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Methylcellulose replacement with different enzymatically treated plant fibres as a binder in the production of plant-based meat patties

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ABSTRACT

Texturised vegetable protein (TVP) is a sustainable and economical base for plant-based meat patties but requires binders to create an emulsified gel and hold the patty structure together. This study evaluated the physico-chemical and sensory attributes of TVP patties incorporated with three different enzymatically-treated plant fibres i.e., pea (EPF), citrus (ECF) or apple (EAF) as a binder compared to positive control (methylcellulose, MC) and negative control (no binder, NC). All the patties with plant fibres had similar water-holding capacity compared to the MC. EAF exhibited the least fluid release and uniform surface, while ECF demonstrated the least cooking loss and shrinkage, uniform surface, hard texture, better cohesiveness, gumminess and chewiness compared to other samples. All the plant fibre-incorporated patties scored similarly for taste, texture, juiciness and overall acceptability compared to the positive control. The agglomerative hierarchical clustering revealed that the EPF had similar characteristics to the MC but the principal component analysis indicated that citrus fibre was a superior binder to pea fibre, therefore it could be used to replace methylcellulose for plant-based meat patties. Future research should explore more variations in plant-based binders to optimise the performance and sensory attributes of different types of texturised vegetable protein-based meat analogues.

1. Introduction

Meat is composed of essential nutrients necessary for various physiological functions (Elmadfa & Meyer, 2017) and provides approximately 15% of our daily protein intake (Williams, 2007). However, the increased consumption of animal meat can also contribute to colorectal cancer, type 2 diabetes and cardiovascular disease (Richi et al., 2015). According to the 2020 World Population Data Sheet, the global population is rapidly growing and will approach 9 billion by 2050, therefore, at least double the meat compared to what is currently produced will be required. In addition, the high demand for meat production contributes to environmental issues such as increased carbon and water footprint contributing to global warming (Hoekstra, 2009). Although consumer awareness has increased regarding the environmental impact of producing animal meat protein, it is still challenging to develop animal meat alternatives with similar tastes and textures.

Currently, plant-based meat analogues (beans and legumes), edible insect-based meat analogues, cultured meat and 3D-printed meat (Bonny, Gardner, Pethick, & Hocquette, 2015; Goldstein, Moses, Sammons, & Birkved, 2017) are of interest due to their potential health benefits and sustainable production. Plant-based meat analogues have the potential to fulfil the future meat product demand (Lee, Yong, Kim, Choi, & Jo, 2020) and are available in two forms, i.e., high moisture meat analogue and textured vegetable protein (TVP). While high-moisture meat analogues are similar to animal meat and require no further processing before consumption, TVP requires rehydration before

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cooking. Therefore, TVP is used as a complete or partial replacement of animal meat in different meat-based formulations as a sustainable and healthy alternative. However, TVP alone cannot form a coherent product, thus requiring the use of binders (Kyriakopoulou, Keppler, & van der Goot, 2021).

Methylcellulose (MC) is a commonly used binder due to its gelling and emulsifying properties to hold the TVP-based patty together. It is a chemically modified polymer synthesised by etherification through a caustic alkaline medium along with the addition of an etherifying agent such as dimethyl sulphate (Nasatto et al., 2015). It can be found in the ingredient list of commercialised plant-based burger patties produced by several leading companies such as Impossible Meat, Beyond Meat, and Harvest Gourmet Nestle. However, due to its thermo-reversible gelling properties, additional stabilisers and hydrocolloids must be used to maintain the gelled structure of the finished product. Different concentrations of MC (1.5, 3 and 4%) were incorporated into commercial TVP to produce plant-based meat analogues resulting in 3% MC as the most ideal for manufacturing meat analogues when compared to beef as the control (Bakhsh, Lee, Lee, Sabikun, et al., 2021). The incorporation of MC also showed a greater texture parameter, lower cooking loss, and higher flavour retention compared to transglutaminase as a binder for plant-based burger patties (Chen, Lan, Wang, Zhang, & Wang, 2023). Plant-based patties containing MC demonstrated significantly higher values for hardness, springiness, cohesiveness, and chewiness compared to plant-based patties containing κ-carrageenan and xanthan gum (Tunnarut, Nopwinyuwong, & Tanakamolpradit, 2022). Although MC shows promising results as the binder for plant-based meat products, researchers are actively seeking alternatives to MC that can provide similar functionality while offering a cleaner label.

Enzymatically modified plant fibres are a possible alternative to MC. They consist of pectin, a cell wall polymer but require further processing to improve its functional properties for incorporation into food products (Canela-Xandri, Balcells, Villorbina, Cubero, & Canela-Garayoa, 2018). Pectin methylesterase is often used to degrade the cell wall and improve the plant fibres' gelling and emulsifying properties. Plant fibres have been proven as good binders in meat products. Citrus fibre was used to replace sodium tripolyphosphate in Bologna resulting in similar cook/chill yields and emulsion stability compared to the control (Powell, Sebranek, Prusa, & Tarté, 2019). Similarly, a study using pea fibre as the binder to replace wheat crumb in beef burgers resulted in a lower cooking loss (Pietrasik, Sigvaldson, Soladoye, & Gaudette, 2020). Apple pomace (high in fibre) also shows a good water-holding capacity, emulsion stability and cooking yield when incorporated into buffalo meat emulsion (Kumar, Yadav, Rani, & Pathera, 2024). Although these plant fibres were applied in meat products, a similar treatment could be used for plant-based meat products. Therefore, this study evaluated the physicochemical and sensorial properties of plant-based meat patties made with three enzymatically modified plant fibres, pea, citrus and apple. Specifically, we aimed to understand how the incorporation of these fibres influences the texture, moisture retention, gel strength, emulsion stability and overall acceptability of the plant-based patties, thereby elucidating their potential as sustainable and functional alternatives to traditional binders like MC.

2. Materials and methods

2.1. Raw materials

Texturised vegetable protein (GemPro) was from Simran NutriFoods Pvt. Ltd (Madhya Pradesh, India), beetroot powder was from Xinghua Hongsheng Foods Co Ltd (Xinghua City, China), mushroom seasoning (Love Earth) was from Singapore, calcium carbonate (NOW Foods) was from Bloomingdale, USA, yeast extract (Bendosen Laboratory Chemicals) was from Norway and methylcellulose was purchased from Methocel, manufactured by DuPont, USA. The pea protein isolate and Pea Fiber i50M were from Roquette (France), Citrus Fiber HB and Apple Fiber AP200 were from InterFiber (Poland), and pectin methylesterase (Novoshape) (purified from *Aspergillus aculeatus*; consisted of 5% pectin methylesterase, 10% potassium chloride, 40% water, and 45% glycerol; in a liquid form; and the activity = 8.7 PEU/g) was from Novozymes (Denmark). The corn starch (Star Brand), vegetable shortening (Adela) and black pepper (Aji Shio) were purchased from a local grocery store (Seri Kembangan, Malaysia).

2.2. Preparation of patties containing different plant fibres

Five patty treatments were designed for this study, including two control patties i.e., the negative control patty (NC) was a patty without methylcellulose/enzymatically treated plant fibre, and the positive control patty (MC) was a patty with methylcellulose patty. In addition, three other patties contain enzymatically treated pea fibre (EPF), enzymatically treated citrus fibre (ECF), and enzymatically treated apple fibre (EAF). To produce patties, texturised vegetable protein (TVP) was hydrated with water (2:1 = weight of the TVP: water) for 30 min. Then, hydrated TVP was blended with all the other ingredients (Table 1) using a Kitchen Aid mixer (5KSM150, Whirlpool Corporation, US) at medium speed number 4 to form an emulsion. The emulsion was stored at 4 °C overnight. The next day, patties were formed with 90 g of weight, 100 mm diameter and 90 mm thickness for each patty using a patty moulder and kept in the freezer at −18 °C before further cooking and analysis. For the cooking process, the patties were cooked in a non-stick pan at medium heat for 5 min on each side with a core temperature >80 °C. All the analyses were carried out in triplicate.

2.3. Proximate analysis

The proximate compositions (protein, crude fat, crude fibre, moisture, and ash) were determined following the method of AOAC (2002). Carbohydrate content was calculated using Eq. (1),

$$\% \text{ Carbohydrate} = 100\,\% - (\% \text{ moisture} + \% \text{ crude protein} + \% \text{ crude fat} + \% \text{ ash}) \quad (1)$$

2.4. pH

Three grams of sample was homogenised in 20 ml of distilled water. The pH was then measured using a digital pH meter (S20, Mettler Toledo, USA). The readings were obtained in triplicate (Bakhsh, Lee, Lee, Hwang, & Joo, 2021).

Table 1
Formulation of plant-based meat patties containing different binders.

Ingredients (%)	MC	NC	EPF	ECF	EAF
Texturised vegetable protein (TVP)	25	25	25	25	25
Water	50	50	49.3	49.3	49.3
Beetroot powder	2	2	2	2	2
Corn starch	5	5	5	5	5
Vegetable shortening	10	10	10	10	10
Pea protein isolate	2	4	2	2	2
Mushroom seasoning	1	1	1	1	1
Yeast extract	2	2	2	2	2
Black pepper	1	1	1	1	1
Methylcellulose	2	–	–	–	–
Pea fibre	–	–	2	–	–
Citrus fibre	–	–	–	2	–
Apple fibre	–	–	–	–	2
Calcium carbonate	–	–	0.2	0.2	0.2
Pectin methylesterase	–	–	0.5	0.5	0.5
Total (%)	100	100	100	100	100

MC: Plant-based meat patty with methylcellulose; NC: Plant-based meat patty with neither methylcellulose nor enzymatically treated plant fibre; EPF: Plant-based meat patty with enzymatically treated pea fibre; ECF: Plant-based meat patty with enzymatically treated citrus fibre; EAF: Plant-based meat patty with enzymatically treated apple fibre.

2.5. Water holding capacity

The water holding capacity (WHC) was determined following the method of Köhn et al. (2015). Raw samples (5 g) were mixed with 32 ml distilled water and manually shaken for 1 min in a pre-weighed 50 ml centrifuge tube. After standing for 10 min, the mixture was centrifuged (Kubota 3740, Japan) at 2900×*g* for 25 min. Then, the supernatant's weight and the centrifuge tube were weighed. The supernatant was discarded, the remaining pellet was dried in the oven at 50 °C for 20 min, and the centrifuge tube turned upside down at 10–20°. The dried pellet was weighed, and WHC was calculated using the following Eq (2),

$$\mathrm{WHC} = \left[\frac{(\mathrm{b}\text{-}\mathrm{a})\text{-}(\mathrm{c}\text{-}\mathrm{a})}{(\mathrm{b}\text{-}\mathrm{a})}\right] \times 100 \quad (2)$$

where, a = weight of empty centrifuge tube; b = weight of centrifuge tube with supernatant and c = weight of dried centrifuge tube.

2.6. Gel strength

The gel strength of the cooked samples was recorded following the method of Ismail, Chong, and Ismail-Fitry (2021) with modification. Texture analyser TA-XT2i (Stable Micro Systems, UK) with a 25 kg load was used to determine the maximum shear force (N) and work of shearing (N.s). Briefly, a 1 mm thick Warner-Bratzler shear blade was used to cut the sample at 2.5 cm length at the speed of 1.5 mm/s with 100 % cutting percentage.

2.7. Emulsion stability

The emulsion stability of the raw samples was measured following the method of Ismail, Bakar, Sazili, and Ismail-Fitry (2021). Briefly, raw samples (15 g) were stuffed in a centrifuge tube, capped and centrifuged (Kubota 3740, Japan) at 1500×*g* for 15 min for thorough mixing and eliminating air bubbles. After centrifugation, the sample was heat-treated in a water bath at 75 °C for 30 min. The cap was then opened, and the tube was turned upside down and left to stand for 60 min. The pellet that remained in the tube was weighed, and the percentage of total fluid released was calculated using the following Eq (3),

$$\text{Total fluid released } (\%) = \frac{\text{the initial weight of the sample-weight of the pellet}}{\text{the initial weight of the sample}} \times 100 \quad (3)$$

2.8. Cooking loss

The cooking loss of plant-based meat patty was determined by the method by Hollenbeck et al. (2019). The cooking loss was calculated using the following Eq. (4),

$$\text{Cooking loss } (\%) = \frac{\text{raw patty weight-cooked patty weight}}{\text{raw patty weight}} \times 100 \quad (4)$$

2.9. Dimensional change

The dimensional change was determined following the method of Ismail, Chong, et al. (2021). The diameter and thickness of the plant-based meat patty were measured before and after cooking. The dimensional change was calculated following Eq. (5),

$$\left[\text{Dimensional shrinkage } (\%) = \frac{(\text{thickness of raw patty - thickness of cooked patty}) + (\text{diameter of raw patty - diameter of cooked patty})}{\text{thickness of raw patty} + \text{diameter of raw patty}}\right] \times 100 \quad (5)$$

2.10. Texture profile analysis

The texture profile of plant-based meat patties was determined using a texture analyser (TA-XT2i, Stable Micro System, UK) based on Aslinah, Mat Yusoff, & Ismail-Fitry (2018). The textural parameters, including hardness (N), adhesiveness (N.s), springiness (%), cohesiveness (%), gumminess (N), chewiness (N) and resilience, were recorded in triplicate by the equipped software. The measurements were measured in triplicate. The measuring parameters were set as pre-test speed = 2 mm/s, post-test speed = 5 mm/s, test speed = 2 mm/s, and trigger force = 5 g.

2.11. Colour measurement

The external colours of raw and cooked patties were measured with slight modifications from Bakhsh, Lee, Lee, Hwang, et al. (2021). The sample's colours were measured using a spectrophotometer (Aeros, Hunterlab) with D65 illumination and a 10° observer angle. The units were based on the CIE (Commission Internationale de L'Eclairage) $L^*a^*b^*$ colour space (L^* for lightness, a^* for redness, b^* for yellowness). Colour measurements of both raw and cooked patties were recorded in triplicates. The total colour difference was calculated by following Eq. (6),

$$\Delta E = \sqrt{\Delta L^2 + \Delta a^2 + \Delta b^2} \quad (6)$$

2.12. Microstructural properties

The microstructures of cooked patties were analysed by scanning electron microscopy (SEM) as described by Gordon and Barbut (1992). First, the samples were mounted over the stubs with a double-sided carbon conductivity tap. After that, samples were coated with a thin layer of gold using an automated sputter coater (Model: JOEL JFC-1600) for 3 min and scanned under the scanning electron microscope (JSM 5600, JOEL, Japan) at 1000× magnification.

2.13. Sensory evaluation

The sensorial properties of plant-based meat patties were carried out in a proper sensory laboratory by 50 untrained panellists involving 19 men and 31 women with ages ranging between 21 and 36 years old. The panellists were the undergraduate and postgraduate students, laboratory staff and lecturers from the Faculty of Food Science and

Technology, Universiti Putra Malaysia with experience conducting sensory evaluation previously. All the panellists agreed to join the sensory evaluation session voluntarily after an explanation was given regarding the type of samples used, possible allergenicity, safety of the samples, confidentiality of information, and ability to withdraw from the evaluation at any time. A preference test of the 9-point hedonic scale with each sensory attribute ranging from 9 = extremely like, 5 = neither like nor dislike and 1 = extremely dislike was used. The samples were coded with three-digit random numbers, and the presentation was random. The measured sensory attributes were taste, appearance, texture, juiciness and overall acceptability.

2.14. Statistical analysis

Statistical analysis was conducted using Minitab version 18 (Minitab Inc., State College, PA, USA). One-way analysis (ANOVA) at a 95 % confidence level was used to determine the significant differences in the data obtained with Tukey's multiple comparison test. The values were reported as a mean ± standard deviation. In addition, multivariate data analysis, i.e., dataset pre-processing, principal component analysis and agglomerative hierarchical clustering, was carried out using XLSTAT 2017 (Addinsoft, Paris, France).

2.14.1. Dataset pre-processing

The dataset consisting (1) physicochemical properties, i.e., proximate, pH, WHC, gel strength, emulsion stability, cooking loss, dimensional change, texture profile, colour measurement and microstructural characterisation, and (2) sensory properties, i.e. taste, appearance, texture, juiciness and overall acceptability were normalised via standardising (n-1) transformation technique at a significant level (α) of 0.05 to before carrying out a test for sampling adequacy via Keiser-Meyer Olkin (KMO) test, principal component analysis (PCA) and agglomerative hierarchical clustering (AHC) (Ismail, Sani, et al., 2021). The PCA and AHC were carried out when the KMO value > 0.5, indicating that the dataset in this study was adequate for multivariate data analysis (Idris et al., 2022).

2.14.2. Principal component analysis

The PCA of Pearson correlation was carried out to (1) identify the significant physicochemical and sensory properties of the plant-based meat patties and (2) propose which properties characterised the plant-based meat patties. The normalised dataset from the pre-processing step was transformed into a new dataset consisting of independent variables denoted as principal components (PCs) at α of 0.05. The cumulative variability of the PCs was assessed to determine the percentage of the dataset explained in this study. At the same time, the physicochemical and sensory properties were ranked based on their factor loadings: Strong for $FL \geq |0.750|$, moderate for $|0.500| < FL < |0.749|$ and weak for $FL \leq |0.499|$. Finally, based on the variable plot and biplot of the PCA, the significant properties in this study were decided, and the properties characterising the plant-based meat patties were proposed (Sani, Bakar, Azid, & Iqbal, 2022).

2.14.3. Agglomerative hierarchical clustering

Agglomerative hierarchical clustering (AHC), an unsupervised technique, was employed to determine the similarity among the plant-based meat patties. The normalised dataset was subjected to clustering analysis via the Pearson correlation coefficient of the unweighted pair-group average method. The plant-based meat patties were grouped into classes based on the property similarities within a class and dissimilarity between different classes. The classes were further confirmed with the PCA's biplot (Daddiouaissa, Amid, Abdullah Sani, & Elnour, 2021).

Table 2
Proximate composition of plant-based meat patties containing different binders.

Samples	Moisture (%)	Ash (%)	Protein (%)	Fibre (%)	Fat (%)	Carbohydrates (%)
MC	49.83 ± 0.74 ^{ab}	3.00 ± 0.00 ^{bc}	16.27 ± 0.12 ^{b}	7.67 ± 0.06 ^{b}	8.53 ± 1.37 ^{b}	14.70 ± 2.01 ^{a}
NC	50.03 ± 1.03 ^{ab}	3.30 ± 0.17 ^{a}	17.77 ± 0.23 ^{ac}	7.60 ± 0.20 ^{b}	10.90 ± 0.66 ^{a}	10.40 ± 0.16 ^{b}
EPF	51.23 ± 0.45 ^{a}	2.83 ± 0.06 ^{c}	16.13 ± 0.12 ^{bc}	8.27 ± 0.12 ^{ab}	9.83 ± 0.06 ^{ab}	11.70 ± 0.36 ^{b}
ECF	51.30 ± 0.17 ^{a}	3.00 ± 0.00 ^{bc}	15.83 ± 0.25 ^{c}	8.87 ± 0.31 ^{a}	9.97 ± 0.21 ^{ab}	11.03 ± 0.55 ^{b}
EAF	49.40 ± 0.27 ^{b}	3.07 ± 0.06 ^{b}	16.40 ± 0.27 ^{b}	8.60 ± 0.46 ^{a}	10.00 ± 0.20 ^{ab}	12.53 ± 0.42 ^{a}

Data are mean ± standard deviation of triplicate (n = 3).
Different superscripts in a column indicate a significant difference ($p < 0.05$).
MC = Plant-based meat patty with methylcellulose; NC = Plant-based meat patty without any binder, EPF = Plant-based meat patty with enzymatically treated pea fibre; ECF = Plant-based meat patty with enzymatically treated citrus fibre; EAF = Plant-based meat patty with enzymatically treated apple fibre.

3. Results and discussion

3.1. Proximate composition

The proximate composition (moisture, ash, protein, fibre, fat and carbohydrate) of plant-based meat patties with different binders is presented in Table 2. The moisture content of EAF, EPF and ECF was not significantly different compared to the MC and NC but EAF had a lower ($p < 0.05$) moisture content compared to the EPF and ECF. NC had the highest ash content, whereas the EPF had the lowest ash content. The protein content of all plant-based meat patty was in the range of 15.83–17.77 %. The fibre content of ECF and EAF was higher than

Table 3
pH, water holding capacity, emulsion stability, cooking loss and shrinkage of plant-based meat patties containing different binders.

Sample	pH	Water Holding Capacity (%)	Total fluid release (%)	Cooking Loss (%)	Dimensional Changes (%)
MC	6.58 ± 0.03 ^{a}	83.29 ± 1.79 ^{a}	1.16 ± 0.47 ^{ab}	3.70 ± 0.64 ^{b}	7.44 ± 0.52 ^{b}
NC	6.44 ± 0.09 ^{a}	81.88 ± 0.03 ^{a}	1.51 ± 0.17 ^{ab}	10.00 ± 1.11 ^{a}	10.71 ± 0.00 ^{a}
EPF	6.00 ± 0.19 ^{b}	81.41 ± 0.04 ^{a}	1.33 ± 0.23 ^{ab}	4.07 ± 0.64 ^{b}	6.25 ± 0.89 ^{bc}
ECF	5.94 ± 0.00 ^{b}	81.92 ± 0.13 ^{a}	1.53 ± 0.07 ^{a}	1.85 ± 0.64 ^{b}	5.36 ± 0.00 ^{c}
EAF	5.88 ± 0.02 ^{b}	81.19 ± 0.10 ^{a}	0.84 ± 0.10 ^{b}	4.44 ± 1.92 ^{b}	6.55 ± 1.03 ^{bc}

Data are mean ± standard deviation of triplicate (n = 3).
Different superscripts in a column indicate a significant difference ($p < 0.05$).
MC = Plant-based meat patty with methylcellulose; NC = Plant-based meat patty without any binder, EPF = Plant-based meat patty with enzymatically treated pea fibre; ECF = Plant-based meat patty with enzymatically treated citrus fibre; EAF = Plant-based meat patty with enzymatically treated apple fibre.

control patty samples. Replacing the methylcellulose with enzymatic plant fibres slightly increased the fibre content of plant-based meat patties but there was no significant difference in the fat content of the plant-based meat patties compared to the MC and NC. Nevertheless, the MC recorded significantly lower fat content than the NC. This could be due to the well-distributed and -absorbed fat in MC samples resulting in a lower fat measurement compared to the uneven distribution of fat in NC samples leading to several pockets of higher fat concentration. There was no significant difference in the carbohydrate content between MC and EAF but they were higher ($p < 0.05$) than NC, EPF and ECF. Similar results were reported by Bakhsh, Lee, Lee, Hwang, et al. (2021) for the moisture (51 %), ash (3 %) and protein (16 %) content of plant-based meat patties but they had a slightly lower fibre and higher fat content. This could be due to differences in plant-based meat patty formulations and the origin and processing of these plant fibres (Besbes, Attia, Deroanne, Makni, & Blecker, 2008). Furthermore, the protein and fibre content of all the plant-based meat patties was higher when compared to commercial plant-based meat patties (Curtain & Grafenauer, 2019).

3.2. Physicochemical properties

3.2.1. pH, water holding capacity and emulsion stability

As shown in Table 3, the pH values for the patty samples prepared with the addition of enzymatically treated plant fibres were slightly lower than the control samples (MC and NC) which were similar to those reported by Bakhsh, Lee, Lee, Hwang, et al. (2021). This slight decrease in pH of the plant-based meat patties (EPF, ECF and EAF) was due to the presence of calcium chloride dihydrate that facilitated the pectin methyl esterase and ultimately aided in forming a strong emulsion (Jolie, Duvetter, Van Loey, & Hendrickx, 2010; On-Nom, Grandison, & Lewis, 2012).

The water-holding capacities of all patties were similar suggesting that enzymatically treated plant fibres could entrap the same amount of water in the patties as methylcellulose (Table 3). This could be due to the treatment of plant fibres with pectin methyl esterase which increases their water-holding capacity (Canela-Xandri et al., 2018). Likewise, similar results were observed by Peñaranda and Garrido (2024) wherein plant-based burgers containing fructooligosaccharide as a binder demonstrated water holding capacity of 82.59–88.45%. While Serdaroğlu, Kavuşan, İpek, and Öztürk (2018) found that beef patties containing 5% pumpkin flour had a higher water holding capacity (79.80%) compared to beef patties without any pumpkin flour (75.30%), both of the which are lower than the values observed in our study.

The emulsion stability was expressed in terms of total fluid released from the plant-based meat patties, whereby the less total fluid released, the more stable the emulsion. As shown in Table 3, the total fluid released by EPF, ECF and EAF was comparable to the positive and negative control plant-based meat patties (MC and NC). Also, it is important to note that the EAF released the lowest fluid (0.84 %) compared to the control samples (MC and NC) and EPF and ECF samples, indicating its good emulsion stability index.

3.2.2. Cooking loss and shrinkage

There was no significant difference in cooking loss among the MC and EPF, ECF and EAF-plant-based meat patties (Table 3), but NC showed the highest ($p < 0.05$) cooking loss due to the absence of an effective binder to hold the water during cooking. Higher cooking loss (28–35%) was found in plant-based patties containing MC and modified starch compared to the current study (Vu, Zhou, & McClements, 2022). The presence of pectin in plant fibres is responsible for the good gelation of the plant-fibre patties and similar cooking loss compared to the control sample MC. Moreover, the ECF showed the least cooking loss (1.85 %) among all the samples. The dimensions of EPF and EAF were not significantly different from the positive control (MC) sample. Notably, the dimension change for ECF was less than the MC and NC, confirming the lowest cooking loss in line with a previous study that reported that TVP and plant fibres could efficiently reduce moisture loss and shrinkage during cooking (Bakhsh, Lee, Lee, Hwang, et al., 2021; Gujral, Kaur, Singh, & Sodhi, 2002). The control sample NC (without any binder) showed the greatest dimensional changes (10.71 %) among all the samples (Table 3) and poor integrity as the patties broke into pieces during cooking (Fig. 1).

The plant-based patties with added plant fibre demonstrated comparable physicochemical properties to the methylcellulose-based patties. Furthermore, enzymatically treated citrus fibre showed lower cooking loss and dimension changes than the methylcellulose-based patty samples, proving it is an attractive alternative to methylcellulose

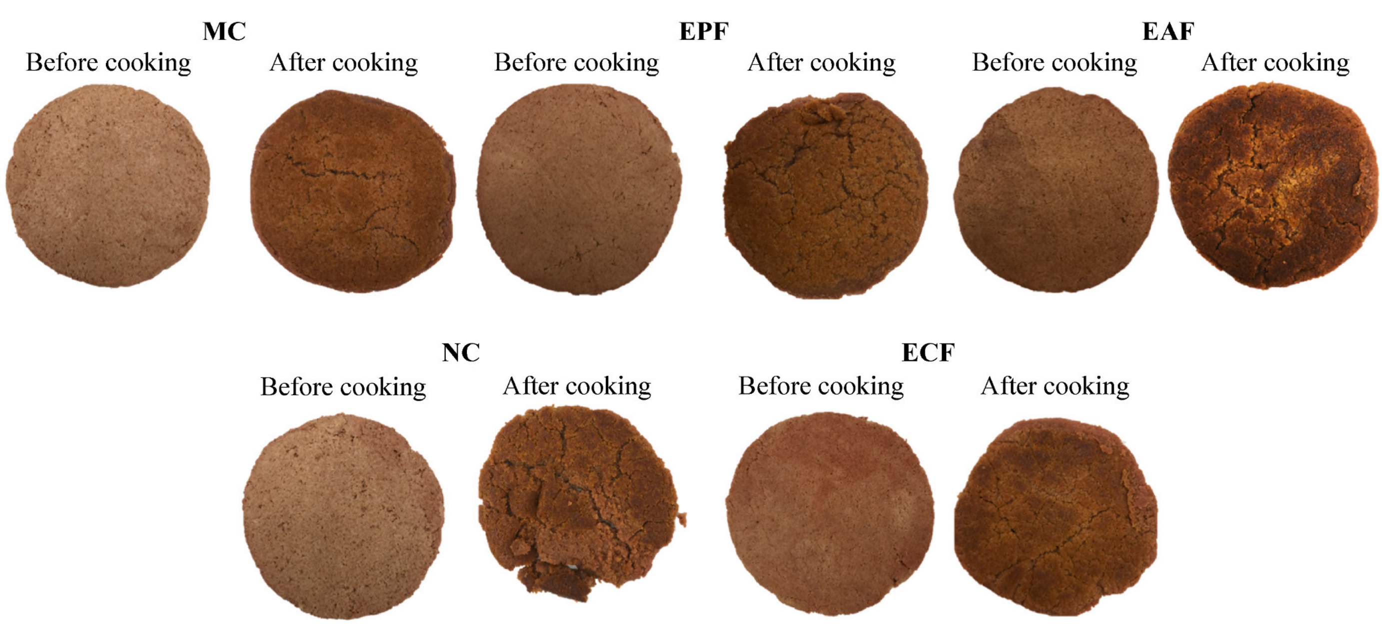

Fig. 1. Visual appearance of plant-based meat patties containing different binders before and after cooking
MC = Plant-based meat patty with methylcellulose; NC = Plant-based meat patty without any binder, EPF = Plant-based meat patty with enzymatically treated pea fibre; ECF = Plant-based meat patty with enzymatically treated citrus fibre; EAF = Plant-based meat patty with enzymatically treated apple fibre.

Table 4
Colour parameters of plant-based meat patties containing different binders before and after cooking.

Colour Scale	MC	NC	EPF	ECF	EAF
Before cooking					
*L**	56.55 ± 0.24 [a]	53.46 ± 0.03 [b]	56.37 ± 0.03 [a]	53.13 ± 0.01 [c]	50.28 ± 0.02 [d]
*a**	15.28 ± 0.06 [d]	15.30 ± 0.01 [d]	16.79 ± 0.02 [b]	17.74 ± 0.02 [a]	16.09 ± 0.01 [c]
*b**	15.29 ± 0.09 [d]	16.71 ± 0.01 [c]	18.23 ± 0.00 [a]	17.63 ± 0.01 [b]	17.61 ± 0.02 [b]
After cooking					
*L**	38.65 ± 0.69 [a]	34.90 ± 1.23 [b]	37.84 ± 0.04 [ab]	36.19 ± 0.38 [ab]	30.13 ± 2.37 [c]
*a**	18.23 ± 0.45 [a]	16.51 ± 0.43 [b]	18.47 ± 0.35 [a]	18.57 ± 0.20 [a]	15.22 ± 0.48 [c]
*b**	23.33 ± 0.66 [ab]	21.48 ± 0.80 [b]	24.04 ± 0.28 [a]	22.61 ± 0.23 [ab]	17.66 ± 1.24 [c]

Data are mean ± standard deviation of triplicate (n = 3).
Different superscripts in a row indicate a significant difference ($p < 0.05$).
MC = Plant-based meat patty with methylcellulose; NC = Plant-based meat patty without any binder, EPF = Plant-based meat patty with enzymatically treated pea fibre; ECF = Plant-based meat patty with enzymatically treated citrus fibre; EAF = Plant-based meat patty with enzymatically treated apple fibre.

binder.

3.2.3. Colour

The colour of plant-based meat patties before and after cooking was recorded in terms of L^* a^* and b^* as displayed in Table 4, while the colour visuals are presented in Fig. 1. The L* value before cooking of the positive control (MC = 56.55) was significantly different to the negative control (NC = 53.46) samples, with the patty with the methylcellulose binder being lighter in appearance compared to the sample having no binder. For the patty samples containing the three different plant-based binders, the L^* value decreased in the following order EPF (56.37) > ECF (53.13) > EAF (50.28), indicating that patty samples containing pea fibre were lighter compared to citrus and apple fibre binder. It is also interesting to note that EPF and MC recorded similar L^* values. The a^* values for EPF, ECF and EAF were comparatively higher than both control samples (MC and NC), indicating that plant-based fibres provided a more reddish hue to the patty samples, whereas EPF, ECF and EAF contributed a more yellow hue to the patty samples compared to control samples MC and NC, as indicated by the higher b^* values.

After cooking, all samples turned darker as demonstrated by the decrease in L^* values with EAF recording the lowest value (30.13). All samples showed a higher red hue (a^* value) whereas MC, EPF and ECF recorded similar values, except NC and EAF recorded a comparatively lower red hue. The cooking of patties also induced a more yellow hue to

Table 5
Texture profile and shear force of plant-based meat patties containing different binders.

	MC	NC	EPF	ECF	EAF
Hardness (N)	27.93 ± 0.77 [c]	7.76 ± 0.27 [d]	28.67 ± 0.52 [c]	68.52 ± 0.69 [a]	38.17 ± 0.58 [b]
Adhesiveness (N.s)	−0.016 ± 0.004 [a]	−0.009 ± 0.001 [a]	−0.001 ± 0.001 [a]	−0.010 ± 0.015 [a]	−0.006 ± 0.004 [a]
Springiness (%)	0.11 ± 0.01 [ab]	0.09 ± 0.02 [b]	0.11 ± 0.00 [ab]	0.13 ± 0.00 [a]	0.11 ± 0.01 [ab]
Cohesiveness (%)	0.09 ± 0.02 [b]	0.08 ± 0.01 [b]	0.10 ± 0.02 [b]	0.16 ± 0.02 [a]	0.09 ± 0.01 [b]
Gumminess (N)	2.73 ± 0.36 [b]	2.47 ± 0.54 [b]	2.84 ± 0.39 [b]	6.53 ± 0.27 [a]	3.40 ± 0.36 [b]
Chewiness (N)	0.30 ± 0.02 [c]	0.13 ± 0.03 [d]	0.32 ± 0.05 [bc]	0.86 ± 0.01 [a]	0.37 ± 0.01 [b]
Resilience	0.03 ± 0.01 [a]	0.03 ± 0.00 [a]	0.03 ± 0.01 [a]	0.05 ± 0.02 [a]	0.03 ± 0.00 [a]
Maximum Shear Force (N)	1.67 ± 0.01 [ab]	0.98 ± 0.01 [b]	1.57 ± 0.20 [ab]	2.16 ± 0.78 [a]	1.67 ± 0.20 [ab]
Work of Shear (N.s)	9.22 ± 4.41 [ab]	6.37 ± 0.29 [b]	7.55 ± 1.08 [b]	15.70 ± 4.71 [a]	5.79 ± 0.39 [b]

Data are mean ± standard deviation of triplicate (n = 3).
Different superscripts in a row indicate a significant difference ($p < 0.05$).
MC = Plant-based meat patty with methylcellulose; NC = Plant-based meat patty without any binder, EPF = Plant-based meat patty with enzymatically treated pea fibre; ECF = Plant-based meat patty with enzymatically treated citrus fibre; EAF = Plant-based meat patty with enzymatically treated apple fibre.

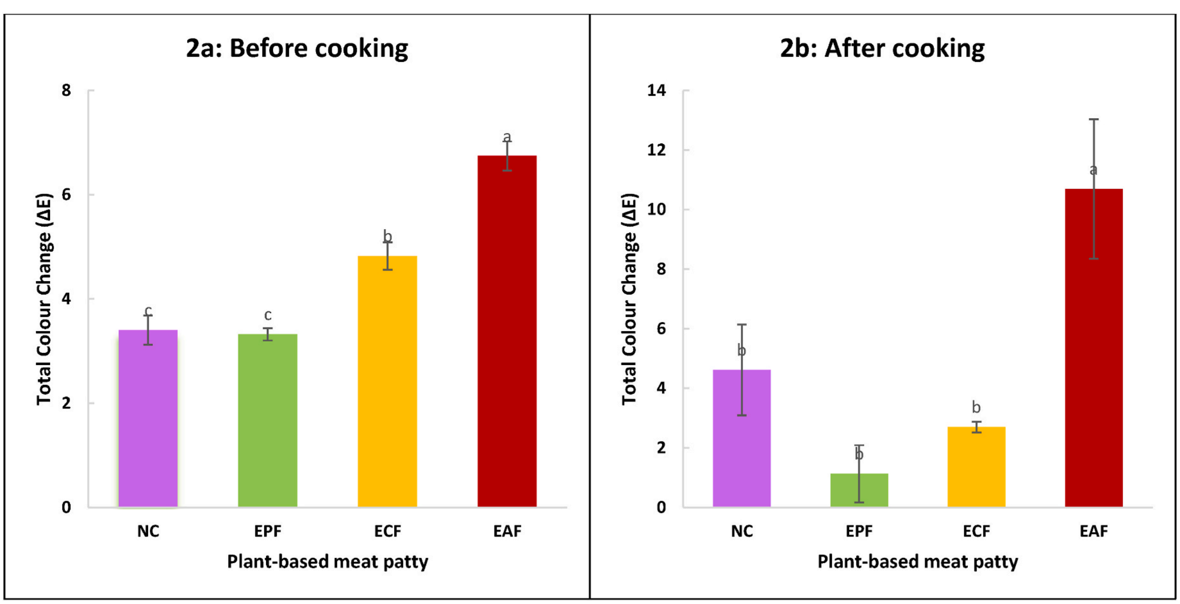

Fig. 2. Total colour change (ΔE) of plant-based meat patties containing different binders before cooking (2a) and after cooking (2b) against the plant-based meat patty with methylcellulose (MC).
Different alphabets in the same graph indicate a significant difference ($p < 0.05$). (n = 3) NC = Plant-based meat patty without any binder, EPF = Plant-based meat patty with enzymatically treated pea fibre; ECF = Plant-based meat patty with enzymatically treated citrus fibre; EAF = Plant-based meat patty with enzymatically treated apple fibre.

samples MC, NC EPF, and ECF. The darker colour of both the raw and cooked EAF patties could be influenced by the brownish colour of the apple fibre, whereas other fibres and MC were originally whitish. Meanwhile, the higher red and yellow hue for most of the cooked samples could be attributed to the Maillard reaction which took place during cooking (Kim, Lee, Lee, Jo, & Choi, 2022).

The total colour changes before cooking of the plant-based meat patties compared to the control sample, MC, are shown in Fig. 2a, with EAF showing the most significant colour changes, followed by ECF, NC and EPF. There were no significant differences in the colour changes between NC and EPF, whereas the total colour changes after cooking of EPF and ECF were the same compared to the NC (Fig. 2b). EAF after cooking has the highest total colour changes similar to the study of Lauková, Kohajdová, and Karovičová (2016), whereby incorporating apple fibres into cookie dough caused darker (-L^* value) colour formation and higher overall total colour changes.

3.3. Textural properties

The textural parameters i.e., hardness, adhesiveness, springiness, cohesiveness, gumminess, chewiness, and resilience for all the samples, are shown in Table 5. Hardness is a crucial attribute for meat patties and reflects the force required to break the food via incisors during mastication. Patties with ECF recorded the highest hardness value, which was comparable to the commercial meat patty sample, as reported by Samard, Maung, Gu, Kim, and Ryu (2021). Patties with EAF had a significantly higher hardness value than the EPF and MC, with the control sample with no binder (NC) being the softest.

Adhesiveness is defined as the force needed to overcome the attractive forces occurring between the food surface and other materials contacted (Szczesniak, 2002) and depends on the viscoelastic properties and the interaction of the adhesive and cohesive forces. Table 5 shows that there was no significant difference in adhesiveness between all patties. Springiness is another textural attribute that records the possibility of returning the tested sample from a deformed state to the initial state (Chang, Wang, Zhou, Xu, & Li, 2010). All plant-based meat patties with enzymatically treated plant fibres (EPF, ECF and EAF) demonstrated similar springiness while the sample NC with no binder had the least springiness.

Cohesiveness explains the strength of internal bonds (Pematilleke, Kaur, Rai Wai, Adhikari, & Torley, 2021) and ECF recorded the highest cohesiveness and was significantly different from all other samples. The gumminess of food products is derived from their hardness and cohesiveness values (Ayandipe et al., 2022) and the gumminess of the patties showed a similar trend to cohesiveness, whereby ECF had the highest value.

Chewiness is necessary to destroy the internal bonds of the test sample (Duma-Kocan, Rudy, Gil, & Stanisławczyk, 2020). The least chewy sample was the plant-based meat with neither methylcellulose nor enzymatically treated plant fibres (NC). Previous studies suggested that an increasing concentration of binders such as methylcellulose proportionally increased the chewiness of products (Bakhsh, Lee, Lee, Hwang, et al., 2021; de Angelis et al., 2020). EPF showed the same chewiness compared to the control sample MC with ECF being the chewiest. Shearing exhibits the cutting action, which splits the food

Table 6
Sensory evaluation scores for the plant-based meat patties containing different binders.

Sample	Taste	Appearance	Texture	Juiciness	Overall Acceptability
MC	7.12 ± 1.19 [a]	6.94 ± 1.08 [a]	7.12 ± 1.00 [b]	7.04 ± 0.93 [a]	6.92 ± 1.09 [a]
NC	6.84 ± 1.15 [a]	3.82 ± 0.98 [c]	4.50 ± 1.23 [c]	4.36 ± 0.85[b]	2.70 ± 0.91 [b]
EPF	7.16 ± 1.13 [a]	6.84 ± 1.00 [a]	6.96 ± 0.90 [b]	7.10 ± 0.95 [a]	6.86 ± 1.05 [a]
ECF	7.22 ± 1.17 [a]	6.78 ± 0.98 [a]	8.28 ± 0.70 [a]	6.94 ± 0.96 [a]	6.88 ± 0.98 [a]
EAF	7.08 ± 1.03 [a]	5.70 ± 0.95 [b]	8.10 ± 0.74 [a]	6.84 ± 1.04 [a]	6.84 ± 1.00 [a]

Data are mean ± standard deviation of replications (n = 50).
Different superscripts in a row indicate a significant difference ($p < 0.05$).
MC = Plant-based meat patty with methylcellulose; NC = Plant-based meat patty without any binder, EPF = Plant-based meat patty with enzymatically treated pea fibre; ECF = Plant-based meat patty with enzymatically treated citrus fibre; EAF = Plant-based meat patty with enzymatically treated apple fibre.

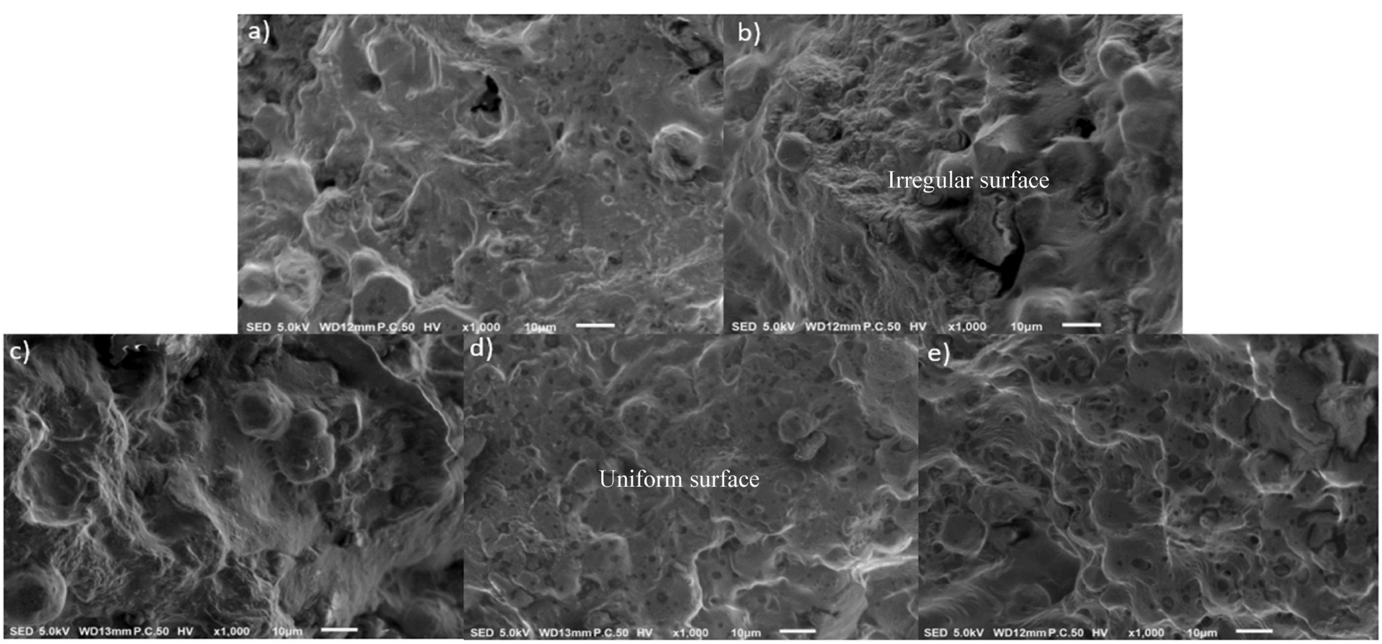

Fig. 3. Microstructural characterization of plant-based meat patties containing different binders (1000× magnification)
a) MC = Plant-based meat patty with methylcellulose; b) NC = Plant-based meat patty without any binder; c) EPF = Plant-based meat patty with enzymatically treated pea fibre; d) ECF = Plant-based meat patty with enzymatically treated citrus fibre; e) EAF = Plant-based meat patty with enzymatically treated apple fibre.

product into two fragments (Novaković & Tomašević, 2017) and ECF had the highest maximum shear force and shear work of all samples tested.

3.4. Microstructure

The microstructure of all the samples in Fig. 3 shows that patties with NC had the most irregular surface layers while MC and EPF showed a uniform surface superior to NC. The plant-based meat patty ECF demonstrated the most uniform surface layer, followed by EAF and EPF. The enzymatically treated plant fibres act as a binder in the plant-based meat patties, thus having a more uniform structure compared to NC without binder. Moreover, the microstructural appearance is in line with the textural properties (section 3.3) and sensory evaluation (section 3.5), confirming that the uniformly structured patty had more integrity.

3.5. Sensory attributes

The sensorial attributes, i.e., taste, appearance, texture, juiciness, and overall acceptability, were evaluated by 50 panellists using a 9-point hedonic scale (Table 6). The EPF (7.16), ECF (7.22) and EAF (7.08) samples showed similar taste scores compared to the control MC (7.12), indicating that the use of different plant-based fibres did not negatively affect the taste of the patties. The appearance of MC (6.94), EPF (6.84) and ECF (6.78) received the same average score which was slightly higher than EAF (5.70), possibly due to the slightly dark colour development after cooking being less appealing to the panellists. Patties with NC scored the least for appearance (3.82) because, without any binder, they could not hold their shape, broke into pieces and did not meet the panellists' expectations.

ECF (8.28) and EAF (8.10) scored the highest for texture compared to EPF (6.96) and MC (7.12) due to their slightly hard texture compared to other plant-based meat patties while the plant-based meat patty with no binder NC (4.50) scoring the least. All patties with binders were awarded similar scores for juiciness in the range of 7.04-6.84. Regarding overall acceptability, the plant-based meat patties with the use of chemical binder (MC) and enzymatically treated plant fibres (EPF, ECF and EAF) had the same acceptability, whereas NC was least acceptable to the panellists.

Table 7
Factor loading (FL) of variables in principal components (PC) for the plant-based meat patties.

Property	Factor loading for principal components [a,b,c]	
	PC1	PC2
Cooking loss	**0.9027**	−0.1691
Dimensional changes	**0.9316**	0.0294
Before cooking L*	−0.0209	**0.8080**
Before cooking a*	**−0.8532**	−0.3518
Before cooking b*	−0.3893	−0.6585
After cooking L*	−0.1533	**0.7691**
After cooking a*	−0.5105	0.5314
After cooking b*	−0.1972	0.6207
Hardness	**−0.9257**	−0.2089
Adhesiveness	−0.1242	−0.4620
Springiness	**−0.8055**	−0.0342
Cohesiveness	−0.7421	−0.2297
Gumminess	**−0.7669**	−0.3335
Chewiness	**−0.8779**	−0.2170
Resilience	−0.6161	−0.2343
Water holding capacity	−0.0228	0.7093
Maximum shear force	**−0.7849**	0.0377
Work of shear	−0.6479	0.1178
Total fluid release	0.0012	−0.1592
pH	0.5946	0.6510
Moisture content	−0.4787	−0.0683
Ash	0.6670	−0.3320
Protein	**0.9157**	−0.2073
Fibre	−0.7493	−0.4995
Fat	0.3155	**−0.7734**
Carbohydrates	−0.1142	0.7493
Taste	−0.3781	0.2367
Appearance	**−0.8282**	0.4864
Texture	**−0.8701**	−0.0757
Juiciness	**−0.8218**	0.2832
Overall acceptability	**−0.8318**	0.2574
Eigenvalue (EV)	13.2256	6.0022
Dataset variability (DV), %	42.6632	19.3618
Cumulative explained variability (CEV), %	42.6632	62.0250

[a] Keiser-Meyer Olkin (KMO) value = 0.6167 (KMO <0.5 = inadequate, 0.5 < KMO <0.7 = mediocre, 0.7 < KMO <0.8 = good, 0.8 < KMO <0.9 = very good and KMO >0.9).

[b] FL ≥ |0.750| = strong factor loading; |0.500| < FL < |0.749| = moderate factor loading; and FL ≤ |0.499| = weak factor loading.

[c] Factor loading with the bold value indicated strong factor loading in the principal component.

3.6. Determination of significant properties and their associations in plant-based meat patties

PCA was performed to identify the significant physicochemical and sensory properties of plant-based meat patties. Table 7 shows the KMO value of 0.6167 which based on the KMO rank by Ismail, Sani, et al. (2021) is adequate for multivariate data analysis. The principal components PC1 and PC2 explained 62 % of the meaningful information from the dataset based on cumulative explained variability (CEV) value. This CEV also indicated that 62.02 % of the properties in the dataset had variability, hence facilitating the selection of significant physicochemical and sensory properties of the plant-based meat patties. The property variability was further explained via the ranking of the factor loading (FL) value for each property in their respective principal component (PC); FL ≥ |0.750| for strong, |0.500| < FL < |0.749| for moderate, and FL ≤ |0.499| for weak property contributions to the plant-based meat patties (Idris et al., 2022). All the variables with strong FLs from PC1 and PC2 listed in Table 7 significantly contributed to the selection and development of plant-based meat patties. Hence, it is recommended that these properties be improved in further studies to develop plant-based meat patties.

The variable plot in Fig. 4a provides information on the correlation between the properties based on their vector direction. For instance, dimensional changes, cooking loss, and protein and ash contents were positively correlated since these properties were in the same vector direction towards the right of the PC1 (Ismail, Sani, et al., 2021). Likewise, the work of shear, maximum shear force, springiness, texture, and chewiness were also positively correlated due to their similar direction to the left of PC1. This indicates that a high value for springiness and chewiness positively affected the work of shear and maximum shear force, thus increasing the acceptability of the texture of the plant-based meat patties (Table 5). However, since these properties, i.e. work of shear, maximum shear force, springiness, texture and chewiness, were in the oppositive vector direction against the dimensional changes, cooking loss, protein and ash content, they were negatively correlated (Abdullah Sani, Ismail, Azid, & Samsudin, 2021).

Interestingly, the carbohydrate content was positively associated with WHC and the colour of the plant-based meat patties after cooking, while these properties were negatively correlated with fat content. The carbohydrate content also did not correlate with the dimensional changes, cooking loss, work of shear, maximum shear force, springiness, texture, chewiness and protein and ash contents because of their vector direction at 90° against these properties (Sani et al., 2022), signifying that it may not contribute to the quality of the plant-based meat patties and the panellist selection during the sensory evaluation.

3.7. Determining properties characterising plant-based meat patties

The PCA also proposed properties characterising the plant-based

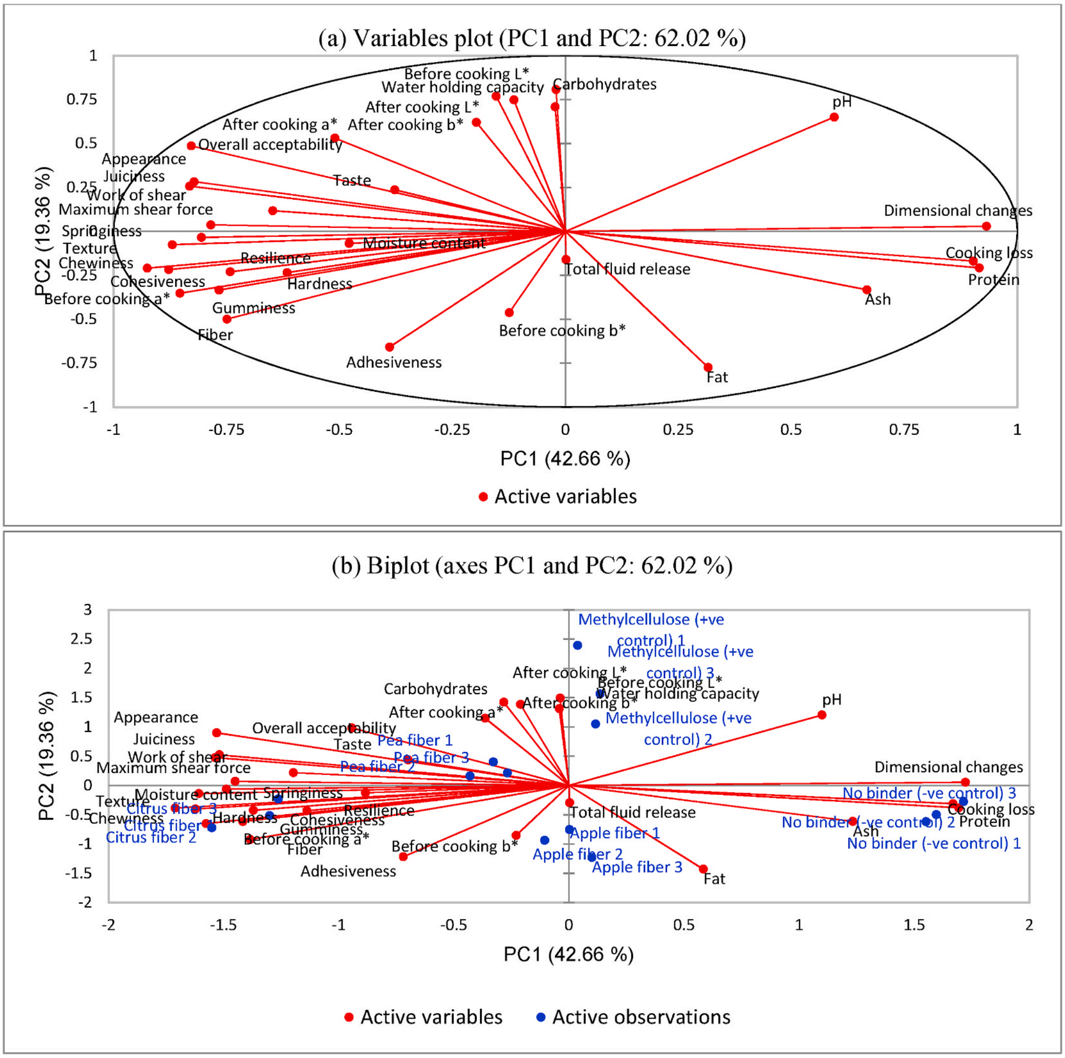

Fig. 4. (a) Variable plot and (b) biplot of plant-based patties.

meat patties via the biplot of the plant-based meat patty types in Fig. 4b. Five groups of blue-coloured plant-based meat patties and red-coloured physicochemical and sensory properties were plotted with the characterisation based on the same and opposite directions of the vector of the plant-based meat patties and the physicochemical and sensory properties.

The carbohydrate, WHC and colour after cooking characterised the positive control consisting of MC since they had the same vector direction. The MC also had a low-fat content, total fluid release and b^* values before cooking, whereas significant dimensional changes, cooking loss, and protein and ash contents characterised the NC which contained no binder. Also, the NC was characterised by a low texture score, low moisture content, low springiness, chewiness, hardness, resilience, cohesiveness, gumminess, fibre content and a^* values before cooking. For the EAF, high total fluid release, fat content, and b^* values before cooking, while low carbohydrate, WHC and colour after cooking contributed to the patty characteristics. High moisture content, high texture score, springiness, chewiness, hardness, resilience, cohesiveness, gumminess, fibre content and a^* values before cooking dominated the ECF. This patty also had low dimensional changes, cooking loss, and protein and ash contents. High work of shear, maximum shear force, a^* values after cooking, juiciness, appearance and overall acceptability, while low dimensional changes, cooking loss, and protein and ash contents contributed to the characteristics of the EPF.

The dendrogram in Fig. 5 displays the similarities among the plant-based meat patties. Based on the properties that characterised the plant-based patties, the similarity rank of the plant-based patties towards the MC was as follows: EPF > ECF > EAF > NC. Therefore, the line connecting EPF to the MC indicated that the EPF could be used as an alternative to MC, followed by the ECF and EAF. However, based on the PCA results (Fig. 4b), ECF was the best binder compared to EPF and MC, indicating that although EPF is the most similar binder to MC, ECF had superior functional properties for a better quality plant-based meat patty.

4. Conclusion

Replacing methylcellulose in plant-based meat patties with plant fibres [pea (EPF), citrus (ECF) and apple (EAF)] slightly increased the fibre content and slightly decreased the pH compared to control patties (MC and NC). The EPF demonstrated comparable water holding capacity, emulsion stability, cooking loss, shrinkage, and textural properties to the control MC. The ECF demonstrated the least cooking loss and shrinkage, uniform surface, hard texture, better cohesiveness, gumminess and chewiness compared to control and other plant fibre-based patties. Both the EPF and ECF were comparable to the control MC in terms of colour appearance, whereas the EAP was darker. EAP also showed good emulsion stability and chewiness. All the plant fibre-based patties scored similarly for taste, texture, juiciness and overall acceptability compared to the control MC. The agglomerative

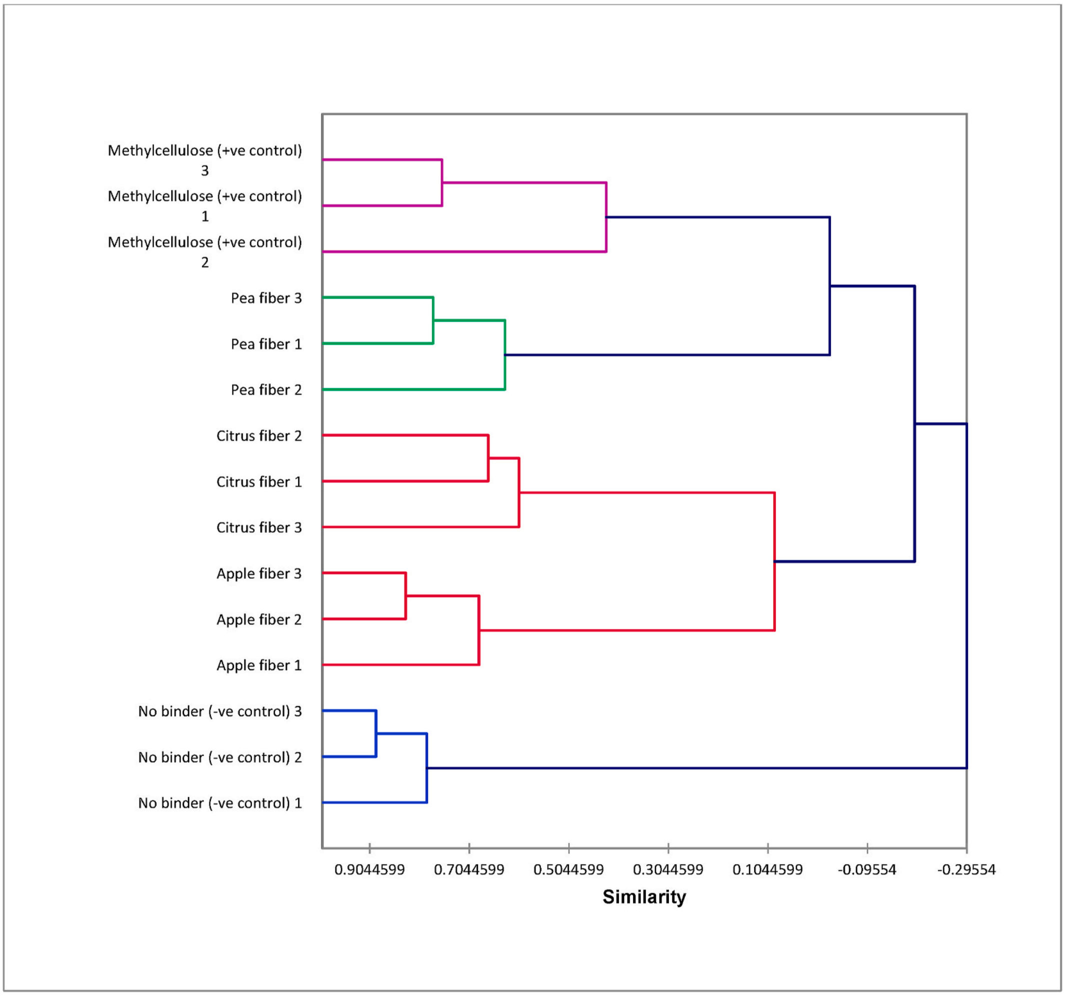

Fig. 5. Dendogram of plant-based patties.

hierarchical clustering revealed that the EPF had similar characteristics to the control MC but the principal component analysis indicated that citrus (ECF) was a superior binder to pea (EPF), therefore it could be used to replace methylcellulose for plant-based meat patties minimising the use of additional stabilisers and hydrocolloids.

Consent to participate

It is confirmed that the appropriate protocols for protecting the rights and privacy of all participants were utilized during the execution of the research, e.g. no coercion to participate, full disclosure of study requirements and risks, written or verbal consent of participants, no release of participant data without their knowledge, ability to withdraw from the study at any time.

CRediT authorship contribution statement

Ain Sze Wei: Conceptualization, Data curation, Writing – original draft. **Fatema Hossain Brishti:** Data curation, Visualization, Writing – review & editing. **Muhamad Shirwan Abdullah Sani:** Data curation, Visualization, Writing – review & editing. **Ismail Ishamri:** Writing – review & editing. **Norizah Mhd Sarbon:** Writing – review & editing. **Mohammad Rashedi Ismail-Fitry:** Conceptualization, Project administration, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.lwt.2024.116231.

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