chromatography Mass Spectrometry. *Journal of AOAC International*, 103(1). https://doi.org/10.5740/jaoacint.19-0201

36. Subasini, S., Bhavadharani, D., Devi, S. G., Kanagalakshmi, M., & Pius, A. (2025). Fabrication of Halochromic Carboxymethylcellulose Strips Integrated with Anthocyanins for Real-time Visual Detection of Meat Quality. *Food Analytical Methods*, 18, 1863-1883. https://doi.org/10.1007/s12161-025-02833-8
37. Jeyaram, S., & Geethakrishnan, T. (2020). Vibrational spectroscopic, linear and nonlinear optical characteristics of Anthocyanin extracted from blueberry. *Results in Optics*, 1, 100010. https://doi.org/10.1016/j.rio.2020.100010