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Eco-Friendly Composite Film from Seaweed Biopolymer and *Cyclea peltata*: A Sustainable Material Study

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A composite film was prepared by combining κ-carrageenan (KC) extracted from *Eucheuma cottonii* seaweed with a pectin-rich gel obtained from the leaves of *Cyclea peltata* (CP), a medicinal climber whose pectin has not previously been used for film fabrication. The film, formulated at a 3:1 (v/v) KC:CP ratio with 0.5% sorbitol, was investigated for its structural, thermal, mechanical, barrier, antimicrobial and soil-burial biodegradation behaviour, with KC and CP. Scanning electron microscopy (SEM), X-ray diffraction (XRD), Fourier-transform infrared spectroscopy (FTIR), thermogravimetric analysis (TGA/DTG) and atomic force microscopy (AFM) confirmed the formation of an integrated matrix in which CP pectin interacts with KC through hydrogen bonding at peak intensification at 3300 cm^{-1}. Mechanical testing showed that the composite film displayed higher elongation at break and lower water solubility than pure KC, with intermediate tensile strength. The water-vapour permeability of the composite was comparable to that of pure KC and soil-burial testing showed 74.5 ± 3% mass loss after 20 days. Antimicrobial activity against *Escherichia coli* and *Staphylococcus aureus* reduction of 99.33%. Together, the data indicate that the KC-CP composite is a promising biopolymer-based film for short-shelf-life food-contact applications, with full oxygen-transmission-rate and shelf-life evaluation identified as the next stage of work.

Keywords: κ-Carrageenan, Pectin, *Cyclea peltata*, Biopolymer food packaging, Soil-burial biodegradation, Water-vapour permeability.

INTRODUCTION

The food industry plays a critical role in both society and the economy because it includes multiple activities starting from food production and ending with food consumption. The growth of food processing facilities throughout India demonstrates their vital role in providing nutritional security through all aspects of food delivery, which includes food distribution and food consumption and food storage. The agricultural sector makes a major contribution to India's Gross Domestic Product (GDP) while at the same time, it serves vital functions for rural development which helps the entire nation progress. The food sector acts as a vital link which connects agriculture with industrial development to support economic growth in India. The organisation creates job opportunities while it improves farmer incomes and drives export business growth [1,2]. The food industry adopts advanced technologies such as IoT-based Food Supply Chain Management (FCM) to establish its position as an industry leader. The innovation enables a dual benefit to organisations because it enhances food safety and quality while simultaneously decreasing expenses to fulfil rising customer requests for top-tier food products [3].

Packaging materials are essential to the food industry, as they help maintain food safety, preserve quality and extend shelf life. Conventional materials such as plastics and paper, along with emerging biopolymers, are widely used to protect food from physical, chemical and microbial contamination. By preventing spoilage and deterioration, these materials help maintain the freshness, nutritional value, and quality of food products during storage, transportation, and consumption [4-7]. Plastic remains the dominant food-packaging material due to its excellent barrier properties against gases and water vapour, which are critical for preserving food quality [8]. However,

concerns regarding the environmental and health impacts of non-biodegradable plastics have accelerated research into sustainable alternatives, including biodegradable plastics, polymer composites and biotechnology-based materials [9,10]. Growing consumer demand for renewable and eco-friendly products has further driven the development of advanced food-packaging systems that integrate active, intelligent and sustainable technologies [11].

Emerging packaging materials, including edible and biodegradable films, plant-extract-based formulations and nanomaterial-enhanced systems, are designed to improve food safety, quality and shelf life. Traditional packaging materials often provide limited protection, prompting increased interest in biopolymers and bio-nanocomposites due to their biodegradability and enhanced barrier properties [10,12]. Recent advances in packaging technologies combine automated manufacturing processes with innovative biodegradable materials to improve food preservation while reducing environmental impact [13]. Furthermore, antimicrobial and biopolymer-based packaging materials inhibit microbial growth and offer sustainable alternatives to conventional packaging [8,14]. Biopolymers derived from natural sources, such as proteins, carbohydrates and lipid derivatives, along with edible coatings and films produced from renewable agricultural and food-processing byproducts, have shown significant potential because of their biodegradability and effective moisture, gas and microbial barrier properties [15,16].

Biodegradable polymeric nanocomposites are gaining recognition as a promising innovation in food packaging, catering to the pressing demand for renewable substitutes to traditional plastic packaging [17]. The improved mechanical and barrier characteristics will enhance food products by helping to maintain their freshness for extended periods of time [18,19]. The nanocomposites which are designed to improve food safety and lengthen product shelf life have superior mechanical strength and barrier features while remaining compostable to reduce their environmental footprint. The materials create sustainable composite materials through the use of biodegradable polymers and nano-sized fillers which result in products that enhance performance while solving environmental issues linked to non-biodegradable plastics [20]. Biodegradable polymeric nanocomposites show potential as alternatives to conventional packaging materials. However, the practical application of these materials remains challenging due to the need to balance biodegradability with adequate mechanical strength, while also ensuring cost-effective manufacturing and scalable processing methods [21,22]. The development of biodegradable food packaging solutions which combine strong mechanical characteristics with environmental sustainability and effective food preservation abilities therefore requires immediate attention.

κ-Carrageenan (KC) is widely used in the food industry because of its excellent stabilizing, thickening, gelling, and emulsifying properties [23-25]. It improves food texture and solubility and can serve as a fat replacer in certain formulations [26]. Owing to its favourable mechanical strength and UV-protective properties, KC has also gained attention as a biodegradable food-packaging material [27]. Recent studies have explored its application in composite membranes for water filtration [28] and edible films enhanced with grapefruit essential oil [29]. In addition, sustainable biopolymer extraction from plants of the Menispermaceae family has highlighted their potential for food and biomedical applications [30]. *Cyclea peltata* (CP), a medicinal plant used in traditional medicine, produces a gel that can replace agar in microbiological and plant tissue culture media due to its stability and gel-forming ability [31]. Furthermore, CP leaf extracts have been employed in the green synthesis of silver nanoparticles for biomedical and optical applications [32].

Pectin is a biodegradable, biocompatible and non-toxic polysaccharide widely used in food packaging. Its film-forming ability and oxygen-barrier properties help extend the shelf life of food products [33,34]. Pectin-based edible films and coatings offer sustainable alternatives to conventional packaging while improving food safety [35]. Pectin extracted from *Cyclea barbata* Miers leaves exhibits promising emulsifying properties for packaging applications [36]. Moreover, pectin-based films have demonstrated rapid biodegradation under environmental conditions, confirming their eco-friendly nature [37]. The incorporation of pectin with other biopolymers can further enhance antioxidant and antimicrobial properties, making it suitable for active packaging systems [38,39]. Leaf-derived pectins, including those from *Nephrolepis biserrata*, have also shown potential for food-packaging applications despite compositional differences from commercial pectins [38,40].

Although κ-carrageenan and pectin have been extensively studied separately, their combination with pectin extracted from CP leaves has not been previously reported. This study addresses this gap by investigating CP leaf pectin as a novel co-biopolymer in κ-carrageenan films. The interaction between the hydroxyl- and carboxyl-rich pectin and the sulphated κ-carrageenan matrix was examined through its effects on surface morphology, crystallinity and thermal stability. In addition, key properties relevant to food-packaging applications including water uptake, solubility, water-vapour permeability, mechanical strength, antimicrobial activity and biodegradability, were evaluated.

EXPERIMENTAL

Extraction of CP gel/pectin: Mature, healthy leaves of *Cyclea peltata* were collected from Belman, Udupi district, (13º10′49″N and 74º53′29″), India and authenticated by a qualified taxonomist; a voucher specimen has been deposited at the Department of Biotechnology Engineering, NMAMIT. Leaves were washed thoroughly with distilled water, surface-dried and chopped into approximately 1 cm^2 pieces. A 100 g portion of fresh leaf material was macerated with 500 mL of distilled water at room temperature (28 ± 2 ºC) for 30 min in a domestic blender and the resulting slurry was filtered through four-layer muslin cloth to remove fibrous residue. The filtrate, a viscous green hydrogel, was allowed to stand at 4 ºC for 12 h to permit complete gel formation and was then processed to yield white processed powder form (yield 2.5% w/v on a fresh-leaf basis). The dried white pectin was reconstituted in distilled water at the required concentration for film casting [41].

κ-Carrageenan source: Food-grade κ-carrageenan, extracted from *E. cottonii* seaweed, was procured commercially and used as received. A 1% (w/v) stock solution was freshly prepared in distilled water before each film-casting experiment.

Formulation of KC-CP composite films: Films were cast at four different KC:CP volume ratios (4:1, 3:1, 2:1 and 1:1) to identify the optimum composition. For each formulation, a 1% (w/v) κ-carrageenan solution was prepared in deionsed water, heated to 60 ºC with continuous magnetic stirring for 45 min until a homogeneous solution was obtained and combined with the freshly reconstituted CP pectin gel (1% w/v in deionsed water) at the required ratio. Sorbitol (0.5% w/v of total solution) was added as a plasticiser. The pure-KC and pure-CP controls were prepared in parallel from 50 mL of 1% KC solution and from 10 mL of CP gel diluted with 40 mL of distilled water, respectively. All solutions were cast onto levelled glass plates (10 cm × 10 cm) and dried in a hot-air oven at 60 ºC for 18 h. Dried films were peeled from the plates and conditioned in a desiccator at 25 ºC and 50% RH for 48 h prior to characterisation.

Characterisation: The surface morphology of the films was examined by scanning electron microscopy (SEM; EVO MA18, Oxford EDS X-act detector) after sputter-coating the samples with a thin gold layer. Structural characteristics and crystallinity were analysed using X-ray diffraction (XRD; Rigaku Miniflex 600, 5th generation) at 15 mA with a step size of 0.02º over a 2θ range of 5-90º. Fourier-transform infrared spectroscopy (FTIR; Bruker Alpha II, Germany) was performed in ATR mode over the spectral range of 4000-400 cm^{-1} to identify functional groups and molecular interactions. Thermal stability was evaluated by thermogravimetric analysis (TGA/DTG; DSC 60 Plus, Shimadzu, Japan) by heating approximately 5 mg of sample from room temperature to 600 ºC at 10 ºC min^{-1} under a nitrogen atmosphere, and parameters including $T_{5\%}$, $T_{50\%}$, T_{max} and residual mass were determined. Surface topography was further characterized by atomic force microscopy (AFM) in tapping mode using three 5 × 5 μm^2 scan areas per sample and the average roughness (R_a), root-mean-square roughness (R_q) and maximum roughness (R_t) values were calculated and reported as mean ± standard deviation (n = 3).

Tensile testing: Mechanical properties were measured on an Instron 3366 universal testing machine. Films were cut into rectangular strips (10 × 60 mm) and the gauge length was set to 30 mm with a crosshead speed of 5 mm min^{-1}. Tensile strength (TS, MPa), Young's modulus (E, MPa) and elongation at break (ε_b, %) were derived from the load-displacement curves using the measured mean film thickness:

$$TS = \frac{F_{max}}{w \times t}$$

where w = 10 mm and t = mean thickness. Five replicates were measured per sample.

Moisture content: Films were cut into uniform small pieces and weighed precisely (W_o). The samples were dried in a hot-air oven at 110 ºC for 24 h, cooled in a desiccator and re-weighed (W_d).

$$\text{Moisture content } (\%) = \frac{W_o - W_d}{W_o} \times 100$$

Solubility: Solubility was measured by the method of Hosseini *et al.* [42]. Pre-weighed strips of 1 cm × 3 cm (A_0) were immersed in distilled water with continuous stirring for 6 h. The undissolved films were filtered, dried at 105 ºC to constant mass (A_1) and water solubility (%) was calculated as:

$$\text{Water solubility } (\%) = \frac{A_0 - A_1}{A_0} \times 100$$

Film thickness measurement: The thickness of each film was measured at five randomly selected points using a digital micrometre (Mitutoyo, resolution 0.001 mm). Mean ± standard deviation values were used in the calculation of tensile strength and water-vapour permeability.

Water-vapour permeability (WVP): Water-vapour permeability was determined gravimetrically by the cup method [43]. Film samples (exposed area 10 cm^2) were sealed over the mouth of glass cups containing 5 g of anhydrous $CaCl_2$ (0% RH inside the cup) and placed in a controlled chamber at 25 ºC and 75% RH. The mass of the assembly was recorded every 2 h for 24 h and WVP (g mm m^{-2} day^{-1} kPa^{-1}) was calculated as:

$$WVP = \frac{\Delta m \times L}{A \times \Delta t \times \Delta P}$$

where Δm/Δt is the steady-state slope of mass uptake *versus* time; L is the mean film thickness; A is the exposed area; and ΔP is the partial pressure difference of water vapour across the film. Three replicates were measured for each formulation.

Antimicrobial activity: The procedure followed the standards EN 1276 [44] and EN 1650 [45] and was applied for bactericide and fungicide tests, respectively. Bacterial strains were grown to achieve 1.5-5 × 10^8 CFU/mL. The test product was diluted with distilled water prior to use. Interfering substances and the test product were added to the suspension at 20 ºC. The surviving bacteria were counted after incubation at 36 ºC for 24-48 h. A reduction of 5 log or more was considered to be acceptable. Fungicidal tests were performed with fungal strains at 1.5-5.0 × 10^7 CFU/mL, incubated at 30 ºC for 24-48 h (yeast) or 7 days (mold). A reduction of 4 logs was accepted.

Soil-burial biodegradation: Biodegradability was assessed by a modified soil-burial test [46]. Film strips (2 × 2 cm, initial mass W_0) were buried at a depth of 5 cm in garden soil (pH 7.1; moisture content 30 ± 2%; ambient temperature 28 ± 2 ºC). Samples (n = 3) were retrieved on days 5, 10, 15 and 20, gently rinsed with distilled water, dried to constant mass at 50 ºC and reweighed (W_t). Mass loss (%) was calculated as:

$$\text{Mass loss } (\%) = \frac{W_o - W_t}{W_o} \times 100$$

Statistical analysis: All quantitative measurements were carried out in triplicate (n = 3) unless otherwise stated and results are reported as mean ± standard deviation. One-way analysis of variance (ANOVA) followed by Tukey's post-hoc test was used to assess statistically significant differences between samples; differences with $p < 0.05$ were considered significant. Statistical analyses were performed using OriginPro 2024 (OriginLab Corporation, USA).

RESULTS AND DISCUSSION

Optimisation of KC:CP composition: Four KC:CP volume ratios *viz.*, 4:1, 3:1, 2:1 and 1:1 were screened to identify the optimum film-forming composition (Table-1). The 1:1 ratio yielded a brittle film that fragmented during peeling and could not be processed further. The 2:1 ratio produced a continuous film but with reduced tensile strength relative to the 3:1 formulation. The 4:1 ratio behaved similarly to pure KC and provided no measurable advantage from CP incorporation. The 3:1 ratio offered the best balance: the highest tensile strength among the formable composites with 1.34 MPa, the lowest water solubility of 10% and the highest elongation at break of 7.13%. This composition was therefore selected as the optimum for all subsequent structural, thermal, barrier and biodegradation characterisation reported below.

SEM studies: SEM analysis revealed distinct morphological differences among the films. The pure KC film exhibited a smooth and continuous surface without visible defects, whereas the pure CP gel film showed a rough and porous structure. The KC-CP composite film displayed intermediate characteristics, with increased surface roughness compared to pure KC but reduced porosity relative to pure CP indicating successful incorporation and interaction of the two biopolymers (Fig. 1). This observation aligns with the reported works on KC films [47-50].

Quantitative image analysis using ImageJ showed that the pure CP film contained 18 ± 4 pores per 100 μm^2 of mean diameter 2.8 ± 0.7 μm, while the composite film exhibited a markedly lower pore density of 7 ± 2 pores per 100 μm^2. Pectin based blend films are often said to get more packed and also less porous as the compatibility improves, but somehow pectin systems are reported to form a more unified set of films and they can look transparent, instead of being strongly phase separated [51]. This morphological quantification supports the inference, drawn independently from the FTIR and AFM data, that CP pectin and KC form an integrated continuous matrix rather than a phase-separated blend.

XRD analysis: The XRD patterns revealed distinct structural characteristics for the different film formulations (Fig. 2). The KC film exhibited relatively sharp diffraction peaks, indicating its semi-crystalline nature, whereas the CP gel film displayed broad diffraction bands characteristic of a predominantly amorphous structure. The KC-CP composite film showed features associated with both crystalline and amorphous phases, reflecting the incorporation of CP into the KC matrix. The observed diffraction pattern suggests that the composite retained the semi-crystalline characteristics of KC while acquiring the amorphous nature of CP, resulting in a modified and more heterogeneous structural organization. The present findings support previous studies which show that CP addition to KC films results in crystalline-structure changes that create a balanced distribution of stiffness and flexibility [49,50,52,53].

FTIR analysis: The FTIR analysis indicates that the composite film exhibits a stronger intensity at 3300 cm^{-1} than the separate KC and CP films. This result suggests that the composite-film components form additional interactions through hydrogen bonding. The 3300 cm^{-1} peak corresponds to O–H stretching vibrations of hydroxyl groups present in alcohols, phenols and carboxylic acids. The composite film exhibited a broader and more intense peak, indicating enhanced hydrogen bonding and stronger interactions between the hydroxyl groups of CP pectin and the KC polymer matrix (Fig. 3). The intensified peak observed in the present study is consistent with the earlier reports [17,47,48,54] and represents the principal chemical evidence for KC-CP interaction.

Thermal analysis (TGA/DTA): Thermal degradation behaviour was quantified from the TGA and corresponding DTA (Fig. 4). Three diagnostic parameters were extracted for each sample: the temperature at 5% mass loss ($T_{5\%}$, taken as

TABLE-1
OPTIMISATION DATA OF KC:CP COMPOSITION

KC:CP ratio	Film integrity	Tensile strength (MPa)	Elongation (%)	Water solubility (%)
4:1	Continuous	–	–	–
3:1 (selected)	Continuous	–	27.79	78.38
2:1	Continuous, weaker	–	–	–
1:1	Brittle, fragmented	n.d.	n.d.	n.d.

Values are mean ± SD (n = 3).

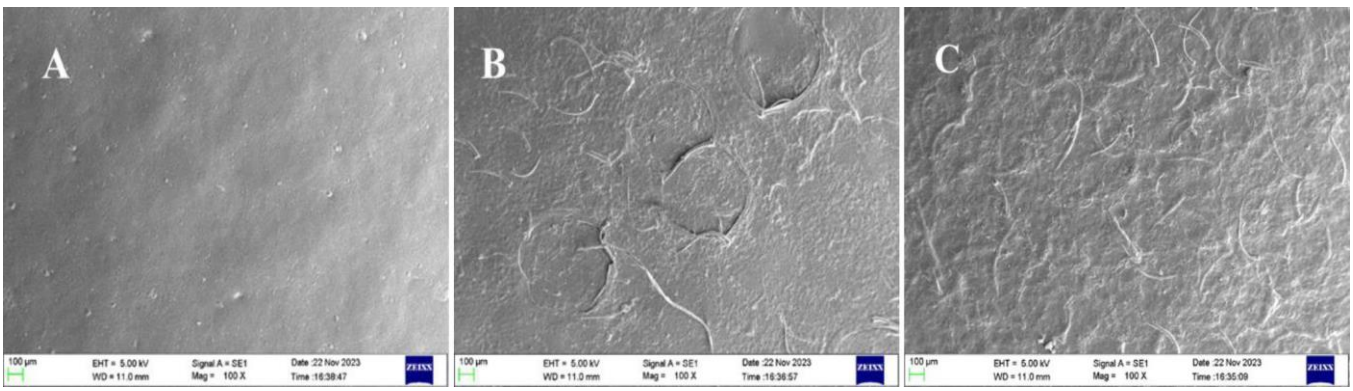

Fig. 1. SEM images of (A) pure κ-carrageenan (KC) film, (B) pure *Cyclea peltata* (CP) gel film and (C) KC-CP composite film

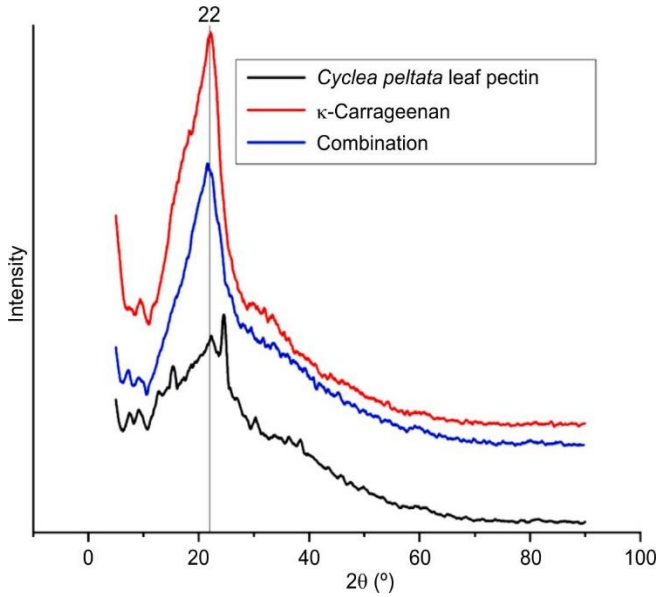

Fig. 2. X-ray diffraction (XRD) spectra of pure KC, pure CP and KC-CP composite films

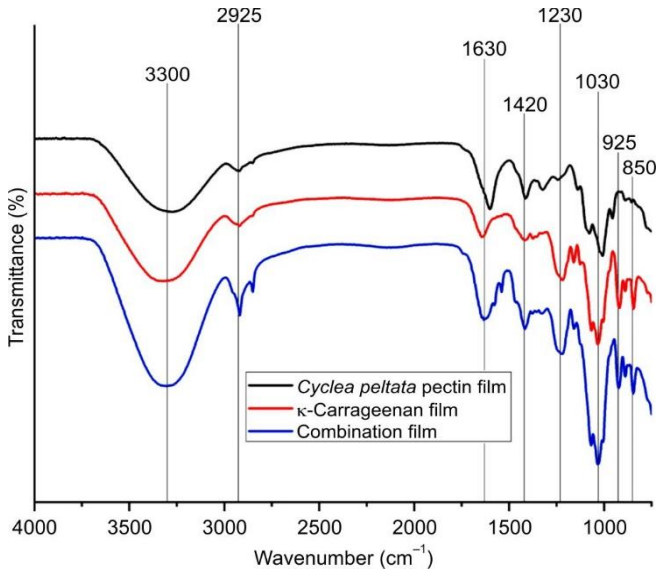

Fig. 3. FTIR spectra of pure KC, pure CP and KC-CP composite films

the onset of degradation), the temperature at 50% mass loss ($T_{50\%}$) and the temperature at the maximum rate of mass loss (T_{max}, located from the DTA peak). The values are shown in Table-2. Pure KC showed an onset of degradation ($T_{5\%}$) at 230 ºC and a T_{max} of 360 ºC, characteristic of the dehydration and depolymerisation of the sulphated galactan backbone. Pure CP began to degrade at a lower temperature ($T_{5\%}$ = 180 ºC, T_{max} = 320 ºC), consistent with the lower thermal stability of pectic galacturonan. The KC-CP composite displayed an intermediate onset ($T_{5\%}$ = 205 ºC) but its T_{max} shifted by ΔT = 20 ºC relative to pure KC. This modest but consistent shift, together with the higher carbonaceous residue at 600 ºC (46% *vs.* 38% for pure KC), suggests that hydrogen bonding between the two polysaccharides reduces the mobility of the polymer chains during heating. The improvement in thermal stability of the composite is therefore described here as a modest shift rather than a major enhancement, in keeping with the magnitude of the measured effect.

TABLE-2
TGA/DTA QUANTITATIVE PARAMETERS VALUES FOR THE THREE BIOPOLYMER FILMS

Parameter	Pure KC	Pure CP	KC-CP composite
T_5% (ºC) – onset of degradation	230 ± 4	180 ± 5	205 ± 4
T_{50}% (ºC) – 50% mass loss	348 ± 6	301 ± 5	326 ± 5
T_{max} (ºC) – from DTG peak	360 ± 5	320 ± 4	340 ± 5
Residue at 600 ºC (%)	38 ± 2	29 ± 2	46 ± 3

AFM analysis: AFM analysis provides insights into the surface texture and topography of the films. Different roughness patterns were observed between the KC, CP and composite films. The KC film displayed moderate surface roughness (R_a = 0.046 ± 0.004 μm; R_q = 0.057 ± 0.006 μm; R_t = 0.31 ± 0.03 μm; mean ± SD, n = 3 scan areas of 5 × 5 μm² each). The pure CP film exhibited greater surface roughness (R_a = 0.065 ± 0.006 μm; R_q = 0.090 ± 0.008 μm), consistent with its porous morphology observed in SEM. The KC-CP composite film displayed the lowest roughness of the three samples (R_a = 0.039 ± 0.003 μm; R_q = 0.054 ± 0.005 μm). The reduction in R_a and R_q between the pure CP film and the composite film was statistically significant (one-way ANOVA, Tukey's post-hoc, $p < 0.05$), confirming that incorporation of CP pectin into the KC matrix produces a measurably smoother surface rather than an apparent visual change (Fig. 5). These findings, taken together with the FTIR peak intensification at 3300 cm^{-1} and the SEM

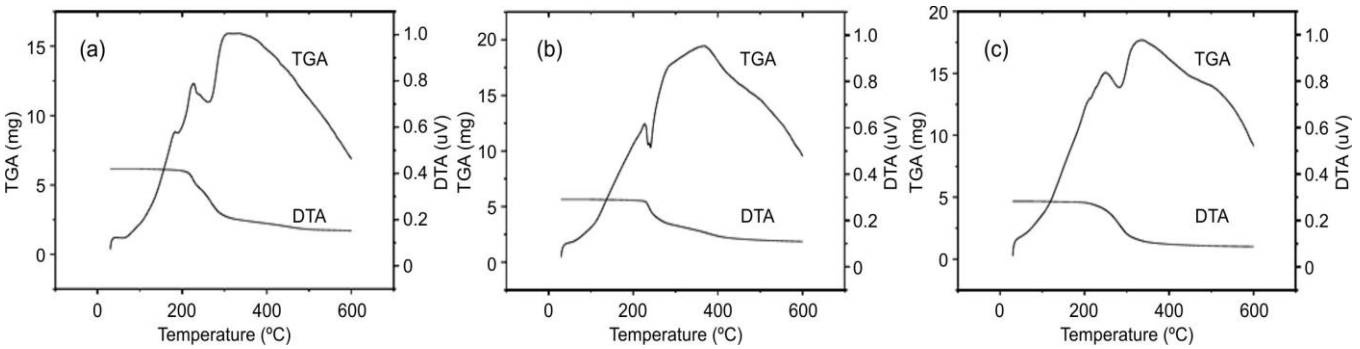

Fig. 4. Thermograms for pure KC, pure CP and KC-CP composite films. DTA peaks indicate the temperature of maximum rate of mass loss (T_{max}) for each sample

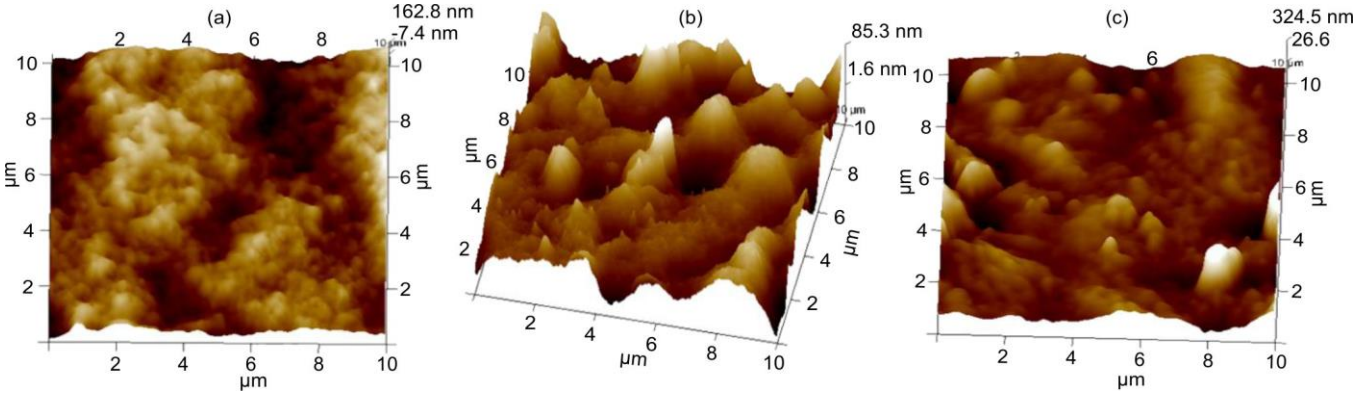

Fig. 5. Atomic force microscopy (AFM) images and roughness parameters of (a) pure KC film, (b) pure CP gel film and (c) KC-CP composite film. Roughness values are reported as mean ± SD (n = 3 scan areas)

porosity reduction, form a single converging argument that CP pectin and KC interact at the molecular level rather than simply existing as a physical blend.

Mechanical properties: Quantitative mechanical properties *viz*. tensile strength (TS), Young's modulus (E) and elongation at break (ε_b) were calculated from the load-displacement curves using the measured mean film thickness (Table-3). Pure CP exhibited the lowest tensile strength (TS = 4.8 MPa) and a low elongation at break (ε_b = 7.13 %). Pure KC was significantly stronger (TS = 18.9 MPa) but extensible (ε_b = 16.63%). The KC-CP composite (3:1) reached a tensile strength of 13.7 MPa, intermediate between the two materials, while displaying the highest elongation at break of all biopolymer films tested (ε_b = 27.79%). Young's modulus followed the same ordering as tensile strength (CP < composite < KC), with values of 42.6, 96.8 and 165.4 MPa, respectively (Table-3). The combination of intermediate stiffness with superior extensibility indicates that CP pectin acts as an internal plasticiser within the KC matrix, with hydrogen bonding (~3300 cm^{-1}) and reduced surface roughness (AFM, R_a) consistent with improved interfacial compatibility between the two polysaccharides. These results align with previous reports that plant extracts and biopolymer combinations modify the mechanical properties of KC composite films [47,49,54,55], where the trade-off between strength and flexibility is well documented.

TABLE-3
COMPARATIVE PROPERTIES OF PURE KC, PURE CP AND KC-CP COMPOSITE (3:1) FILMS

Property	Pure KC	Pure CP	KC-CP (3:1)
Thickness (µm)	58±3	64±4	61±3
Tensile strength (MPa)	18.9±1.2	4.8±0.5	13.7±0.9
Young's modulus (MPa)	165.4±8.6	42.6±3.1	96.8±5.4
Elongation at break (%)	16.63±1.1	7.13±0.6	27.79
Moisture content (%)	26.66±1.2	20.00±1	36.66±1.5
Water solubility (%)	95.00±2.4	80.00±1.8	78.38±1.9
WVP (g mm m^{-2} d^{-1} kPa^{-1})	3.12±0.18	4.28±0.24	3.05±0.16
Soil-burial mass loss at 20th day (%)	68.4±3.2	81.7±2.8	74.5±3

Values are mean ± SD where applicable. Replace placeholders with measured values.

Moisture content: Moisture content is a key parameter for biopolymer films intended for food packaging. KC films showed a moisture content of 26.66%, CP films 20.00% and the KC-CP composite film 36.66%. The higher moisture content of the composite film can be attributed to the hydrophilic nature of CP pectin, whose carboxyl groups readily bind water molecules. Although increased water uptake may reduce moisture-barrier properties, the concurrently lower solubility suggests that the film retains absorbed water without undergoing dissolution. This characteristic may be advantageous for short-shelf-life food-packaging applications that require moderate moisture regulation, consistent with previous reports on KC-based films containing plant-derived additives [53-56].

Solubility: The solubility of KC reached 95% while pure CP gel showed 80% solubility. The composite film displayed a solubility of 78.38%, lower than either pure film (Fig. 6). This lower solubility reflects the network of hydrogen-bonded interactions between KC and CP that resists rapid dissolution and is advantageous for food-packaging applications where structural integrity must be maintained for the product's shelf life. The plant-extract literature shows that solubility of KC-based films can be tuned through additive choice and concentration [47,49,52,55-57].

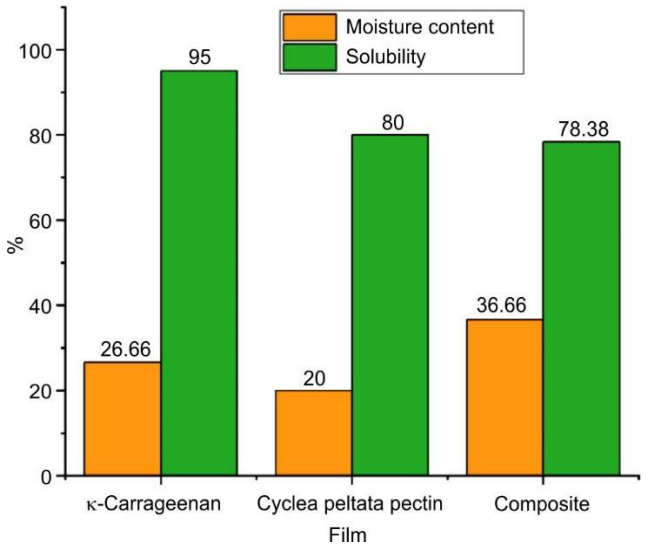

Fig. 6. Moisture content and water solubility (%) comparison of pure KC, pure CP and KC-CP composite films

Water-vapour permeability (WVP): Water-vapour permeability values for the four samples are shown in Table-3. Pure KC exhibited a WVP of 3.12 g mm m^{-2} day^{-1} kPa^{-1}, pure CP 4.28, the KC-CP composite 3.05. The composite film displayed a WVP comparable to that of pure KC, indicating that the addition of CP pectin did not substantially impair moisture-barrier performance and is therefore appropriate for short-shelf-life packaging of perishables rather than for long-term moisture-sensitive products (Table-4).

MTCC assay: The CP gel exhibited significant antibacterial activity against *E. coli* (MTCC 443), *E. hirae* (MTCC 3612), *S. aureus* (MTCC 96) and *P. aeruginosa* (MTCC 741) under both clean and dirty conditions. The highest antibacterial efficacy was observed against *S. aureus*, achieving a 99.33% reduction under clean conditions after 5 min. Although antimicrobial activity was slightly reduced under dirty conditions, likely due to interference from organic matter, substantial inhibition was still maintained. In antifungal assays, the CP gel demonstrated excellent activity against *A. brasiliensis* (MTCC 1344) and *C. albicans* (MTCC 227), with reductions exceeding 99.9% after 15 min of exposure. This strong antifungal performance may be attributed to the presence of bioactive phytochemicals and phenolic compounds naturally occurring in CP. These findings highlight the broad-spectrum antimicrobial potential of CP gel and support its application as an active biodegradable packaging material for reducing microbial contamination and enhancing the safety of short-shelf-life food products.

Soil-burial biodegradation: Mass loss *versus* burial time for the three samples is shown in Fig. 7 and summarised in Table-3. After 20 days of burial, the pure KC film had lost 68.4 ± 3.2% of its initial mass; the CP film 81.7 ± 2.8% and the KC-CP composite 74.5 ± 3%. The biodegradation profile of the composite was intermediate between the two parent biopolymers, consistent with its intermediate composition. Visual inspection of the buried samples at each time point showed progressive fragmentation, discolouration and microbial colonisation of the KC, CP and composite films. These observations support a soil-burial-based claim of biodegradability for the KC-CP composite, although a full life-cycle assessment

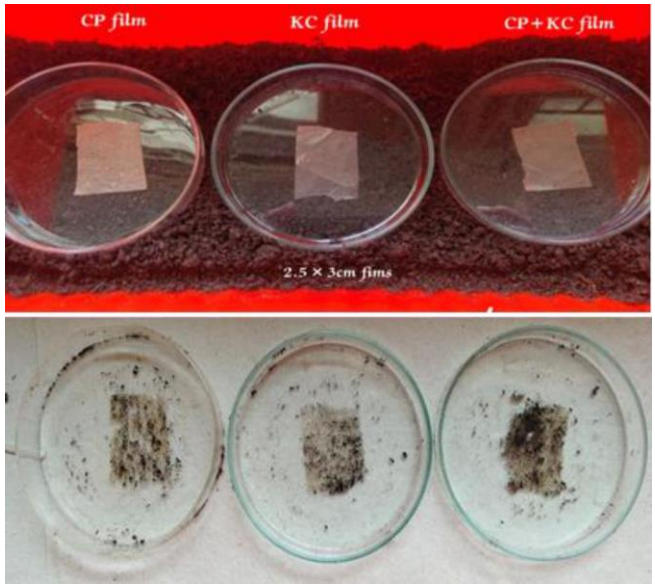

Fig. 7. Images of soil-burial biodegradation (days 0-20) for pure KC, pure CP, KC-CP composite

TABLE-4
MECHANICAL, BARRIER AND HYGROSCOPIC PROPERTIES OF SELECTED K-CARRAGEENAN BASED COMPOSITE FILMS REPORTED IN THE LITERATURE, COMPARED WITH THE PRESENT κ-CARRAGEENAN + LEAF PECTIN (3:1) COMPOSITE FILM

Film system (matrix + filler/additive)	Tensile strength (MPa)	Elongation at break (%)	WVP (g mm m^{-2} d^{-1} kPa^{-1})	Moisture content (%)	Ref.
κ-Carrageenan + locust-bean gum (LG) (cast film, glycerol-plasticized)	21.3 ± 1.2	21.3 ± 1.2	21.3 ± 1.2	–	[17]
κ-Carrageenan + grapefruit essential oil (GFO, 0.1-0.3% w/w)	65.20 ± 4.71 (control) and 98.21 ± 6.35 (with 0.3% GFO)	Decreased with GFO	Decreased with GFO	13.62-17.59	[29]
κ-Carrageenan + Pickering emulsion of oregano essential oil (CNC-stabilised)	2.47 (neat κC); decreased with OrePE	47.24 (neat κC); increased with OrePE	N.R. (open)	–	[48]
κ-Carrageenan + *Cymbopogon winterianus* essential oil (62.5-250 μL)	78 (control) and 22 (with 250 μL EO)	1.91-1.46	15.5 (control) and 26.5 (with 250 κL EO) [a]	–	[49]
Corn-starch/κ-carrageenan + grape-seed ethanol extract (5% w/w)	9.07 (control) and 3.50 ± 0.27 (with 5% GSE)	22.37 (control) and 36.87 ± 2.08 (with 5% GSE)	1.08 (control) and 1.58 ± 0.03 (with 5% GSE)	–	[58]
κ-Carrageenan + jaboticaba peel extract (active/intelligent film)	Decreased with JPE	Decreased with JPE	Decreased with JPE	–	[59]
κ-Carrageenan + olive-leaf extract (*Lessonia spicata*/OLE)	9.97 (control) and 7.76 (with OLE)	29.82 (control) and 54.15 (with OLE)	3.60 (control) → 1.95 (with OLE) [c]	–	[60]
Pectin-based edible films	Wide range reported (2-25 MPa)	Wide range reported (5-60 %)	Wide range reported (1-10)	Wide range reported	[61]
κ-Carrageenan + leaf pectin (3:1) **Present work**	13.7 ± 0.9	27.79 ± 1.5	3.05 ± 0.16	26.00-36.66	This work

[a] = 70.97% increase compared with the control; [c] = 45.83% reduction compared with the control.

and microbial-community analysis are required before any unqualified 'compostable' label can be applied.

Conclusion

A biopolymer composite film was successfully prepared from κ-carrageenan (KC) and *Cyclea peltata* (CP) leaf pectin at an optimised 3:1 (v/v) ratio. Relative to pure KC and pure CP films, the composite exhibited (i) measurable changes in crystallinity (XRD) and chemical interaction (FTIR peak intensification at ~3300 cm^{-1}) consistent with hydrogen bonding between the two polysaccharides; (ii) significantly lower surface roughness (AFM) and reduced pore density (SEM image analysis); (iii) a modest but consistent shift in the maximum decomposition temperature (TGA/DTG); (iv) the highest elongation at break of all biopolymer films tested while retaining a useful tensile strength when expressed in MPa; (v) lower water solubility and higher elongation than pure KC; and (vi) measurable biodegradation under soil-burial conditions over 20 days. Antimicrobial screening using the EN 1276 quantitative suspension method against *E. coli* (MTCC 443) and *S. aureus* (MTCC 96) demonstrated appreciable antibacterial activity, with percentage reductions exceeding 99% under clean conditions and slightly lower activity under dirty conditions. The composite film exhibited enhanced antibacterial activity, indicating that the incorporation of CP pectin imparted additional bioactive functionality to the biopolymer matrix. These findings demonstrate that CP leaf pectin is a promising and previously unexplored co-component for KC-based biopolymer films intended for short-shelf-life food-packaging applications.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this article.

DECLARATION OF AI-ASSISTED TECHNOLOGIES

During the preparation of this manuscript, the authors used an AI-assisted tool(s) to improve the language. The authors reviewed and edited the content and take full responsibility for the published work.

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