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Mechanical properties and texture profile analysis of beef burgers and plant-based analogues

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A B S T R A C T

Cultivated meat, or cultured meat, is lab-grown from animal stem cells, differentiated into muscle and/or fat, to yield meat products. The process is more sustainable and more ethical than traditional farming, allowing to meet growing consumer demand. However, there remains a challenge in replicating the organoleptic properties of commercially available meat products for cultivated meat applications. Consequently, this study employs single-cycle uniaxial testing (flexion, tension, compression, cutting) governed by ISO standards, and texture profiling analysis, to ascertain the modulus, yield strain, hardness, adhesiveness, cohesiveness, springiness, resilience and chewiness of seven commercially available burgers. These were tested both raw and cooked, and comprise beef (including a range of beef contents, fat percentages and price points) and plant-based analogues. Here, we show that (i) both mechanical (flexural, compressive and cutting yield strains) and textural (cohesiveness, springiness and resilience) properties reveal clear and statistically significant divides between the cooked properties of beef compared to plant-based burgers; (ii) moreover, hardness and chewiness yield statistically significant results able to distinguish between high beef content burgers (over 95%), low beef content burgers (below 81%) and plant-based alternatives, and thus, are best suited to characterise burger properties; and (iii) there exists key target values for cultivated meat products to replicate the mechanical and textural characteristics of farmed beef burgers, identified for the first time. These findings provide novel insights into the mechanical and textural characterisation of beef and plant-based burgers, and may contribute to future developments in cultivated meat to ensure consumer acceptance.

1. Introduction

Animal farming accounts for 14.5% of greenhouse gas emissions (Cheng et al., 2022), forecasted to continue increasing due to the sustained growth in global population and meat demand (Kyriakopoulou et al., 2019; Willett et al., 2019; Parlasca and Qaim, 2022). Food production also accounts for 70% of all freshwater, 20% of energy demand and 30% of ice-free land (Aiking, 2011; Poore and Nemecek, 2018; FAO, 2019), thus calling for a reduction in animal protein consumption driven by sustainability (De Boer and Aiking, 2019). This, coupled with contemporary concerns for animal welfare, has led to the wider adoption of plant-based diets (Kyriakopoulou et al., 2019) and the development of plant-based alternatives to animal protein (Asgar et al., 2010; Post, 2012; McClements and Grossmann, 2021; Thakur et al., 2024; Caputo et al., 2023; Rai et al., 2023).

However, a major obstacle to the adoption of plant-based alternatives to animal protein is their textural properties, which do not accurately replicate that of animal products (Hoek et al., 2011; Bohrer, 2019; Kyriakopoulou et al., 2021a,b; Onwezen et al., 2021; Godschalk-Broers et al., 2022). This is an issue, as cross-sectional surveys of consumers suggest that meat alternatives that closely resemble the texture of animal-based meat products are more likely to be accepted (Hoek et al., 2011; Michel et al., 2021). Similar findings have also been demonstrated experimentally, where participants blind tasted and rated plant and insect-based burgers as being less liked than a meat-based burger and provided less positive textural profiles for them, perceiving

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them to be less juicy, more granular and dry (Schouteten et al., 2016). A more recent experimental study has provided further evidence in support of these findings and also reported that participants were willing to pay the most for a 100% beef burger, compared to the plant-based options (Caputo et al., 2023). Indeed, the texture of plant-based alternatives is a recurring barrier to consumer acceptance (Szenderák et al., 2022). This has prompted extensive research into the enhancement of meat analogue texture (Dekkers et al., 2018; Smetana et al., 2018; Chiang et al., 2019; McClements et al., 2021; Godschalk-Broers et al., 2022; Paredes et al., 2022) to increase consumer acceptance.

A different approach to plant and insect-based protein is cultivated meat (also referred to as cultured meat or lab-grown meat), which is grown from animal stem cells cultured in a laboratory environment (Post, 2012, 2014; Ben-Arye and Levenberg, 2019; Moutsatsou et al., 2023). The advent of cultivated meat and its shift towards large-scale production and commercialisation has prompted a renewal of interest in the understanding of the properties of meat products. Indeed, while taste may be subjective, mechanical and textural properties can objectively ensure novel meat analogues resemble existing animal-protein products.

The characterisation of meat texture has been thoroughly detailed in the reviews of Chen and Opara (2013) and Schreuders et al. (2021), with commonly employed tests including mechanical testing (e.g. tension or compression), water distribution, Warner-Bratzler shear force (WBSF), and textural profiling analysis (TPA). However, the latter has been shown to be a more relevant methodology than WBSF (De Huidobro et al., 2005; Novaković and Tomašević, 2017), thereby justifying the focus on TPA for both farmed meat products (De Ávila et al., 2014; Schreuders et al., 2021; Paredes et al., 2022) and more recently cultivated meat (Bomkamp et al., 2022; Dvash and Lavon, 2024; Murugan et al., 2024; Paredes et al., 2022).

Because of the rigour of the underpinning ISO standards associated with mechanical testing (ISO, 2019a,b, 2002) and the relevance and interest in TPA (Brandt et al., 1963; Breene, 1975), both methods are adopted in this work. Additionally, due to their relative ease of production compared to whole cuts of meat for cultivated meat and their high popularity, products such as burgers have attracted considerable research interest (Pawar et al., 2023; Taylor et al., 2020; Pinero et al., 2008; Zhou et al., 2022; Patinho et al., 2021; Rao et al., 2023). Consequently, this paper employs both mechanical testing and textural profiling analysis of beef burgers and plant-based analogues to support the development of cultivated meat products with suitable characteristics to ensure consumer acceptance. Seven commercially available products are investigated, in both raw (relevant to supply chain and cooking experience) and well as cooked (relevant to consumer experience) states.

The aim of this study is to provide a database of the ideal properties to successfully replicate that of meat products, based on commercially available beef and plant-based burgers, while also identifying which exact mechanical and textural properties are the main differentiators of quality beef burgers. As such, it is anticipated these findings will support the wider development of alternatives to farmed meat products by identifying objective metrics to increase their attractiveness to consumers by design.

The remainder of the paper is structured as follows. First, Section 2 details the commercial products investigated, the experimental setup for mechanical testing and textural profiling, data analysis and its associated uncertainty. Then, Section 3 details the results for single-cycle uniaxial testing (flexion, tension, compression, cutting) and texture profiling analysis. The significance of the findings are discussed in Section 4, and, finally, the main outcomes are summarised in Section 5.

2. Methods

2.1. Burger products and preparation

Seven commercially available burgers were selected and tested: five beef burgers and two alternative protein burgers, namely pea and soya protein. To obtain a representative characterisation of their mechanical and textural properties across the breadth of commercially available products, the selected burgers include high (>19%) and low (<5%) fat content, as well as high ($>10\,£\,\text{kg}^{-1}$) and low ($<10\,£\,\text{kg}^{-1}$) cost. Additionally, burger B5 is handmade, compared to all other factory-made. All burgers were fresh, i.e. never frozen. The details of the seven burgers labelled B1 to B7, and their commercial descriptions are presented in Table 1, including the ingredients list.

All burgers were tested raw and cooked, the former being relevant to manufacturing, transport and customer handling, while the latter being relevant to mouthfeel and consumer acceptance. Experiments were conducted at temperatures and humidities $15.8°\text{C} \leq T \leq 24.2°\text{C}$ and $0.26 \leq \varphi \leq 0.41$, respectively. Raw burgers were tested at room temperature and testing was conducted on the day the manufacturer's packaging was opened. The burgers were prepared in line with previous work, namely cooked in a preheated oven at 200°C (Cho and Ryu, 2022) for 8 min, 4 min per side (Hautrive et al., 2019). All cooked burgers were then left to cool at room temperature for a minimum of 4 h, and tested within 24 h of cooking. The cooking yield by mass Y_M and by volume Y_V are respectively computed as

$$Y_M = \frac{M_{\text{cooked}}}{M_{\text{raw}}}, \tag{1}$$

and

$$Y_V = \frac{V_{\text{cooked}}}{V_{\text{raw}}}, \tag{2}$$

where M_{cooked} is the cooked mass, M_{raw} is the raw mass, V_{cooked} is the cooked volume, and V_{raw} is the raw volume.

2.2. Experimental setup and protocol

Experiments were performed on two universal testing machines at Aston University. Single-cycle experiments, namely flexion, tension, cutting and compression were conducted on a TA ElectroForce 3200 Series III. A 10 N (1000 gf) load cell (LC1) was employed for raw burgers and a 450 N load cell (LC2) was fitted for cooked burgers. The former is best suited to raw burgers owing to the small forces measured and small measurement bias. Conversely, cooked burgers withstand higher forces, hence the higher force threshold of LC2 compared to LC1.

The testing and data acquisition parameters are as follows. Measurements were sampled at 100 Hz and at a displacement rate of 2 mm min^{-1} with both load cells, employing a 0.1 N pre-load applied at 2 mm min^{-1} displacement rate. The experimental setups for single-cycle uniaxial testing are presented in Fig. 1. Flexural tests were undertaken in accordance with the ISO 178 (ISO, 2019a), using a 3-point bending setup, pictured in Fig. 1(a), where the contact points were 4 mm diameter cylinders. Tensile tests, as shown in Fig. 1(b), followed the ISO 527 (ISO, 2019b), with serrated jaw pads 15 mm wide by 10 mm long. For compression, tests were conducted based on the ISO 604 (ISO, 2002), and featured 20 mm diameter compression plates, visible in Fig. 1(c). Lastly, for cutting tests, depicted in Fig. 1(d), a square blade, 11 mm wide by 1 mm thick with a 30° bevel was employed.

Multi-cycle experiments, namely texture profiling analysis (TPA), were conducted on an Instron 5965 series fitted with a 500 N load cell (LC3). Here, testing and data acquisition parameters were a displacement rate of 1 mm s^{-1} and a sampling frequency of 1000 Hz. The higher sampling frequency for multi-cycle experiments (1000 Hz) compared to single-cycle (100 Hz) arises from the faster regulatory displacement rate, namely 1 mm s^{-1} for multi-cycle c.f. 2 mm min^{-1} for single-cycle. Two loading cycles (where a cycle is defined as compression followed by withdrawal) were performed, each to a strain $\epsilon = 0.50$, with a 1 s pause between the first withdrawal and second compression.

Table 1
Summary of the burgers tested, based on manufacturer's packaging information. *prices as of April 2023.

Label	Protein source	Commercial description	Fat [%]	Price* [£ kg^{-1}]	Main ingredients
B1	Beef	Marks & Spencer 4 Aberdeen Angus Burgers	19.4	10.46	British beef (95%), water, dried potatoes, rice flour, sea salt, cracked black pepper, preservative (E223 (sulphites), salt, dextrose).
B2	Beef	Morrisons 4 British Beef Quarter Pounders	19.2	5.93	Beef (76%), pea flakes, water, cracked black pepper, salt, sea salt, preservative (sodium metabisulphite), coarse tellicherry pepper, antioxidant (ascorbic acid), rapeseed oil.
B3	Beef	Morrisons 4 Beef Burgers 5% Fat	4.7	8.81	Beef (96%), rice flour, black pepper, salt, preservative (sodium sulphite), antioxidant (sodium ascorbate).
B4	Beef	Marks & Spencer Select Farms 4 Beef Burgers 3% Fat	2.8	12.5	Beef (81%), water, roast beef stock (water, beef bones, tomato purée, mushrooms, seaweed, onions, carrots, white wine vinegar), dried potatoes, onions, broad bean flour, rice flour, sea salt, salt, preservative: E223 (sulphites), cracked black pepper, dextrose.
B5	Beef	Haji Baba Halal Beef Burger	3.8	17.57	Beef (82%), chilli burger seasoning (8%) (rusk (wheat flour (calcium carbonate, iron, niacin, thiamine), salt), spices (chilli, paprika, cumin, chipotle chilli) (13.34%), salt, red peppers, demerara sugar, stabilisers (E450), preservative (E223) (1.13%) (sulphite), spice extracts (pepper, chilli), antioxidant (E300)), chilli, coriander.
B6	Pea	Beyond Meat 2 Plant Based Burgers	19.0	17.70	Water, pea protein (16%), canola oil, coconut oil, rice protein, flavouring, stabiliser (methylcellulose), potato starch, apple extract, colour (beetroot red), maltodextrin, pomegranate extract, salt, potassium salt, concentrated lemon juice, maize vinegar, carrot powder, emulsifier (sunflower lecithin).
B7	Soya	Tesco Plant Chef 2 Meat Free Burgers	12.1	6.86	Reconstituted soya protein (47%), water, rapeseed oil, rice flour, shea fat, maize flour, soya protein concentrate, pea fibre, stabiliser (methyl cellulose), coconut oil, colours (plain caramel, beetroot red), salt, yeast extract, flavouring, smoked rice flour, black pepper, maize starch, maltodextrin, modified tapioca starch, sugar, dextrose, onion.

2.3. Single-cycle uniaxial testing

2.3.1. Flexion

The flexural strain ϵ_f is defined as

$$\epsilon_f = \frac{6wh}{s^2}, \tag{3}$$

where w is the measured deflection, h is the thickness of the sample, and s is the span between support points. In this work, $s = 40\,\text{mm}$.

Then, the flexural stress σ_f is given as

$$\sigma_f = \frac{3Fs}{2bh^2}, \tag{4}$$

where F is the measured force, and b the width of the sample.

Finally, the tensile modulus E_f is computed using the linear least squares method for $0.005 \leq \epsilon_f \leq 0.025$, provided that the coefficient of determination $R^2 \geq 0.995$, such that

$$E_f = \frac{\sigma_f}{\epsilon_f}. \tag{5}$$

Indeed, should $R^2 < 0.995$, then the upper bound of ϵ_f is reduced from the ISO recommendation of $0.005 \leq \epsilon_f \leq 0.025$ by the minimum amount to yield $R^2 \geq 0.995$ between $\epsilon_f = 0.005$ and the maximum possible of $\epsilon_f \leq 0.025$, to satisfy the defined coefficient of determination criterion. This is necessary due to the varying failure behaviour and yield strains of the different burgers, meaning the upper bound $\epsilon_f = 0.025$ defined by ISO may not be relevant in all cases.

2.3.2. Tension, compression, cutting

For tension, compression and cutting tests, the strain ϵ is

$$\epsilon = \frac{\Delta L}{L}, \tag{6}$$

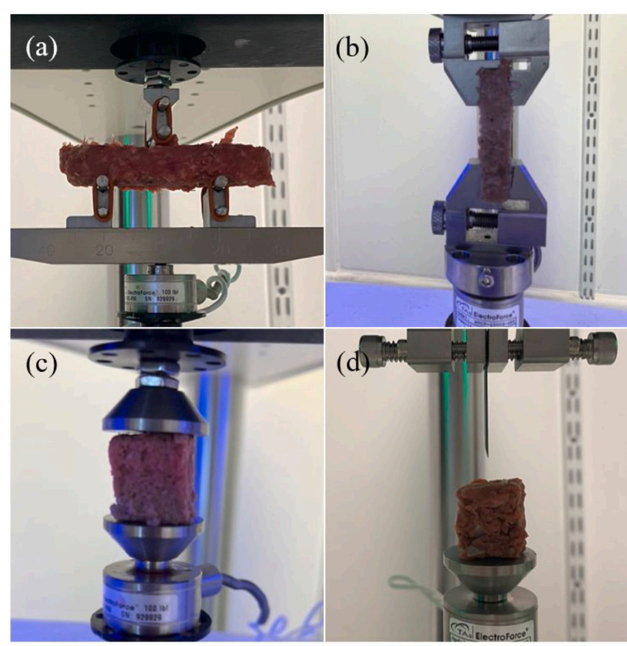

Fig. 1. TA ElectroForce 3200 Series III experimental setup for (a) flexion, (b) tension, (c) compression, and (d) cutting.

where ΔL is the measured change in length (elongation in tension, contraction in compression and cutting), and L is the original length of the sample. Note that L is the gauge length L_0 in tension, while it corresponds to the sample thickness h, i.e. the distance between the bottom compression plate and the top compression plate or blade, for compression and cutting, respectively.

Then, the stress σ is given as

$$\sigma = \frac{F}{bh}, \tag{7}$$

where bh is taken as the cross-sectional area of the sample perpendicular to the load direction for tension and compression, or as the projected area of the blade for cutting.

Ultimately, the modulus E is given as

$$E = \frac{\sigma}{\epsilon}. \tag{8}$$

The same methodology as defined for the flexural modulus is employed here: E is computed using the linear least squares method for $0.005 \leq \epsilon \leq 0.025$, with the upper bounder of ϵ reduced by the minimum amount to achieve $R^2 \geq 0.995$, where necessary. The properties for tension, compression and cutting will, respectively, be denoted by the subscripts t, c and cut.

2.4. Texture profiling analysis (TPA)

For TPA, a force-time curve is acquired over two compression cycles, exerted to a strain $\epsilon = 0.50$ at a displacement rate of 1 mm s^{-1} with a 1 s pause between the two cycles. A sample curve is presented in Fig. 2, from which the following quantities can be ascertained:

- F_1, the peak force of the first compression cycle;
- t_1 and t_2, the times required for the sample to reach maximum load from initial deformation for the 1st and 2nd compression cycle, respectively;
- A_a, the area under the force-time curve during the 1st compression (downstroke);
- A_b, the area under the force-time curve during the 1st withdrawal (upstroke) while $F \geq 0$;
- A_c, the area under the force-time curve 1st withdrawal (upstroke) and for $F \leq 0$;
- A_d, the area under the force-time curve during the 2nd compression (downstroke); and
- A_e, the area under the force-time curve during the 2nd withdrawal (upstroke) and for $F \geq 0$.

From the above quantities, the following properties can be ascertained:

- The hardness H,

$$H = F_1, \tag{9}$$

which relates to the stiffness of the burger and directly influences to the mouthfeel of the first bite.

- The adhesiveness A,

$$A = A_c, \tag{10}$$

which corresponds to a negative force being generated due to the stickiness of the burger.

- The cohesiveness C_o,

$$C_o = \frac{A_d + A_e}{A_a + A_b}, \tag{11}$$

defined as the ratio of the area under the force-time curve of the second compression cycle (downstroke and withdrawal) compared to the first cycle. Cohesion relates to the consistency of the burger, a lower value being characteristic of disintegration.

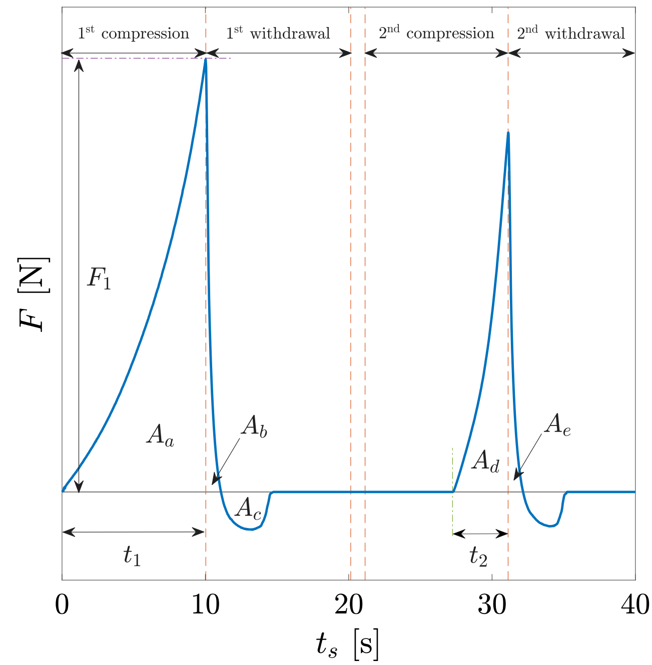

Fig. 2. Sample force-time curve resulting from TPA, displaying the two compression and withdrawal cycles separated by a 1 s pause, and definition of the hardness F_1, times t_1 and t_2, and areas A_a, A_b, A_c, A_d and A_e.

- The springiness S,

$$S = \frac{t_2}{t_1}, \tag{12}$$

computed as the ratio of the time needed to reach maximum force for the 2nd downstroke compared to the first. As such, a high value corresponds to the ability of the burger to recover to its original geometrical shape between the two compression cycles.

- The resilience R,

$$R = \frac{A_b}{A_a}, \tag{13}$$

which quantifies the recovery from deformation during the first compression cycle and is defined as the ratio of the area under the curve of the first withdrawal compared to the first compression.

- The chewiness C_h,

$$C_h = \frac{F_1 t_2}{t_1 \frac{A_d + A_e}{A_a + A_b}} = HSC_o, \tag{14}$$

which is indicative of the ease of biting and energy needed to chew, thereby representing a key mouthfeel indicator.

2.5. Uncertainty and statistical analysis

The uncertainty U of the results is expressed as the root sum of the bias B and the precision P, such that

$$U = \sqrt{(P^2 + B^2)}. \tag{15}$$

The bias of a given quantity X, computed using a number N of independent measured variables x_i, is given as

$$B(X) = \left[\sum_{i=1}^{N}\left(\frac{\partial X}{\partial x_i}B(x_i)\right)^2\right]^{\frac{1}{2}}, \tag{16}$$

where the bias limits $B(x_i)$ associated with the measured quantities and load cells employed are detailed in Table 2.

Table 2
Summary of bias limits for the three load cells.

Measurement bias	TA ElectroForce		Instron
	LC1 (10 N)	LC2 (450 N)	LC3 (500 N)
Force, $B(F)$ [N]	0.00013	0.00020	0.0005
Width, $B(b)$ [mm]	0.005	0.005	0.005
Thickness, $B(h)$ [mm]	0.005	0.005	0.005
Length, $B(L)$ [mm]	0.005	0.005	0.005
Elongation, $B(\Delta L)$ [mm]	0.00073	0.00233	0.0005
Span, $B(s)$ [mm]	0.005	0.005	0.005
Deflection, $B(w)$ [mm]	0.00073	0.00233	0.0005
Sampling time, t_s [s]	0.005	0.005	0.0005

The precision is computed as at the 95% confidence level, such that

$$P = \frac{t_{95}\sigma_{\text{dev}}}{\sqrt{n}}, \tag{17}$$

where $t_{95} = 2.201$ for the number of samples tested $n = 12$ and σ_{dev} is the standard deviation. The uncertainty associated with the mechanical properties quantified in this work is represented as vertical error bars in the Results section.

The statistical significance of the results is computed using analysis of variance (ANOVA) (St et al., 1989). This is followed by Tukey's honestly significant difference (HSD) test (Tukey, 1991), as adopted for meat analogue tests by Godschalk-Broers et al. (2022). Results are deemed statistically significant for $p < 0.05$ (Piepho, 2018; Hosseinzadeh et al., 2020).

3. Results

In this section, we present the results for single-cycle uniaxial testing (Section 3.1), namely flexion, tension, compression and cutting, and texture profiling analysis (Section 3.2) including hardness, adhesiveness, cohesiveness, springiness, resilience and chewiness. The aim is to quantify the properties of the various burger types under investigation and identify any trends that distinguish beef burgers from plant-based alternatives in order to inform the development of cultivated and alternatives to farmed meat products. This Results section focuses on the mechanical and textural properties, while Section 4 will tackle the statistical significance of the results to provide recommendations for target properties for cultivated meat, where a statistical difference in the results has been demonstrated.

The cooking yields, both by mass and volume, for the seven burgers under investigation are quantified in Table 3. No correlation between cooking yields and the properties detailed in Sections 3.1 and 3.2 was identified. Additionally, no statistical significance between the burger types and yields was identified in Table 3. Following cooking yield measurements on whole burgers, the samples were cut, resulting in the sample sizes characterised in Table 4, where the absence of statistical significance in the variations of sample sizes for any given tests confirms the systematic approach to mechanical and textural testing, despite the challenges associated with achieving identical sizes from burger products.

3.1. Single-cycle uniaxial testing

3.1.1. Flexion

The flexural results for the raw and cooked modulus $E_{f,\text{raw}}$ and $E_{f,\text{cooked}}$ and the raw and cooked yield strain $\epsilon_{f,\text{raw}}$ and $\epsilon_{f,\text{cooked}}$ are presented in Fig. 3. First, it is noted the absence of results for the raw B6, in Fig. 3(a) and Fig. 3(c). This is because the burger could not maintain sufficient integrity for testing, even when reducing the span from $s = 40$ mm down to $s = 20$ mm. This behaviour is attributed to the presence of coconut oil in the burger's composition (see Table 1), an ingredient which is liquid at the testing temperature. Second, B5 stands out with a significantly higher modulus (raw and cooked) and yield strain (cooked) than all the other burgers in this study. As B5 is the only handmade burger tested, it is hypothesised that this could result from either (i) its manufacturing process, which most likely involves the use of coarser ground meat compared to the factory-produced burgers, yielding larger chunks of beef and allowing it to exhibit higher mechanical properties in flexion; or (ii) enhanced binding abilities owed to the wheat flour, using for the burger only.

Table 3
Cooking yield by mass Y_M and volume Y_V ($n \geq 4$). In a given column, values followed by a common letter are not significantly different based on HSD at the 5% level of significance ($p < 0.05$).

Burger	Y_M [–]	Y_V [–]
B1	0.522 ± 0.10^{c}	0.849 ± 0.13^{c}
B2	0.537 ± 0.08^{c}	0.871 ± 0.06^{c}
B3	0.755 ± 0.15^{a}	0.953 ± 0.07^{a}
B4	0.655 ± 0.07^{ab}	0.876 ± 0.12^{bc}
B5	0.599 ± 0.09^{bc}	0.882 ± 0.03^{bc}
B6	0.612 ± 0.09^{bc}	0.890 ± 0.14^{abc}
B7	0.623 ± 0.10^{bc}	0.946 ± 0.05^{ab}

The cooking process leads to an increase in the flexural modulus of circa an order of magnitude compared to the raw modulus. However, strains remain comparable, with a slight increase for meat products, contrasted by a slight decrease for the plant-based B7. The values of $\epsilon_{yf,\text{cooked}}$ are of particular interest and exhibit a relevant trend to the burger quality: plant-based options being notably lower than meat-based products. The three highest values are achieved by the handmade (B5) and high beef content products (B1 and B3, 95% and 96% beef, respectively), with $\epsilon_{yf,\text{cooked}} \geq 0.190$. The low beef content products (B2 and B4, 76% and 81%, respectively) exhibit similar values $\epsilon_{yf,\text{cooked}} \approx 0.148$, and then plant-based burger $\epsilon_{bf,\text{cooked}} \leq 0.115$ show a much lower yield strain. This may, therefore, help characterise desirable mechanical properties for alternatives to farmed meat products.

3.1.2. Tension

Tensile results are presented in Fig. 4(a) and (b) for the raw and cooked modulus, respectively, and in Fig. 4(c) and (d) for the raw and cooked yield strain, respectively. As noted for the flexural tests, burger B6, containing coconut oil, exhibited poor structural integrity. As a result, it could not undergo structural testing, and thus, no data is presented for B6 in Fig. 4(a) and Fig. 4(c). As before, the handmade burger B5 exhibits the highest modulus, both raw and cooked, than all other burgers. As in Section 3.1.1, this is attributed to its manufacturing process. Because no pattern emerges, and no statistically significant results are achieved between burger types, either for the modulus or yield strain, between the various types of burgers, we conclude that tensile tests, while benefiting from a well-established test protocol (ISO, 2019b), are not able to inform the desirable properties of meat analogues.

3.1.3. Compression

The compressive results, shown for the raw and cooked modulus in Fig. 5(a) and (b), respectively, and the yield strain in Fig. 5(c) and (d), provide striking differences between the beef and plant-based burgers. Indeed, for raw beef burgers $0.09\,\text{MPa} \leq E_{c,\text{raw}} \leq 0.12\,\text{MPa}$, whereas $E_{c,\text{raw}} \leq 0.003\,\text{MPa}$. Once cooked, beef burgers exhibit moduli $0.94\,\text{MPa} \leq E_{c,\text{cooked}} \leq 1.12\,\text{MPa}$, in comparison to the plant-based values $E_{c,\text{raw}} \leq 0.42\,\text{MPa}$. As such, there is a clear divide in terms of moduli, which is also found in the compressive yield strains, where higher values are achieved by plant-based burgers $\epsilon_{yc,\text{cooked}} \geq 0.210$, compared to the high beef content and handmade burgers having intermediate values $0.149 \leq \epsilon_{yc,\text{cooked}} \leq 0.084$, and the low beef content burgers having the lowest values, ascertained at $\epsilon_{yc,\text{cooked}} \approx 0.048$. Consequently, cooked beef products are characterised by a high compressive

Table 4
Average sample sizes ($n = 12$) for all burgers and tests. Note: for a given test (namely: flexion, tension, cutting, compression and TPA) there is no significant difference in the same sizes based on Tukey's honestly significant difference test (Tukey, 1991) at the 5% level of significance.

Burger	Dimension	Flexion		Tension		Cutting		Compression		TPA	
		Raw	Cooked	Raw	Cooked	Raw	Cooked	Raw	Cooked	Raw	Cooked
All	Gauge length, L_0 [mm]	n/a	n/a	20	20	n/a	n/a	n/a	n/a	n/a	n/a
	Span, s [mm]	40	40	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
	Length, L [mm]	n/a	n/a	n/a	n/a	14.98 ± 0.36	16.48 ± 0.28	16.33 ± 0.39	17.16 ± 0.30	16.78 ± 0.41	15.26 ± 0.20
B1	Width, b [mm]	16.31 ± 0.47	15.46 ± 0.42	12.03 ± 0.43	13.01 ± 0.27	15.46 ± 0.41	16.63 ± 0.40	16.44 ± 0.32	16.83 ± 0.17	16.52 ± 0.47	16.14 ± 0.35
	Thickness, h [mm]	11.68 ± 0.31	10.73 ± 0.40	10.82 ± 0.32	9.97 ± 0.29	20.46 ± 0.40	21.82 ± 0.62	20.70 ± 0.28	21.25 ± 0.44	16.87 ± 0.27	15.49 ± 0.46
	Length, L [mm]	n/a	n/a	n/a	n/a	16.54 ± 0.24	16.55 ± 0.19	16.51 ± 0.27	16.64 ± 0.25	16.42 ± 0.93	16.43 ± 0.24
B2	Width, b [mm]	16.01 ± 0.46	15.65 ± 0.33	12.61 ± 0.22	12.57 ± 0.15	16.08 ± 0.41	16.85 ± 0.22	16.49 ± 0.23	15.56 ± 0.11	16.29 ± 0.43	16.50 ± 0.66
	Thickness, h [mm]	10.05 ± 0.26	10.72 ± 0.26	10.40 ± 0.23	10.31 ± 0.32	17.97 ± 0.30	19.02 ± 0.40	18.63 ± 0.19	19.02 ± 0.44	17.00 ± 0.28	16.19 ± 0.29
	Length, L [mm]	n/a	n/a	n/a	n/a	16.02 ± 0.30	16.40 ± 0.30	16.10 ± 0.28	16.31 ± 0.26	16.45 ± 0.43	16.84 ± 0.82
B3	Width, b [mm]	16.03 ± 0.40	15.85 ± 0.27	12.07 ± 0.33	12.39 ± 0.22	15.48 ± 0.26	16.62 ± 0.21	15.92 ± 0.25	16.55 ± 0.37	16.40 ± 0.49	16.29 ± 0.34
	Thickness, [mm]	11.54 ± 0.31	11.41 ± 0.54	10.31 ± 0.31	10.26 ± 0.21	17.22 ± 0.28	20.95 ± 0.27	17.69 ± 0.25	19.51 ± 0.45	17.42 ± 0.89	14.28 ± 0.46
	Length, L [mm]	n/a	n/a	n/a	n/a	16.90 ± 0.31	15.19 ± 0.49	16.44 ± 0.44	16.38 ± 0.46	17.06 ± 0.46	16.87 ± 0.51
B4	Width, b [mm]	16.51 ± 0.34	16.53 ± 0.19	11.61 ± 0.64	10.34 ± 0.32	16.85 ± 0.41	15.23 ± 0.53	16.26 ± 0.51	16.10 ± 0.46	16.42 ± 0.29	16.55 ± 0.37
	Thickness, h [mm]	11.51 ± 0.40	10.24 ± 0.35	11.04 ± 0.54	10.51 ± 0.34	16.73 ± 0.31	17.76 ± 0.46	16.31 ± 0.52	16.63 ± 0.30	16.81 ± 0.72	16.04 ± 0.54
	Length, L [mm]	n/a	n/a	n/a	n/a	17.42 ± 0.63	16.04 ± 0.40	17.58 ± 0.53	15.75 ± 0.26	17.01 ± 0.39	17.28 ± 0.34
B5	Width, b [mm]	16.57 ± 0.45	16.36 ± 0.52	12.77 ± 0.31	11.72 ± 0.51	15.99 ± 0.46	16.38 ± 0.63	17.28 ± 0.42	15.32 ± 0.36	16.42 ± 0.48	16.54 ± 0.81
	Thickness, h [mm]	11.60 ± 0.49	12.14 ± 0.37	11.28 ± 0.38	9.84 ± 0.25	17.12 ± 0.62	16.78 ± 0.51	15.69 ± 0.62	16.40 ± 0.43	16.81 ± 0.61	16.79 ± 0.43
	Length, L [mm]	n/a	n/a	n/a	n/a	18.27 ± 0.92	18.37 ± 0.73	16.75 ± 0.61	16.83 ± 0.47	16.37 ± 0.45	17.64 ± 0.69
B6	Width, b [mm]	16.62 ± 0.41	17.33 ± 0.88	12.24 ± 0.47	11.07 ± 0.47	19.37 ± 0.60	16.40 ± 0.74	18.23 ± 0.58	17.13 ± 0.83	16.21 ± 0.14	17.59 ± 0.51
	Thickness, h [mm]	11.55 ± 0.31	10.70 ± 0.36	11.76 ± 0.35	11.31 ± 0.72	17.17 ± 0.92	18.45 ± 0.40	16.51 ± 0.91	17.57 ± 0.96	16.24 ± 0.28	17.34 ± 0.48
	Length, L [mm]	n/a	n/a	n/a	n/a	17.32 ± 0.51	16.85 ± 0.87	17.02 ± 0.46	16.98 ± 0.52	17.11 ± 0.68	16.86 ± 0.77
B7	Width, b [mm]	16.90 ± 0.47	14.81±	12.47 ± 0.36	11.56 ± 0.48	17.69 ± 0.64	16.09 ± 0.81	17.28 ± 0.42	15.71 ± 0.33	16.47 ± 0.51	16.38 ± 0.54
	Thickness, h [mm]	11.57 ± 0.54	10.83 ± 0.37	10.67 ± 0.29	9.81 ± 0.32	18.73 ± 0.53	18.96 ± 0.74	18.91 ± 0.45	17.94 ± 0.55	18.26 ± 0.84	17.70 ± 0.47

modulus and low compressive yield strain, in direct contrast to the plant-based alternatives that feature a low compressive modulus and high compressive yield strain. As such, we have identified a clear and statistically significant distinction that may inform the development of novel meat products to meet consumer expectations while being governed by an established test procedure to ensure reproducibility (ISO, 2002). Although compression is most relevant to mouthfeel and, therefore, crucial to consumer acceptance, the first physical perception of the product is made through cutting. Therefore, whether the present findings remain applicable when looking at cutting properties, was investigated further.

3.1.4. Cutting

The results of the cutting tests, depicted in Fig. 6 reveal similar distinctions between the burgers as the compressive tests. Both the raw and cooked moduli, presented in Fig. 6(a) and (b), respectively, reveal significantly lower values for the plant-based options (B6 and B7). For cooked burgers, a further distinction can be made between the high beef content and handmade beef burgers ($E_{cut,\text{cooked}} \geq 0.53$ MPa), low beef content burgers ($0.38\text{ MPa} \leq E_{cut,\text{cooked}} \leq 0.41\text{ MPa}$) and plant-based burgers ($E_{cut,\text{cooked}} \leq 0.25$ MPa). As in compression, the cooked yield strains show that the highest values are achieved for plant-based burgers ($\epsilon_{ycut,\text{cooked}} \geq 0.416$), followed by high beef content and handmade ($0.3 \leq \epsilon_{ycut,\text{cooked}} \leq 0.295$) and low beef content burgers ($\epsilon_{ycut,\text{cooked}} \leq 0.245$).

These quantify another sensory aspect of the burgers, establishing clear trends between the various types, which can be used to inform the development of future cultivated meat products.

This section focused on single-cycle uniaxial testing, compression, and cutting, which have yielded similar results of crucial relevance. Flexural results also provided valuable insights, though tensile testing did not reveal any clear differences. As such, novel findings have arisen from this section, wherein all tests were conducted in line with ISO standards (ISO, 2019a,b, 2002), ensuring their reproducibility. While textural profiling analysis does not benefit from established standards, it may yield properties more relevant to food products. Consequently, the results arising from TPA are investigated in the following section.

3.2. Texture profiling analysis

3.2.1. Hardness

The hardness, previously defined in Eq. (9), corresponds to the maximum force during the first downstroke, taken to the same strain value for all samples. As such, it is logical for the hardness results for raw and cooked burgers, presented in Fig. 7(a) and 7(b), respectively, to be consistent with the compressive modulus results of Section 3.1.3. As expected, plant-based burgers continue to exhibit lower values compared to beef burgers. Indeed, when cooked, $H \leq 24.845$ N for plant-based compared to $34.487\text{ N} \leq H \leq 43.863\text{ N}$ for beef. An additional statistically significant distinction may be introduced between low beef content burgers where $34.487\text{ N} \leq H \leq 37.814\text{ N}$ and high beef content and handmade burgers where $41.177\text{ N} \leq H \leq 43.863\text{ N}$. This further confirms the compression and cutting findings that beef burgers have a greater resistance to deformation or greater firmness compared to plant-based alternatives.

3.2.2. Adhesiveness

Adhesiveness was tested for both raw and cooked burgers. However, the latter did not show any adhesiveness, irrelevant of the burger type. Consequently, results are only presented for raw burgers in Fig. 8. Here, no clear trend is evidenced, although the values may be relevant to the manufacturing process, where the adhesiveness of raw burgers would be significant for machinery, e.g. conveyor belts.

3.2.3. Cohesiveness

Cohesiveness is the primary quantity determining the integrity of food products, with lower values indicating food disintegrating easily. The raw results in Fig. 9(a) and cooked results in Fig. 9(b) show minimal changes between both states but also reveal the lower values of plant-based burgers. Indeed, beef burgers exhibit a cohesiveness range $0.376 \leq C_o \leq 0.397$, in contrast to the plant-based alternatives where $0.300 \leq C_o \leq 0.306$. This is statistically significant, consistent with previous results, and further enables numerical quantification of the difference between beef burger 'firmness' and plant-based burger 'mushiness'.

3.2.4. Springiness

Springiness is another key metric to characterise the textural properties of food and is related to the ability to recover to the original shape between the two downstrokes. Low cohesiveness would, therefore, likely correlate with low springiness, and this is the case for both raw and cooked burgers, as presented in Fig. 10(a) and (b). For all burgers, the cooking process results in an increase in springiness. Additionally, for both raw and cooked results, high beef content and handmade beef burgers exhibit the highest springiness ($0.684 \leq S_{\text{raw}} \leq 0.812$ and $0.852 \leq S_{\text{cooked}} \leq 0.881$), followed by the low beef content ($0.500 \leq S_{\text{raw}} \leq 0.585$ and $0.761 \leq S_{\text{cooked}} \leq 0.822$) and plant-based options ($0.359 \leq S_{\text{raw}} \leq 0.464$ and $0.626 \leq S_{\text{cooked}} \leq 0.678$), albeit

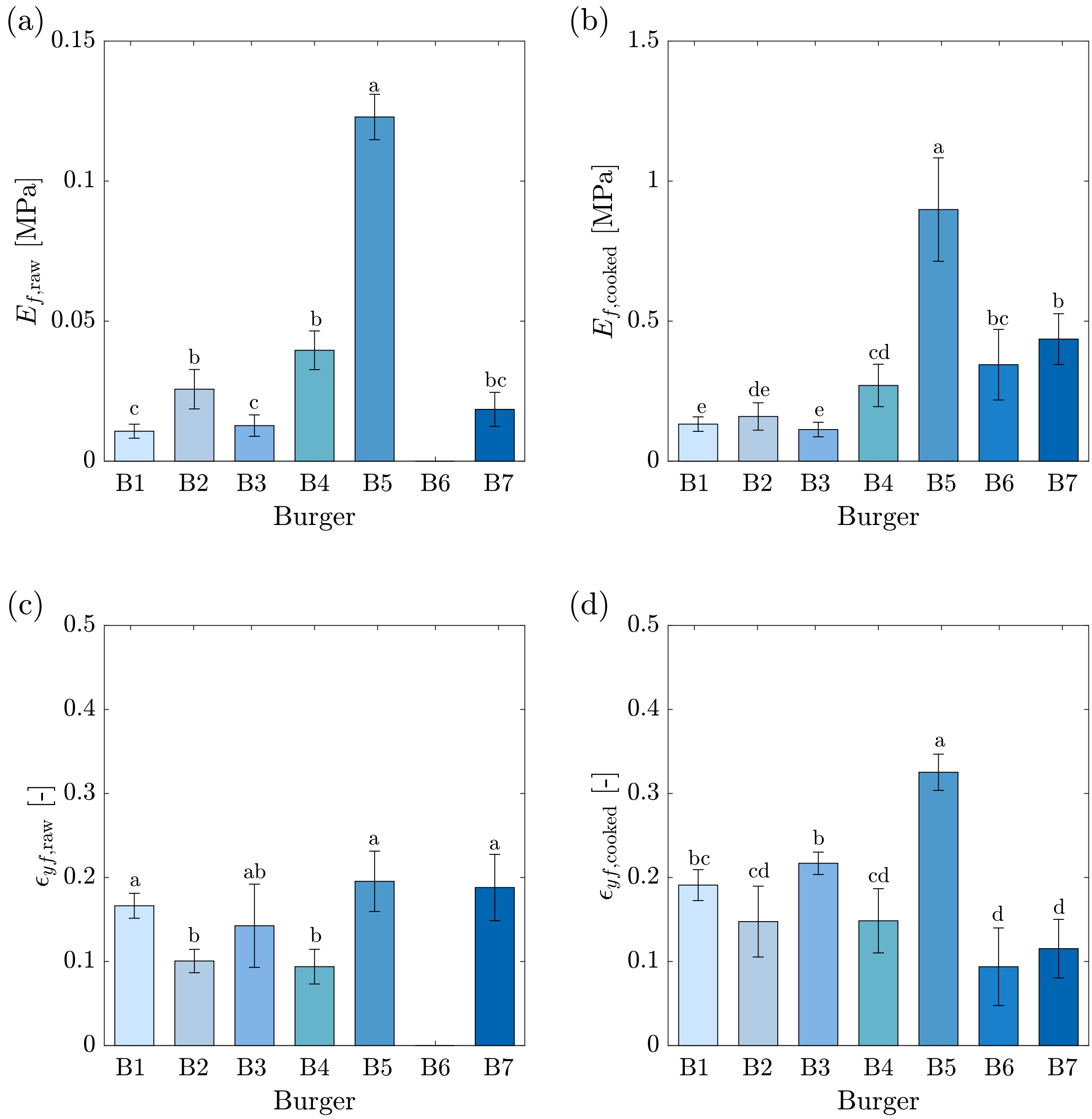

Fig. 3. Flexural results for (a) the raw burger modulus $E_{f,\text{raw}}$, (b) the cooked burger modulus $E_{f,\text{cooked}}$, (c) the raw yield strain $\epsilon_{yf,\text{raw}}$ and (d) the cooked yield strain $\epsilon_{yf,\text{cooked}}$ (n = 12). In a given subplot, values followed by a common letter are not significantly different based on HSD at the 5% level of significance ($p < 0.05$). Note: no results are presented for B6 in subfigures (a) and (c) as the B6 burger did not have sufficient structural integrity to undergo the tests when raw.

without a statistically significant difference. This suggest springiness may not be the most relevant property to characterise burgers, and therefore set target properties for cultivated meat.

3.2.5. Resilience

A further metric to quantify the recovery of the burgers is resilience, which is the ratio of the area under the curve of the first withdrawal compared to the first compression, as defined in Eq. (13). The raw values, presented in Fig. 11(a) show a small difference between beef burgers ($0.056 \leq R_{\text{raw}} \leq 0.069$) and the plant-based alternatives ($0.045 \leq R_{\text{raw}} \leq 0.049$). This is accentuated when looking at the cooked results in Fig. 11(b), in which the beef products now exhibit comparatively higher values, namely $0.139 \leq R_{\text{cooked}} \leq 0.159$, compared to the plant-based alternatives, where $0.106 \leq R_{\text{cooked}} \leq 0.107$.

3.2.6. Chewiness

As the product of the hardness, springiness and cohesivenes, see Eq. (14), the chewiness provides an aggregated indication of the burger's mouthfeel, and thus is fundamental to increase consumer satisfaction with alternative meat products. For the raw results presented in Fig. 12(a), no distinction can be made between beef burger types. This is because no distinction is apparent in the underlying raw hardness (Section 3.2.1) and raw cohesiveness (Section 3.2.3) results. However, there is a clear distinction between the beef, where $0.701\,\text{N} \leq C_{h,\text{raw}} \leq 1.516\,\text{N}$ and the tested plant-based options where $0.242\,\text{N} \leq C_{h,\text{raw}} \leq 0.302\,\text{N}$. Significantly, there are clear differences evidenced for the cooked burgers in Fig. 12(b), where the chewiness yields a clear divide between high beef content and handmade burgers ($13.544\,\text{N} \leq C_{h,\text{cooked}} \leq 14.143\,\text{N}$), low beef content burgers (where $10.822\,\text{N} \leq C_{h,\text{cooked}} \leq 11.254\,\text{N}$) and plant-based burgers (with a chewiness such that $4.469\,\text{N} \leq C_{h,\text{cooked}} \leq 5.054\,\text{N}$). This is significant not

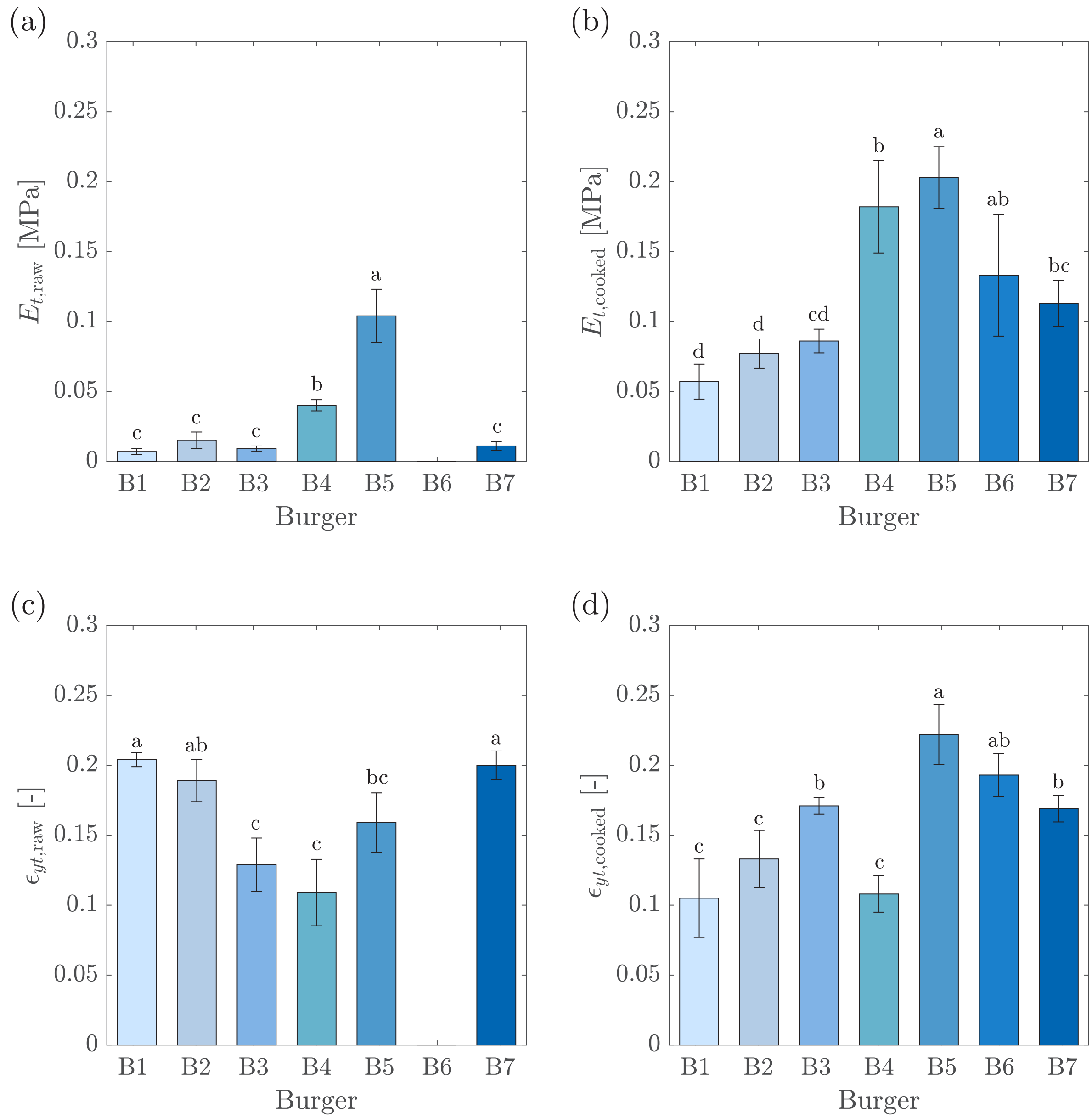

Fig. 4. Tensile results for (a) the raw burger modulus $E_{t,raw}$, (b) the cooked burger modulus $E_{t,cooked}$, (c) the raw yield strain $E_{yt,raw}$ and (d) the cooked yield strain $E_{yt,cooked}$ ($n = 12$). In a given subplot, values followed by a common letter are not significantly different based on HSD at the 5% level of significance ($p < 0.05$). Note: no results are presented for B6 in subfigures (a) and (c) as the B6 burger did not have sufficient structural integrity to undergo the tests when raw.

only because it enables a very clear characterisation of the textural properties of the various types of burgers, but also because of the very narrow range of properties achieved, varying by only 4.4% for high beef content and handmade burgers and 4.0% for low beef content burgers. Plant-based options, on the other hand, exhibited a higher variability of 11.5%.

In this section, the textural properties of the seven burgers under consideration have been quantified, revealing a stark contrast between beef and plant-based burgers across all quantified properties. For beef burgers, further distinctions can be made between high beef content and handmade burgers versus low beef content for some of the properties, namely hardness, springiness and chewiness. Despite the limitations associated with TPA, namely the absence of established ISO standards, the present results yield significant novel insights to inform future alternative meat product developments. Consequently, it is also recommended that an ISO standard for TPA be developed.

4. Discussion

In Section 3.1, the mechanical properties of a range of burgers were quantified, and in Section 3.2, their textural properties were ascertained. In this section, the statistical relevance of the results, considered at $p < 0.05$ is discussed to identify of the most relevant tests to be undertaken and key properties to be targeted to maximise consumer acceptance when designing alternative meat products. As such, this section will focus on the cooked results, similar to Paredes et al. (2022), as these yield the most evident distinctions and are most relevant to the consumers' experience.

In this work, the effect of each individual ingredient and additive on textural properties is not attempted, and would yield poor conclusions given the unspecified quantities in manufacturer's specifications. Indeed, such studies tackle variations in the quantity of individual ingredient in burgers of known compositions, as in Longato et al. (2019), Cócaro et al. (2020), Rabadán et al. (2021), and Shahiri Tabarestani et al.

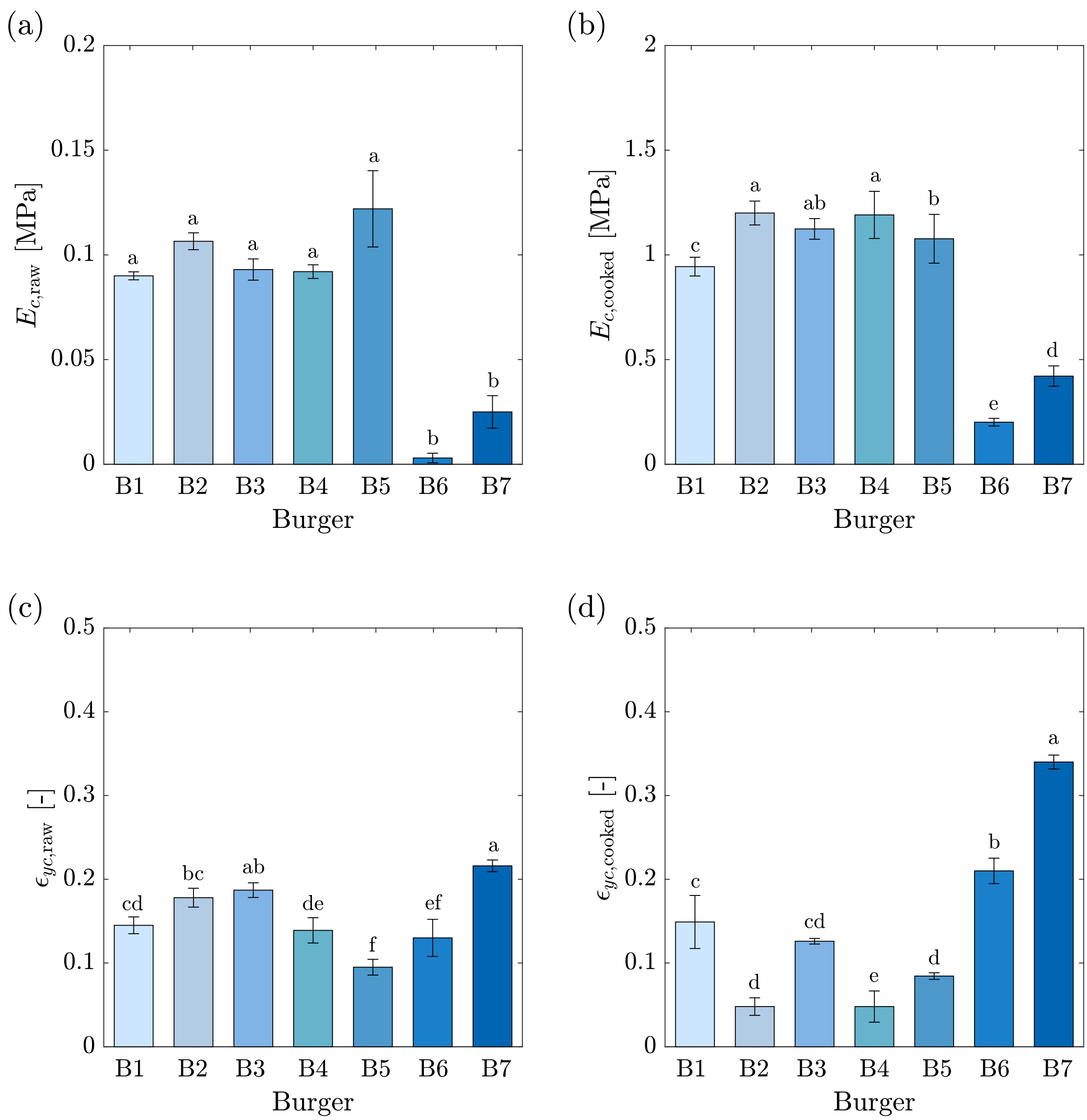

Fig. 5. Compressive results for (a) the raw burger modulus $E_{c,\text{raw}}$, (b) the cooked burger modulus $E_{c,\text{cooked}}$, (c) the raw yield strain $\epsilon_{yc,\text{raw}}$ and (d) the cooked yield strain $\epsilon_{yc,\text{cooked}}$ ($n = 12$). In a given subplot, values followed by a common letter are not significantly different based on HSD at the 5% level of significance ($p < 0.05$).

(2022). Nevertheless, two key ingredients are discussed here. First is water, absent in burger B3, which results in a statistically significant and highest yield by mass and volume. As a consequence, B3 exhibited smaller variations in mechanical properties between its raw and cooked state compared to other burgers. This is heavily influenced by the cooking method (Vu et al., 2022), as shown by Bainy et al. (2015) on burgers, with baking (as done in this work) as opposed to grilling, resulting in a higher water retention, associated with better textural properties. The second ingredient worth mentioning is coconut oil, which is present in burger B6. Because of its low melting point which is close to room temperature, the properties of products in their raw state can be significantly affected: in this study, raw burger B6 did not have sufficient structural integrity to undergo flexural or tensile tests. This may, therefore, affect consumer experience during the food preparation stage. While the use of coconut oil in plant-based burger helps achieve comparable nutritional qualities to meat-based burgers, as shown by De Huidobro et al. (2005), the present work highlights a limitation associated with this ingredient.

The analysis of the results shows that not all tests yield a statistically significant distinction between beef and plant-based option. Indeed, no distinction emerged from for the flexural modulus, tensile modulus and yield strain, or springiness. As such, these properties may not be best suited to characterise burger products. On the other hand, statistically significant results were clearly achieved for the flexural yield strain, compressive modulus and yield strain, cutting modulus and yield strain, hardness, cohesiveness, resilience and chewiness. Therefore, our results enable a quantitative distinction between meat-based and plant-based burgers, numerically quantifying the sensory distinction made by consumers in the recent studies of Sogari et al. (2023) or Forster et al. (2024). This is crucial to ensure consumer acceptance, as Hoek et al. (2011) and Michel et al. (2021) showed that texture closely resembling that of animal-based meat products are more likely to be accepted by the end users. Plant-based options have been characterised as having a lower modulus and higher yield strain in compression and cutting, compared to beef burgers. In flexion, however, the plant-based products

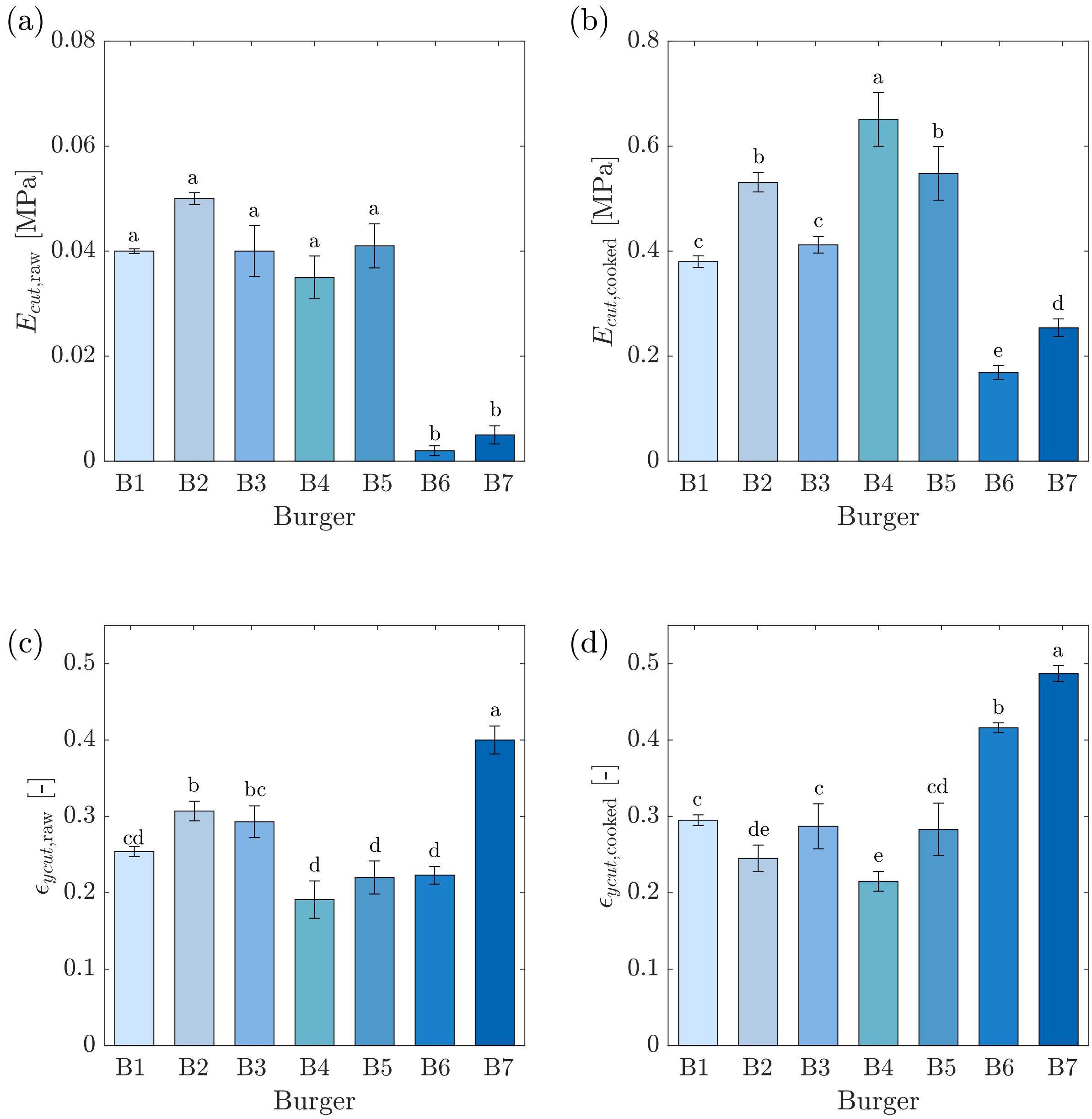

Fig. 6. Cutting results for (a) the raw burger modulus $E_{cut,\mathrm{raw}}$, (b) the cooked burger modulus $E_{cut,\mathrm{cooked}}$, (c) the raw yield strain $\epsilon_{ycut,\mathrm{raw}}$ and (d) the cooked yield strain $\epsilon_{ycut,\mathrm{cooked}}$ ($n = 12$). In a given subplot, values followed by a common letter are not significantly different based on HSD at the 5% level of significance ($p < 0.05$).

showed lower yield strains. As such, the yield strain, whether in flexion, compression or cutting, is deemed the most relevant metric for mechanical tests undertaken in line with established ISO standards (ISO, 2019a, 2002). The yield strain characterises when plastic deformation occurs, and, thus, is particularly relevant to mouthfeel. Plant-based options were also shown to systematically exhibit lower textural properties than beef products when assessed for hardness, cohesiveness, resilience and chewiness.

Furthermore, statistically significant distinctions between the various types of beef-burger investigated in this work have also been identified for hardness and chewiness, both being related, as $C_h = HSC_o$. These two properties provided the clearest distinction in textural properties to distinguish between the various burgers tested. Such statistical significance for these tests did not emerge in previous work, such as that of Godschalk-Broers et al. (2022), and is attributed to the high number of repeats employed here, namely $n = 12$, compared to the standard $n = 5$ dictated by ISO standards (ISO, 2019a,b, 2002), or similar (e.g. $n = 6$ in Paredes et al. (2022)). Interestingly, the present results revealed no distinctions due to fat content, but yielded a clear divide between beef products. The effect of fat content on the textural properties of burgers well document (Berry and Leddy, 1984; Angor and Al-Abdullah, 2010) but did not emerge in this work because of the burger compositions. Indeed, while B1 and B4 are the high-fat and low-fat burger options from the same provider, their beef quantities are 95% and 81%, respectively, the low-fat option featuring a lesser beef content and more ingredients. Conversely, looking at B2 and B3, also the high-fat and low-fat options from the same provider, the beef content is 76% and 96%, respectively, with the high-fat option now having a lesser beef content and additional ingredients. However, this has determined beef content as the main differentiator for properties and, thus, consumer experience.

Thanks to the experimental results and key observations made, the recommended property ranges for novel cultivated-meat products to achieve similar properties to farmed-beef products, and superior

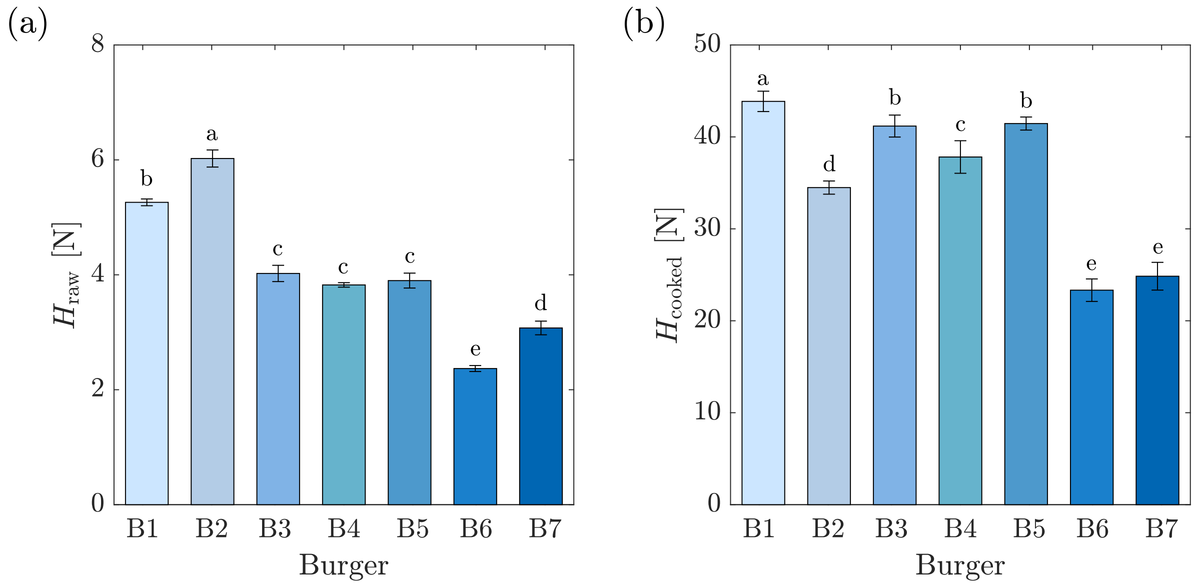

Fig. 7. Hardness results for (a) raw burgers and (b) cooked burgers ($n = 12$). In a given subplot, values followed by a common letter are not significantly different based on HSD at the 5% level of significance ($p < 0.05$).

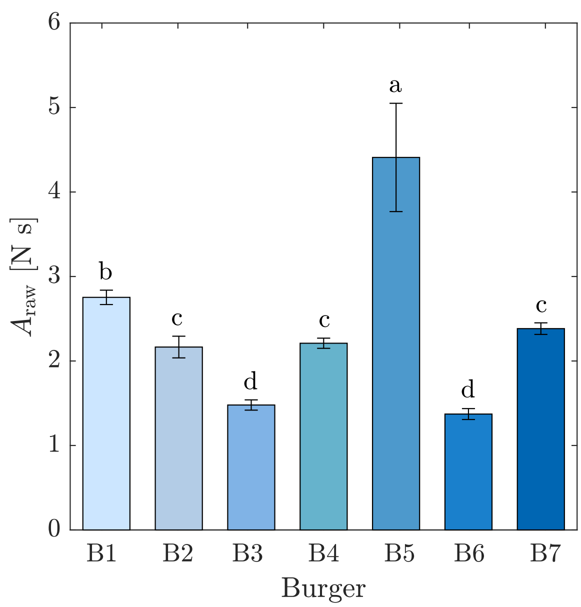

Fig. 8. Adhesiveness results for raw burgers ($n = 12$). Values followed by a common letter are not significantly different based on HSD at the 5% level of significance ($p < 0.05$).

properties to that of current plant-based alternatives, are presented in Table 5. All these properties are statistically significant ($p < 0.05$), with a distinction made between high beef content and low beef content only where a statistically significant difference has been identified. Because the textural properties of cultivated meat can be comparatively lower than that of the farmed product (Paredes et al., 2022) the present values provide novel guidelines to ensure cultivated meat products can be engineered to replicate the desired properties of traditionally farmed meat.

5. Conclusions and future work

Contemporary concerns for sustainability and the United Nations Sustainable Development Goals have driven a shift towards alternative proteins. One such alternative is cultivated meat. However, to ensure consumer acceptance of this novel food product without suffering from the textural criticisms associated with plant-based burgers, an understanding of the mechanical and textural properties must be gained. Consequently, two approaches were employed in this experimental characterisation study. First, mechanical testing, which benefits from well-established ISO test protocols but is not intended for food products, was performed. Secondly, textural profiling analysis, intended to characterise the textural properties of food, albeit without a standardised protocol, was undertaken.

There exist clear distinctions between both the mechanical and textural properties of cooked high beef content and handmade beef burgers, low beef content burgers and plant-based burgers. Specifically, the flexural, compressive and cutting yield strains proved to be the best mechanical indicators of such distinctions. In addition, textural profiling analysis properties, namely hardness, cohesiveness, resilience and chewiness, show a clear divide between beef and plant-based burgers. Further differences can also be quantified between high beef content and handmade versus low beef content burgers for the hardness and chewiness, thus appearing as the most suitable metrics. The absence of a clear divide between low-fat and high-fat burgers provides further motivation for the implementation of cultivated meat, instead of plant or insect-based alternatives, as it is the beef content that appears to govern the differences in mechanical and textural properties.

As a result, we present a target range of mechanical properties to guide future developments in cultivated meat burgers, allowing us to replicate the specifications of beef products, while avoiding the same textural criticisms that have been made towards plant-based alternatives. Therefore, our results offer novel insights into the characterisation of the mechanical and textural properties of both beef and plant-based burgers and may contribute to further developments in cultivated meat to ensure consumer acceptance through tailoring some of their organoleptic characteristics. It is suggested that further work explores (i) the effect of the texture profiling analysis variables (such as displacement rate and maximum strain) on the resulting properties of meat products; (ii) extends the tested variables to compare fresh and frozen burgers, study the effect of cooking parameters, and further widen the range of burgers considered; (iii) the mechanical testing of cultivated meats and, where relevant, their edible micro-carriers; (iv) the relationship between the textural properties and the psychology of consumer acceptance, undertaking sensory evaluation to contrast human perception with the key textural properties identified in this work.

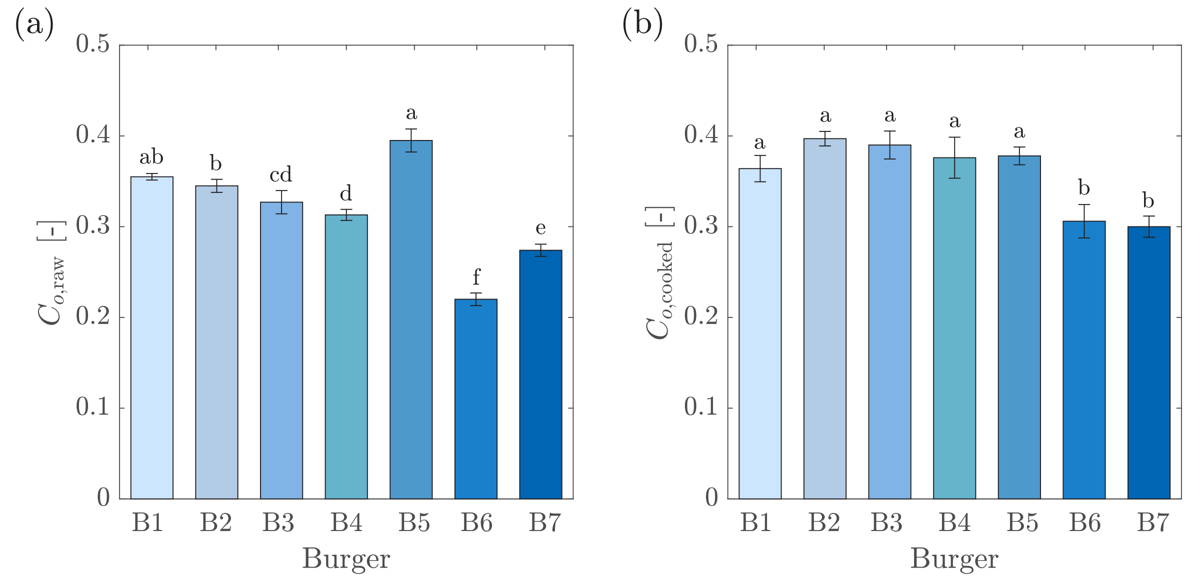

Fig. 9. Cohesiveness results for (a) raw burgers and (b) cooked burgers ($n = 12$). In a given subplot, values followed by a common letter are not significantly different based on HSD at the 5% level of significance ($p < 0.05$).

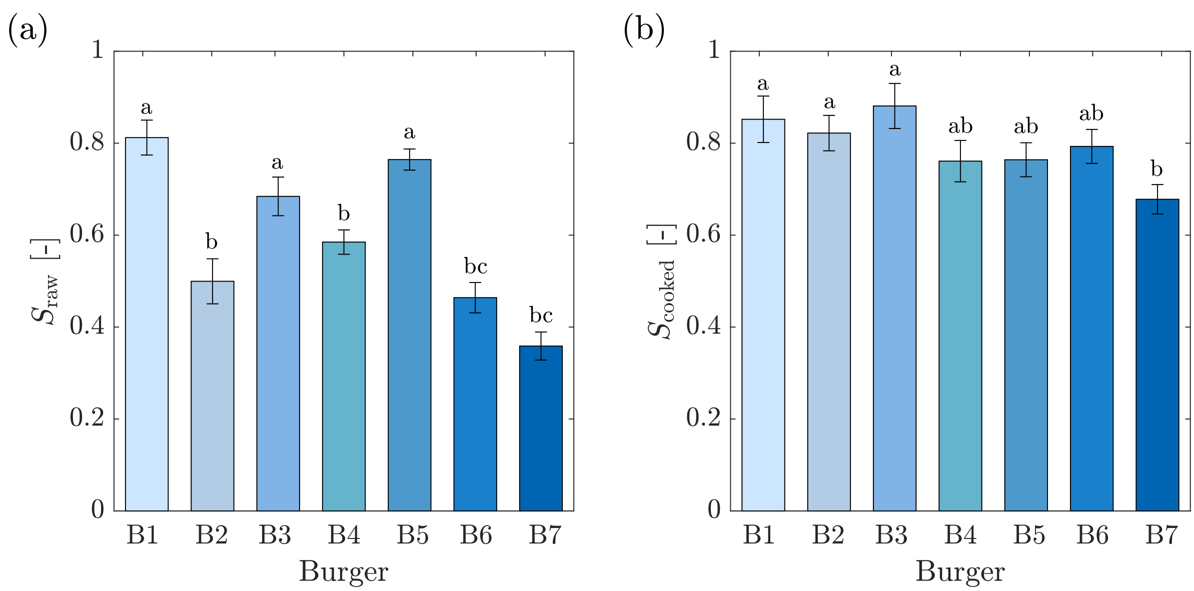

Fig. 10. Springiness results for (a) raw burgers and (b) cooked burgers ($n = 12$). In a given subplot, values followed by a common letter are not significantly different based on HSD at the 5% level of significance ($p < 0.05$).

Table 5
Recommended range of values for the mechanical and textural properties of beef burgers and plant-based alternatives. Distinctions are only presented where statistically relevant, based on HSD at the 5% level of significance ($p < 0.05$).

	Property	Beef burger		Plant-based burger
		High beef content and handmade	Low beef content	
Mechanical	Flexural yield strain, $\epsilon_{yf,\text{cooked}}$ [–]	0.325–0.148		0.115–0.094
	Compressive yield strain, $\epsilon_{yc,\text{cooked}}$ [–]	0.149–0.048		0.340–0.210
	Cutting yield strain, $\epsilon_{ycut,\text{cooked}}$ [–]	0.283–0.215		0.416–0.487
Textural	Hardness, H_{cooked} [N]	43.863–41.177	37.814–34.487	24.845–23.329
	Cohesiveness, $C_{o,\text{cooked}}$ [–]	0.397–0.376		0.306–0.300
	Springiness, S_{cooked} [–]	0.881–0.761		0.678–0.626
	Resilience, R_{cooked} [–]	0.159–0.139		0.107–0.106
	Chewiness $C_{h,\text{cooked}}$ [N]	14.143–13.544	11.254–10.822	5.054–4.469

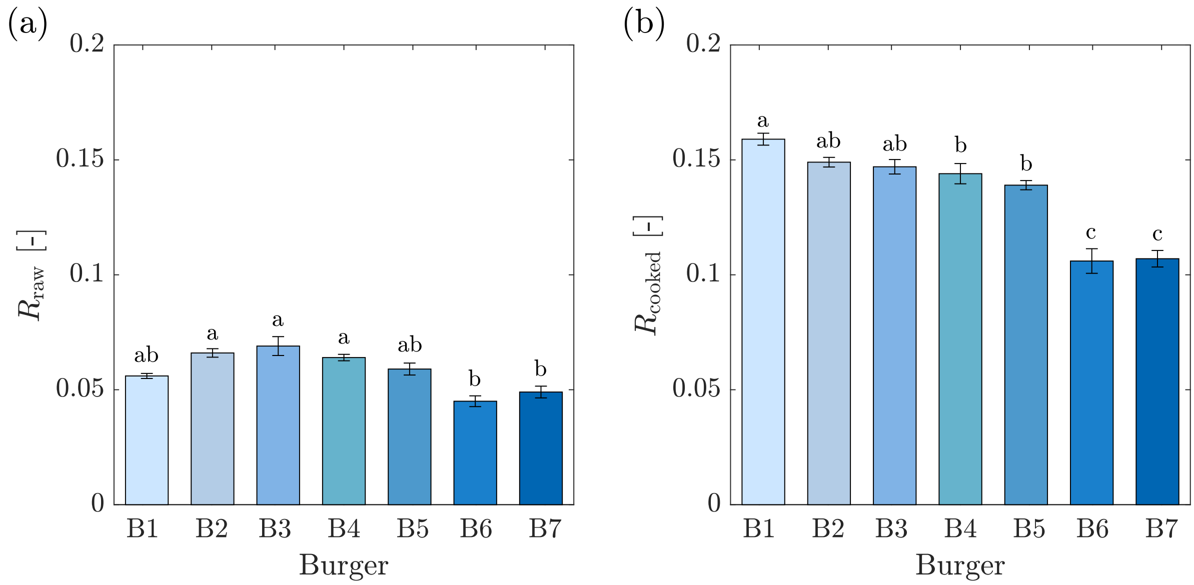

Fig. 11. Resilience results for (a) raw burgers and (b) cooked burgers ($n = 12$). In a given subplot, values followed by a common letter are not significantly different based on HSD at the 5% level of significance ($p < 0.05$).

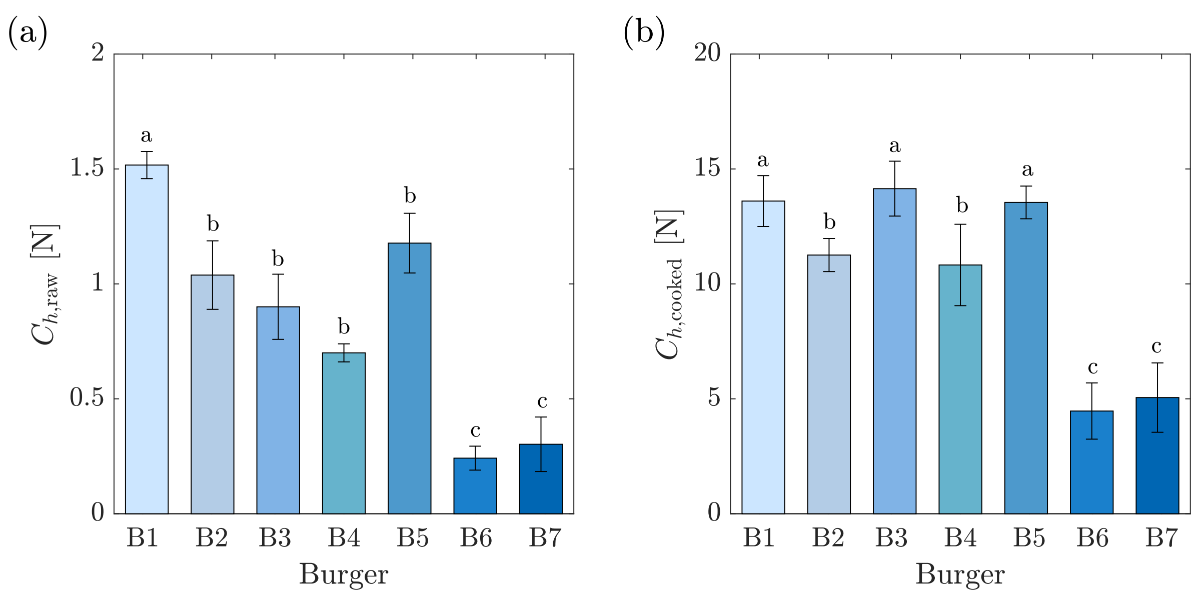

Fig. 12. Chewiness results for (a) raw burgers and (b) cooked burgers ($n = 12$). In a given subplot, values followed by a common letter are not significantly different based on HSD at the 5% level of significance ($p < 0.05$).

CRediT authorship contribution statement

Jean-Baptiste R.G. Souppez: Writing – original draft, Visualization, Validation, Supervision, Methodology, Formal analysis, Data curation, Conceptualization. **Benjamin A.S. Dages:** Writing – review & editing, Investigation. **Geethanjali S. Pavar:** Writing – review & editing, Software, Methodology, Data curation. **Jack Fabian:** Writing – review & editing, Formal analysis. **Jason M. Thomas:** Writing – review & editing. **Eirini Theodosiou:** Writing – review & editing, Supervision, Conceptualization.

Declaration of competing interest

None.

Data availability

Data will be made available on request.

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