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Morphological and structural characterization, storage stability, and biodegradability study of carrot and beetroot peel incorporated edible cutlery

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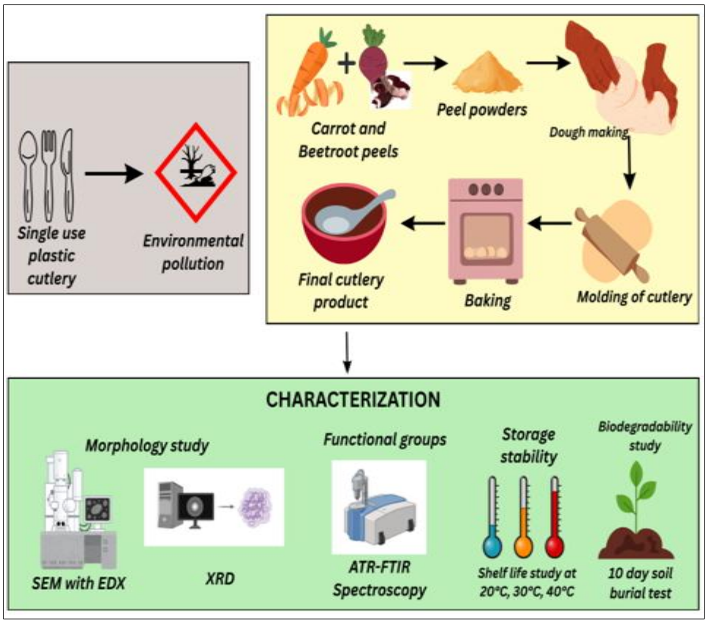
Abstract
In this study, the morphological and structural properties, storage stability and biodegradability of carrot and beetroot peel based edible cutlery using whole wheat flour, sago starch, white sesame seeds and cinnamon powder were studied. The optimized formulation with 10% combined carrot and beetroot peel powders was tested to ascertain effectiveness and compared to a control formulation with 0% peel powder. The surface morphology and the elemental composition of the obtained samples were obtained by scanning electron microscopy and energy dispersive X-ray spectroscopy (SEM-EDX), whereas the structural characteristics were obtained by X-ray diffraction (XRD) and attenuated total reflectance Fourier transform infrared (ATR-FTIR) spectroscopy. SEM analysis showed a more compact and aggregated microstructure in the peel-enriched formulation than in the control, which meant that good incorporation of peel particles into the edible matrix of the cutlery has been achieved. The EDX analysis indicated the presence of carbon and oxygen as the major components, while potassium was only detected in the peel incorporated optimized formulation. The XRD patterns showed mostly the amorphous nature, and suggested reduced crystallinity after peel incorporation. The ATR-FTIR spectra identified hydroxyl, carbonyl, amide and carbohydrate-associated functional groups that are typical of the composite biopolymer matrix. The moisture uptake rates for accelerated storage ranged from 0.298 to 0.311% day-1 and moisture based shelf life was estimated to be approximately 23-25 days at the chosen moisture end point of 11%. Burial experiments in the soil revealed that the biodegradation rate was 13.27 ± 3.85% after 10 days. The results suggest that carrot and beetroot peel powders can be effectively added to edible cutlery to create a structurally stable, biodegradable, edible product while also encouraging the valorization of vegetable processing by-products for food applications.

Keywords: Edible cutlery, carrot peel powder, beetroot peel powder, SEM-EDS, ATR-FTIR, XRD, shelf-life, biodegradable, valorization

1. Introduction
Single-use plastics are a worldwide issue that has led to a significant environmental problem, as the accumulation of non-biodegradable waste in both aquatic and terrestrial environments (Roy & Morya, 2022). To address this, sustainable substitutes like biodegradable and edible cutleries have been developed, providing not only an environmental solution to curb plastic waste but also nutritional value (Roy *et al*., 2025). Tableware parts made from plant flour based materials from cereals, legumes, and tubers are highly popular in the production of edible tableware due to their sustainability and ability to create durable structures (Roy *et al*., 2025). It is difficult to produce a durable edible matrix unless the base flour composition is highly optimized. Whole wheat flour is widely used because of its excellent textural characteristics, which supply a gluten structure for the reinforcement of baked utensils and a dense carbohydrate base (Roy *et al*., 2025). It is, however, usually mixed with other starches to reduce the heaviness, and to enhance the binding qualities. Sago starch is more valued for its gelatinization and retrogradation properties, which are beneficial for the hardness and structural integrity of edible films and spoons (Siddiqui *et al*., 2023; Erami *et al*., 2025). Sago is non-toxic and biodegradable, but it has moisture sensitivity, requiring the development of composite matrices to achieve the best water absorption kinetics and mechanical strength (Siddiqui *et al*., 2023). Recent developments highlight the potential of valorising wastes from agricultural and vegetable processing to reinforce these matrices

(Premarathne *et al*., 2026) [5, 9, 10, 11, 13]. By-products like peels and pomace contain a valuable source of biopolymers (cellulose, pectin) and bioactive compounds (phenolics, antioxidants) which are vital for the development of functional biodegradable packaging and cutlery (Premarathne *et al*., 2026) [9]. Empty fruit bunch (EFB) fibers are found to enhance the mechanical strength, moisture content and water resistance of biodegradable spoons (Tajuddin *et al*., 2026) [15]. Likewise, the flexural modulus and microstructural uniformity of soy protein isolate cutlery are improved by the reinforcement with morning glory stem fibers (Choeybundit *et al*., 2022) [2]. Citrus by-products like mosambi peel powder have been incorporated into sago-based spoon products and effective biodegradable spoons with good sensory qualities have been produced (Siddiqui *et al*., 2023) [13]. In addition, morphological and elemental analyses (SEM-EDX) of citrus peel powders show that the surface roughness, particle geometry and elemental distribution are critical, impacting the structural processing and sensory acceptance of such bio-composites (Singh & Mishra, 2022) [14]. Use of non-traditional flours like acorn and pumpkin seed has also made a substantial contribution to the phenolic content, antioxidant activity and textural hardness of edible spoons (Dordevic *et al*., 2025) [3]. Carrot and beetroot peels are especially high in dietary fiber and natural pigments as well as antioxidants, which are all abundant agricultural waste. Derivatives of beetroot (*Beta vulgaris*) have been extracted as natural colorants and are found to be effective as aesthetic enhancers and also possess significant antibacterial activity against pathogenic bacteria like *Escherichia coli* and *Staphylococcus aureus* (Zia *et al*., 2021) [16]. Recent studies on biodegradable films made using carrot and beetroot peel powders show their effectiveness in increasing the flexibility of the film, changing the crystalline structures (XRD), functional groups (FTIR) and rapid soil degradation (Grace *et al*., 2025) [6]. Even with these developments the incorporation of these specific peel powders into a complex multi-component edible cutlery matrix, in combination with whole wheat flour, sago starch, white sesame seeds and cinnamon powder, has not been fully explored. The feasibility or sensory acceptance of such formulations could be determined separately, but the insight into the microstructural, elemental and crystalline interactions that underpin the physical stability of the formulations are not fully understood. The available literature is mainly about the basic physicochemical characterization of starch films from single sources or simple blends of multi-starch sources with a lack of detailed morphological and structural characterization of multi-component edible cutlery (Premarathne *et al*., 2026; Roy *et al*., 2025) [9, 10]. To understand the matrix compatibility of peel incorporated formulations and their structural integrity, thorough investigations using scanning electron microscopy with energy-dispersive spectroscopy (SEM-EDS), X-ray diffraction (XRD) and attenuated total reflectance Fourier transform infrared (ATR-FTIR) spectroscopy are necessary (Erami et al., 2025; Grace *et al*., 2025) [5, 6]. To address this, the present study was designed to analyse the morphological, elemental and structural characteristics of edible cutlery made with carrot peels and beetroot peels, as well as to assess the storage stability and biodegradability of the edible cutlery. In particular, the study was designed for comparing the surface morphology and elemental composition of the control and optimized 10% peel-incorporated formulations using scanning electron microscopy coupled with energy-dispersive spectroscopy (SEM-EDS); identification of major functional groups and possible chemical interactions using attenuated total reflectance Fourier transform infrared (ATR-FTIR) spectroscopy; evaluation of changes in crystalline characteristics using X-ray diffraction (XRD); assessment of storage stability under accelerated temperature conditions and estimation of shelf life; and determination of biodegradability of the developed edible cutlery under soil-burial conditions.

Graphical Abstract



2. Materials and methods

2.1 Raw Material Procurement and Preparation

All the ingredients used for preparing the edible cutlery included whole wheat flour, sago starch, white sesame seeds, cinnamon powder and salt, which were purchased up from local retail shops in Lucknow, Uttar Pradesh, India. Fresh carrot (*Daucus carota*) and beetroot (*Beta vulgaris*) were bought from local vegetable market near BBAU, Lucknow.

Mature and fresh vegetables with no damage were used for preparation of peel powder. Washed, blanched, dried at 55-60 °C and ground to fine powders, were collected. Carrot and beetroot peels were first processed according to the reported method for the preparation of dried carrot peel powder (Chantaro *et al*., 2008) and dried beetroot peel powder (El-Beltagi *et al*., 2022) with modifications as appropriate [1, 4].

2.2 Formulation and Development of Edible Cutlery

The control and optimized formulations used in the present study are presented in table 1. The base formulation (0% peel powder) was the control formulation while the optimized formulation (10% combined carrot and beetroot peel powders in a 1:1 ratio) was the formulation F2. In the control formulation 1 g salt was used and salt was omitted in formulation F2 and the same amount was replaced with sago starch.

Table 1: Formulation of edible cutlery

Ingredients	Control (0%)	F2 (10%)
Wheat flour	70 g	60 g
Sago Starch	17 g	18 g
White sesame seeds	10 g	10 g
Beetroot Peel Powder (BPP)	0 g	5 g
Carrot Peel Powder (CPP)	0 g	5 g
Cinnamon Powder	2 g	2 g
Salt	1 g	-
Water	As required	As required

Both formulations were prepared using the procedure presented in the flowchart (Figure 1).

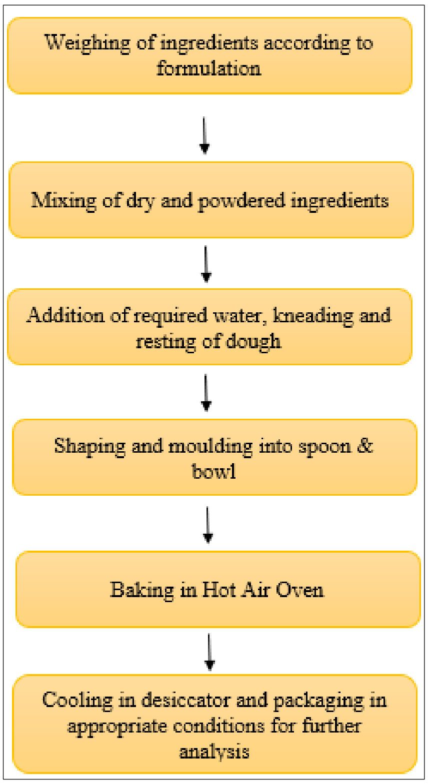


Fig 1: Preparation flowchart of edible cutlery

The optimized and the control formulations were then compared using SEM-EDX and XRD analyses. Optimized F2 formulation was subjected to further characterization and evaluation, such as ATR-FTIR spectroscopy, storage stability and soil-burial assessment.

2.3 Morphological, Elemental and Structural Characterization

2.3.1 Scanning Electron Microscopy and Energy Dispersive X-ray Spectroscopy (SEM-EDX)

The surface morphology of the optimized carrot and beetroot peel incorporated edible cutlery was analyzed by Scanning Electron Microscopy (SEM). The sample was dried and then mounted on an aluminum stub with conductive carbon tape and coated with a thin layer of gold before analysis. Micrographs were taken under the optimum magnification at an accelerating voltage of 15kV in a vacuum chamber. The resulting images were analysed to assess the surface properties such as compactness, roughness, porosity and structural integrity of the edible spoon matrix. An Energy Dispersive X-ray Spectroscopy (EDX) detector attached to the SEM system was used to determine the elemental composition. At the same time as the observations in SEM, spectra were recorded at 15 kV of accelerating voltage. The characteristic X-rays that were emitted were analyzed to determine the different elements present in the edible sample of a spoon.

2.3.2 X-ray Diffraction (XRD) Analysis

The structural characteristics and crystallinity of the optimized edible cutlery with carrot and beetroot peels were investigated by X-ray diffraction (XRD) analysis. The dried sample was finely ground and subjected to XRD analysis, the diffraction pattern was recorded as the intensity versus diffraction angle (2θ). The diffractogram obtained was utilized to determine the crystalline and amorphous regions of the edible cutlery matrix as well as the structural organization of the biopolymeric constituents. The diffraction peaks and the overall pattern were used to understand the crystallinity characteristics of the developed edible spoon.

2.3.3 Attenuated Total Reflectance-Fourier Transform Infrared Spectroscopy (ATR-FTIR)

The Fourier Transform Infrared Spectroscopy (FTIR) was performed using a Thermo Nicolet Summit X FTIR spectrometer (Thermo Fisher Scientific, USA) by Attenuated Total Reflectance (ATR) technique. The optimized sample was analysed in the spectral range between 7800-400 cm^{-1}. The spectra obtained were plotted in the form of percentage transmittance versus wavenumber and analysed to interpret the characteristic functional groups present in the edible cutlery matrix. The absorption bands were used to determine the molecular composition and interactions of the constituents of the developed edible cutlery.

2.4 Moisture-Based Accelerated Shelf-Life Estimation

To evaluate the optimized edible cutlery, a moisture uptake accelerated shelf-life study was carried out, with moisture uptake as the quality parameter. Each sample was aseptically transferred in a pre-weighed covered petri plates and kept at 20, 30 and 40 °C. Mass changes in the samples were determined at fixed time points (Days 0, 4, 8, 12 and 16) during the storage period. Cumulative moisture gain was determined by subtracting the initial sample mass from the sample mass, and then dividing by the initial sample mass. The moisture content was presented on dry basis and initial moisture content was 2.89%. The moisture uptake rate (k,% day^{-1}) was determined from the slope of the linear regression of moisture content against storage time. Moisture-content endpoints 7%, 9% and 11% were chosen for moisture-based estimation of storage-life of the edible spoon formulation, as published moisture levels for edible spoon formulation (Hutabarat & Gustasiana, 2025) [7]. Each of the selected moisture endpoints were used to estimate the time required to reach it from the linear regression relationship. The moisture range covered from 7% to 11% was the range of experimentally observed moisture levels, and the moisture endpoints of 7%, 9% and 11% were estimated by interpolation and linear extrapolation. The moisture uptake was tested as a function of temperature by applying the Q_{10} approach as described by Labuza and Schmidl (1985) [8]. The rates of moisture uptake of the samples were determined at various storage temperatures and the Q_{10} value was calculated.

2.5 Biodegradability Assessment

A soil burial test was performed to assess the biodegradability of the optimized 10% peel incorporated edible cutlery. Three earthen pots (about 7 inches in height) were filled with a burial medium composed of commercially available potting soil mix and vermicompost and had drainage holes in the bottom. The cutlery was broken up into small pieces and three sample pieces were chosen for the study. The three pots contained three independent replicates and each fragment was weighed separately on a digital balance before being buried. The pre-weighed fragments were placed under the soil and vermicompost and completely covered with the burial medium. There was enough headspace at the top of each pot to allow for aeration (approx. 3 cm). Throughout this investigation, the pots were kept in natural environmental conditions and water was periodically sprayed into the pots to keep the burial medium from drying out excessively and to ensure the microbial activity. The period of biodegradation was monitored by visual observations which recorded physical changes in the buried samples. After five days, the surface layer of the burial material was gently removed without disturbing the placement of the fragments and changes in colour, surface characteristics and microbial growth were identified. After observation the samples were reburied and stored under the same conditions until the end of the experiment. The fragments were removed from the pots after 10 days, cleaned with a brush to dislodge any particles of soil, and then air-dried before weighing. Each fragment was weighed and the weight loss due to its biodegradation was evaluated in percentage, as calculated in the equation below:

$$\text{Weight Loss (\%)} = \frac{W_i - W_f}{W_i} \times 100$$

Where;

- W_i is the initial weight of the sample before burial and
- W_f is the final weight after the biodegradation period.

The experiment was conducted in triplicate (n = 3), and the results were expressed as mean percentage weight loss ± standard deviation.

2.6 Statistical Analysis

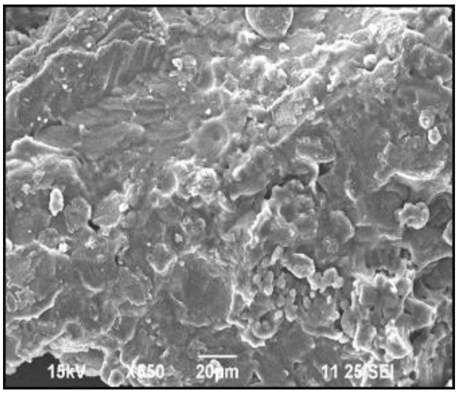
Experimental data were expressed as mean ± standard deviation (SD) of three independent determinations. Descriptive statistical analysis was performed for biodegradability and storage stability studies. SEM, EDX, FTIR, and XRD results were evaluated qualitatively based on the obtained micrographs, spectra, and diffraction patterns.

3. Results and discussion

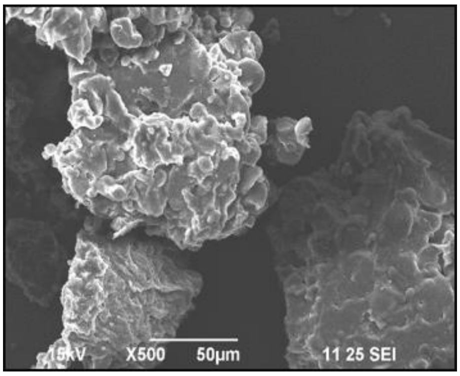
3.1 Morphological and Elemental Characterization of the Edible Spoon

3.1.1 SEM-EDX Analysis

The SEM images at 500× magnification revealed some distinct differences in the base formulation and the optimized 10% peel incorporated edible cutlery formulation. The base formulation had a relatively rough and heterogeneous surface, while the optimized formulation had a more compact and aggregated surface. The larger agglomerated domains and relatively continuous matrix observed in the peel-enriched sample suggested good embedding of the carrot and beetroot peel powders in the edible spoon matrix. The variations in the surface morphology indicated that the structural organization of the formulation was affected by the incorporation of the peel. Similar modifications in surface morphology after incorporation of plant-derived fibers and peel materials have been reported by Singh and Mishra (2022) and Choeybundit *et al.* (2022) [2, 14].



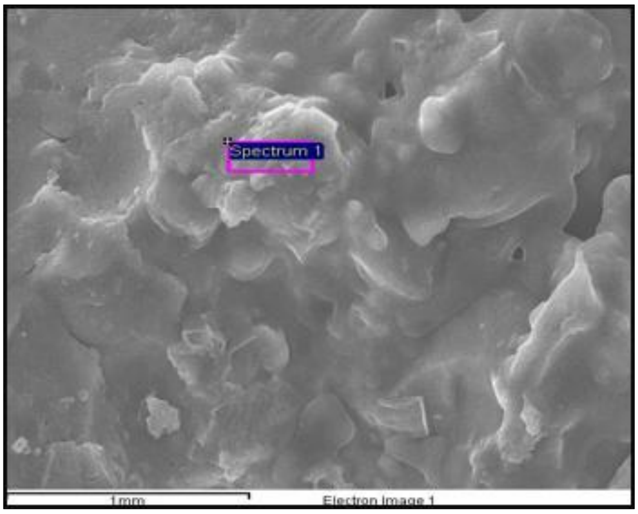
a)



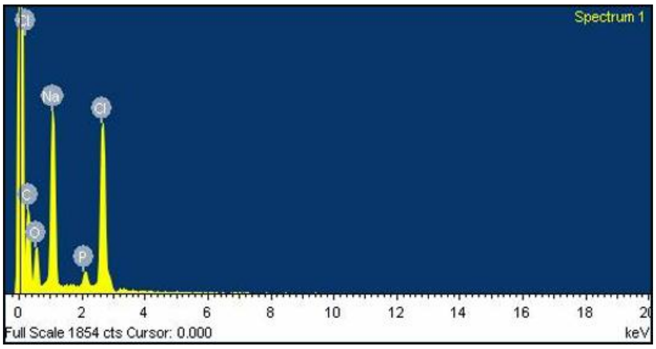
b)

Fig 2: SEM magnification at x500 (a) Base formulation and (b) Optimized formulation

Elemental compositions of control formulation and optimized formulation were determined by EDX analysis (Figure 3 & 4 and Table 2). Both samples were found to contain mainly carbon and oxygen, indicating the organic nature of the edible cutlery matrix. The control formulation contained carbon (57.10 wt.%), oxygen (19.53 wt.%), sodium (12.54 wt.%), phosphorus (0.29 wt.%), and chlorine (10.54 wt.%). In contrast, the optimized formulation contained carbon (53.16 wt.%), oxygen (45.70 wt.%), phosphorus (0.66 wt.%), and potassium (0.47 wt.%). Carrot and beetroot peel powders in the optimized formulation could be responsible for the increased oxygen content in the formulation, as they contain oxygen rich polysaccharides, dietary fiber and other plant-based components. The mineral components of the vegetable peels were revealed by the detection of potassium in the optimized formulation. The presence of salt in the formulation led to the detection of sodium and chlorine in the control sample; the optimized sample was prepared without salt and did not contain these elements. Overall, the EDX results showed differences in the elemental composition of the formulations, and confirmed that the matrix of the edible cutlery consisted of carbon and oxygen rich materials.

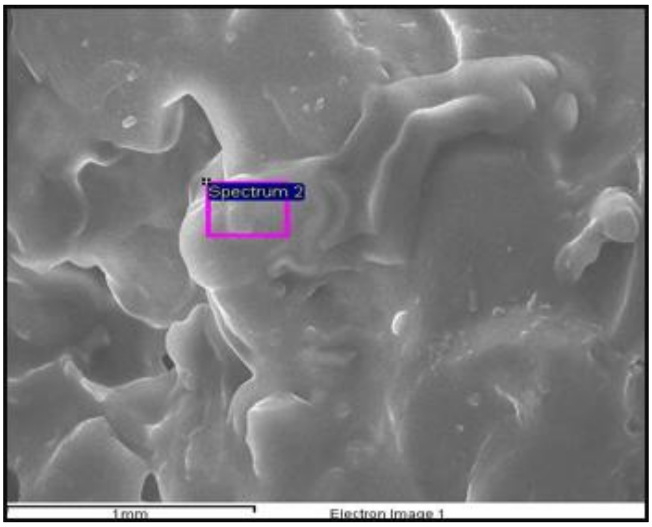


a)

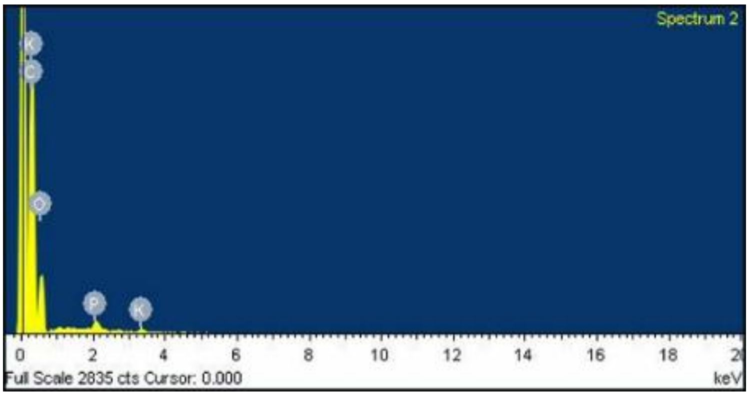


b)

Fig 3: SEM micrographs and corresponding EDS spectra of control formulation (x,y)



c)



d)

Fig 4: SEM micrographs and corresponding EDS spectra of optimized formulation (c,d)

Table 2: EDS elemental composition of the control and optimized peel incorporated edible cutlery formulations.

Element	Control (wt.%)	Optimized (wt.%)
Carbon (C)	57.10	53.16
Oxygen (O)	19.53	45.70
Sodium (Na)	12.54	ND
Phosphorus (P)	0.29	0.66
Chlorine (Cl)	10.54	ND
Potassium (K)	ND	0.47

ND = Not detected

3.1.2 XRD Analysis

Both the base formulation (C) and the optimized formulation (F2) showed a broad diffraction peak in the range 15°-30° (2θ) suggesting an amorphous structure from the XRD analysis. The optimized formulation showed a wider diffuse peak and lower crystalline reflections than the base formulation suggesting a decrease in the ordered structure after the addition of carrot and beetroot peel powders. The reduced crystallinity suggests that the fiber-rich constituents of carrot and beetroot peels interfered with the regular arrangement of starch polymer chains, resulting in a more amorphous matrix. Similar reductions in crystallinity have been reported in starch-based biodegradable films containing plant-derived additives and peel powders (Grace *et al*., 2025; Erami *et al*., 2025) [5, 6].

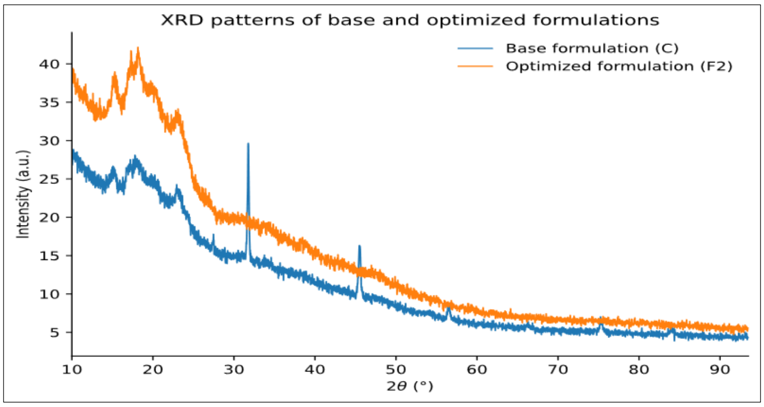


Fig 5: Comparative XRD pattern of base formulation and optimized formulation

3.1.3 ATR-FTIR Analysis

The optimized peel incorporated edible cutlery sample showed several characteristic absorption bands of the functional groups in the formulation in its ATR-FTIR spectrum (Fig. 6). A wide absorption band at 3288.11 cm-1 was noted and attributed mainly to the O-H stretching vibrations from hydroxyl groups that are found in polysaccharides present in the food, known as dietary fibre, and other plant-based components. The bands at 2923.35 cm-1 and 2853.77 cm-1 were assigned to aliphatic C-H stretching vibrations, which suggested the presence of methylene and methyl groups that were related to the organic constituents, such as lipids. The absorption band at 1744.55 cm-1 was assigned to the C=O stretching vibrations characteristic of carbonyl functional groups, which could be part of lipids. The band at 1643.57 cm-1 may be attributed to the amide I vibration and/or the bending vibration of bound water; the band at 1535.93 cm-1 was assigned to amide II vibrations (N-H bending and C-N stretching). The bands at 1376.92 and 1241.65 cm^{-1} were attributed to the C-H deformation and C-O/C-N stretching vibrations, respectively. The C-O-C and C-O vibrations in the region 1148.61-992.77 cm^{-1} were typical of the vibrations of the carbohydrate rich matrix, especially starch and other polysaccharides. The band at 860.51 cm^{-1} was another carbohydrate associated fingerprint vibration. The ATR-FTIR profile of the optimized formulation showed the presence of hydroxyl, aliphatic C-H, carbonyl, amide and carbohydrate associated functional groups, indicating the presence of various chemical constituents of the formulated edible cutlery. The observed band assignments were consistent with previously reported FTIR spectra of starch-based biodegradable films and polysaccharide-rich biopolymer matrices (Erami *et al*., 2025; Grace *et al.,* 2025) [5, 6].

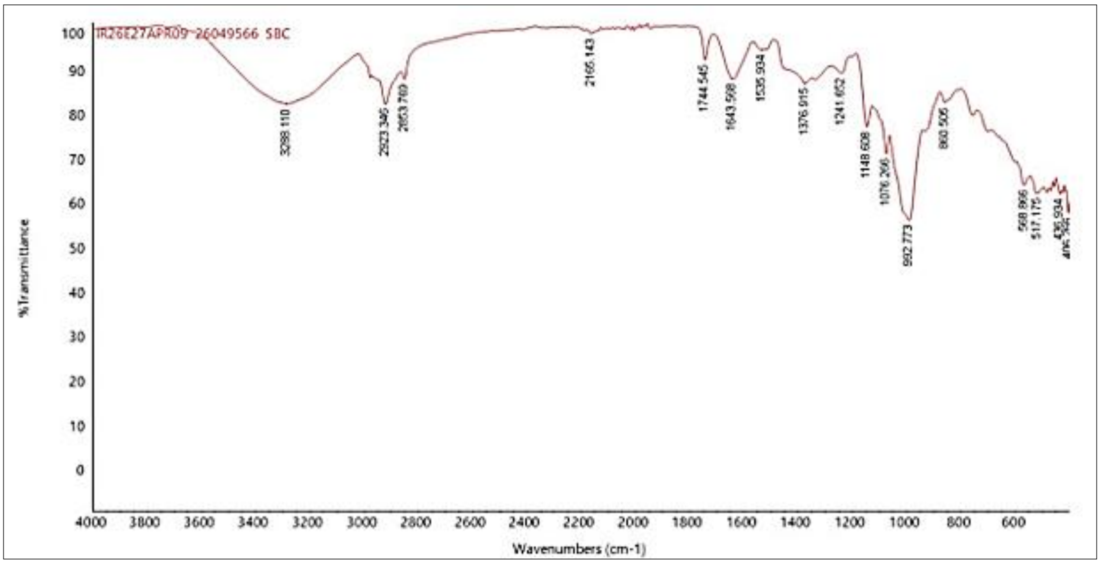


Fig 6: ATR-FTIR spectrum of the optimized peel incorporated edible cutlery

3.2 Moisture-Based Accelerated Shelf-Life Estimation

The moisture content of optimized edible cutlery increased during storage at all the temperatures (Table 3). The initial moisture content was 2.89% (dry basis). The moisture content had reached 7.96%, 7.58% and 7.70% at 20, 30 and 40 °C, respectively, by Day 12, and remained unchanged until Day 16. Cumulative moisture-gain also displayed a similar pattern, and in 40 °C reached 0.075 g, 0.073 g and 0.075 g by Day 12, without any further increase till Day 16. The moisture uptake rates (k) determined from the linear regression of moisture content on storage time were 0.311, 0.298 and 0.309% day^{-1} at 20, 30 and 40 °C, respectively. The similarity of these values was close, suggesting that there was not a strong temperature dependence of moisture uptake in the temperature range examined. The estimated times to reach 7% moisture were 10.5, 12.0 and 11.8 days at 20, 30 and 40 °C, respectively. The estimated times to reach 9% moisture were 16.9, 18.7 and 18.3 days while the estimated times to reach 11% moisture were 23.3, 25.4 and 24.7 days, respectively. The endpoint at 7% moisture content was estimated by linear extrapolation between the other moisture content values, in the range of moisture contents experimentally determined, while the endpoints at 9 and 11% moisture content were estimated by linear extrapolation from the other moisture content values, as they were outside the range of moisture contents determined in this 16-day storage experiment. Hence, the predicted times for the 9% and 11% endpoints are estimates based on moisture and do not represent directly observed endpoint times. The moisture uptake rate was calculated to compute the Q_{10} value, which was around 1.00, signifying that moisture uptake rate is little sensitive to the temperature range studied. The moisture-based storage period predicted was about 23-25 days (3-4 weeks) based on the moisture content endpoint of 11%. This is a moisture-based prediction and not an experimental validated shelf life, actual shelf life may vary depending on relative humidity, packaging properties, formulation and storage conditions.

Table 3: Moisture-based estimated storage time of optimized edible cutlery at selected moisture-content endpoints

Storage temperature	Moisture uptake rate, k ($\% \ day^{-1}$)	7% endpoint (days)	9% endpoint (days)	11% endpoint (days)
20 °C	0.311	10.5	16.9	23.3
30 °C	0.298	12.0	18.7	25.4
40 °C	0.309	11.8	18.3	24.7

3.3 Biodegradability Assessment

Day 0 Observation

The 10% peel incorporated edible cutlery pieces showed high structural integrity with smooth surface and dense and rigid baked surface on the first day of the burial study. Dry weight of each fragment was measured prior to burial. Samples were then buried to a depth of about 5 cm in the soil that contained vermicompost. No surface degradation or microbial colonization were noticed at this stage. The matrix was baked, and the initial moisture content was low, so there was probably less of an immediate interaction with the surrounding soil environment.

Fig 7: Clean cutlery fragments before burial (day 0)

Day 5 Observation

By Day 5 the buried fragments had visibly altered in both their surface characteristics and appearance. Although the samples did not lose a significant amount of structural form, microbial colonization was observed on the exposed surfaces with the adhesion of soil particles to the sample matrix. The fungus growing on the soil surface was greenish-grey, which was observed to be active under the moist soil conditions. The surface colonization observed could have contributed to the gradual degradation of the edible matrix by the activity of microorganisms that were able to decompose the easily biodegradable components, like starch, proteins, and other organic materials. The greater contact between the soil moisture and microorganisms, and between the sample surface and the soil moisture, was indicative of the beginning of the visible biodegradation process that occurred during the burial period.

Fig 8: Discolouration of fragments and visible fungal hyphae

Day 10 Observation

After 10 days, the physical changes were visible on the edible cutlery and the weight was lost. The weight of each individual sample at the beginning and the end of the measurement is shown in Table 4. The weight loss was 17.60% for Sample A, 10.22% for Sample B and 12.01% for Sample C, with a mean weight loss of 13.27 ± 3.85%. The range between replicates might be due to the differences in the degree of microbial colonization, moisture interaction and physical breakdown of each fragment in the burial process.

Fig 9: Cutlery fragments after 10 days of soil burial

Table 4: Quantitative In-Soil Degradation Matrix of the Formulated Edible Cutlery

Sample	Initial Weight on Day 0 (g)	Final Weight on Day 10 (g)	Absolute Mass Loss (g)	Weight Loss%
A	3.296	2.716	0.580	17.60%
B	3.014	2.706	0.308	10.22%
C	3.082	2.712	0.370	12.01%
	Mean Weight Loss ± SD (%)			13.27 ± 3.85%

The observed mass loss and the gradual colonization of the surface and degradation of the edible part over the burial period suggest that the peel-enriched edible cutlery would degrade under the conditions tested. The short time taken to achieve a measurable mass loss shows that the matrix is biodegradable, both made from starch and plant-based material. Similar biodegradation behaviour has been reported for starch-based biodegradable spoons and films containing plant-derived fibers and agricultural residues (Tajuddin *et al*., 2026; Grace *et al*., 2025) [6, 15]. The results from the present study, however, should not be regarded as a complete picture of biodegradation or mineralization because it was run over 10 days of soil burial under specific experimental conditions. More long-term testing with other data such as CO_2 evolution or organic carbon conversion would be needed to determine the degree of complete biodegradation.

4. Conclusion

The present study proved that the edible cutlery formulation based on starch can be successfully formulated with carrot and beetroot peel powders without compromising the structural integrity of the edible cutlery. The optimized formulation was found to have a compact and aggregated microstructure by SEM, indicating that the peel particles were well integrated in the edible spoon matrix. The predominance of carbon and oxygen rich organic components was confirmed by EDX analysis and the compositional differences were shown between the control and peel incorporated formulations. The XRD results indicated that both the formulations were mainly in the amorphous form and the optimized amorphous formulation had less crystallinity than the other formulation, while the ATR-FTIR result confirmed the presence of hydroxyl, carbonyl, amide, and carbohydrate associated functional groups. The moisture based shelf-life study gave an estimated shelf-life of about 23-25 days under the conditions tested which is considered to be reasonable resistance to moisture uptake. In addition, the assessment of biodegradability of the developed cutleries through soil burial process showed that there was a mean weight loss of 13.27 ± 3.85% after 10 days, thus proving that the developed cutleries are biodegradable. In general, the use of carrot and beetroot peel powders enhanced the physical characteristics of the edible cutlery, while simultaneously facilitating the valorisation of vegetable-processing by-products, thus providing a more sustainable alternative to conventional single-use plastic disposables.

This present study outlines the key features of the peel enriched edible cutlery along with their storage stability and potential for biodegradability, but some limitations need to be considered. Biodegradability assessment was conducted only for 10-day soil-burial study, which is not an exhaustive study of biodegradability behaviour in different environmental conditions. Likewise, the storage stability testing comprised only moisture uptake, and did not involve microbiological, sensory or oxidative stability testing in storage. Further study is recommended to carry out long-term biodegradation studies under various environmental conditions, examine mechanical and thermal properties and study various packaging systems to improve storage stability. Additionally, investigating different levels of carrot and beetroot peel content and other fruit and vegetable processing by-products could aid in the creation of edible cutlery featuring enhanced functional properties and greater market potential.

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Conflict of interest

The authors declare that there is no conflict of interest.

Declaration of ai use

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