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RESEARCH ARTICLE

Optimizing Hybrid Burger Formulations: Impact on Texture and Quality

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Abstract

This study aimed to evaluate the impact of selected plant-based ingredients and structural additives on the sensory, textural, and nutritional properties of hybrid burgers (contained 50% meat part and 50% plant part). Hybrid formulations containing seitan, soy protein, methylcellulose (Emulan 2 ATFL and Methocel), as well as a mixed additive blend (each additive included at levels ranging from 0.3 to 3 g per 100 g of the plant-based portion, based on manufacturer recommendations or own assumptions), were analysed for their impact on thermal processing yield, colour parameters, water activity and proximate composition and texture of hybrid burgers. Sensory evaluation revealed high acceptability across all variants. Nutritional assessment indicated that Emulan 2 ATFL increased fat content up to 13.3% (10% in control variant) and energy value without affecting other parameters. Texture analysis showed that the addition of Emulan 2 ATFL increased the cooking yield and penetration force of warm samples, while seitan reduced this parameter. Despite minor differences, none of the structural additives significantly altered colour perception of burgers. The results suggest that hybrid burgers successfully maintain desirable sensory attributes while reducing meat content. However, further research is needed to optimize texture by refining additive selection and concentrations, ensuring improved technological properties for broader consumer acceptance.

KEYWORDS
texture, sensory acceptability, hybrid burgers, structure-forming additives

Introduction

The global demand for meat continues to grow [Armstrong 2023]. In 2023, global meat production (in total) was estimated to exceed 370 million tons, with 41 million tons produced in the European Union alone [FAOSTAT 2024]. However, concerns regarding its environmental and human health impact are prompting many consumers to reduce meat consumption [Austgulen et al. 2018]. This shift is driven by the increasing awareness of sustainability and health-related issues associated with high processed meat intake [Clonan et al. 2015]. From an environmental perspective, meat production is resource-intensive, contributing significantly to greenhouse gas emissions [Hyland et al. 2017]. Health considerations, such as the link between excessive red meat consumption and cardiovascular diseases, cancer, and obesity, further fuel the demand for alternative protein sources [Godfray et al. 2018]. In response to these concerns, flexitarian diets, which focus on reducing meat consumption without eliminating it entirely, are gaining popularity [Dagevos 2021]. This trend has paved the way for hybrid products, combining meat with plant-based ingredients to balance taste, texture, and nutritional value. Hybrid products aim to meet the expectations of consumers who are unwilling to give up the sensory experience of meat but are motivated to limit intake due to environmental or health concerns [Grasso, Jaworska 2020]. Such products provide a solution to consumers by offering a familiar meat-like taste while maintaining the benefits of plant-based ingredients, such as lower saturated fat content and increased fibre [Langyan et al. 2022].

Developing the hybrid products requires a deep understanding of the quality, nutritional value, and functional properties of plant and meat raw materials. The formulation process often faces technological challenges, such as achieving a meat-like texture, flavour stability, and suitable processing properties [Prajapati et al. 2024; Wang et al. 2023]. Legumes, cereals, and other plant proteins are essential to creating meat analogues [Malav et al. 2015]. Legumes, such as soybeans and peas, offer a rich source of protein and possess functional properties like water and fat absorption, emulsifying capabilities, and gel formation, making them suitable for meat alternative production [Chandler, McSweeney 2022]. Cereals, particularly wheat, play a crucial role in meat analogues, with wheat gluten (seitan) being a prominent ingredient due to its fibrous texture and ability to imitate the mouthfeel of meat [Gasparre et al. 2022]. Combining these plant-based raw materials allows for the creation of products that maintain a desirable texture, flavour, and nutritional profile, thereby catering to the growing demand for more sustainable food options [Malav et al. 2015].

Hybrid meat products, including burgers, nuggets, and sausages, present opportunities and challenges for the food industry. The primary challenge lies in replicating the sensory attributes of meat, such as flavour, juiciness, and mouthfeel – characterized by its tenderness, texture, and the perception of fat and moisture during chewing, while introducing plant-based components. Achieving the desired texture is especially important, as it plays a crucial role in consumer acceptance [Grasso, Goksen 2023; Grasso, Jaworska 2020]. This study aimed to evaluate the impact of selected plant-based raw materials and functional additives on the quality, sensory, and structural characteristics of hybrid meat burgers. The conducted research seeks to provide insights into the technological challenges associated with the production of hybrid products and to identify potential solutions for their successful implementation in the food industry. It is hypothesized that the appropriate selection and optimization of plant-based ingredients will enable the production of a hybrid product with high consumer acceptability while maintaining desirable sensory and nutritional properties.

Materials and Methods

Research material and hybrid burgers production

The research material consisted of hybrid burgers produced from beef (thin flank; 50%) and a developed plant-based component (50%; plants, such as millet groats, dried tomatoes, sunflower seeds, onion, flaxseed pomace).

The basic formula of the meat part was thin flank (Zychowicz Sp. z o.o., Przetwórstwo Mięsa Sp.K., Daleszyce, Poland), curing mixture – 1.7% (Qemetica S.A., Warszawa, Poland), and spices (Kamis, McCormick Polska S.A., Stefanowo, Poland): pepper, granulated garlic, herbes de Provence, sweet ground paprika – 0.3% each, and water – 10%.

To prepare the meat part of hybrid burgers, beef thin flank was ground using a Zelmer ZMM4048B laboratory grinder with a 3.5 mm hole diameter mesh. After grinding, the thin beef flank was analysed for proximatechemical composition using a FoodScan 2® analyser (Foss Analytical, Denmark) – water content 65.4%, fat content 15.3%, protein content 19.0%. The meat, along with curing mixture, water, and spices, was mixed using a Kenwood KM 070 laboratory mixer (Kenwood Ltd., United Kingdom) for about 3 minutes at the lowest speed with a "K" shape paddle.

The basic formula for plant-based part for hybrid burgers production was millet groats (Sante sp. z o.o., Sobolew, Poland) - 55%, dried tomatoes (ROLNIK sp. z o.o., Mikołów, Poland) - 20%, sunflower seeds (Sante sp. z o.o., Sobolew, Poland) - 9%, onion (purchased from a local store) - 8%, flaxseed pomace (obtained during cold pressing of oil using a Fermet press at Kropla Omega oil mill, Starachowice, Poland) - 5%, salt (Kopalnia Soli Kłodawa S.A., Kłodowa, Poland) - 1.7%, spices (Kamis, McCormick Poland, Stefanowo, Poland): pepper, granulated garlic, herbes de Provence, sweet ground paprika – 0.3% each.

The preparation of the plant-based part of hybrid burgers began by cooking millet groats according to the manufacturer's instructions, with the addition of 0.5% salt in relation to the raw material weight. The dried tomatoes, sunflower seeds, and onion were manually chopped with a knife. The onion was sautéed in a pan with a small amount of rapeseed oil. Then, the ingredients were cooled down, and along with flax pomace and spices, were mixed in a Kenwood KM 070 laboratory mixer (Kenwood Ltd., United Kingdom) for approximately 1 minute at the lowest speed using a "K"-shaped paddle. The plant-based part was modified with different structure-forming additives emulsions to improve burgers structure properties. The dosage level of the structure-forming additives and the proportions of the emulsification process were selected based on the manufacturers' recommendations or our own assumptions.

The study used four structure-forming additives in hybrid meat-plant burgers: seitan wheat protein (Intenson S.A.) marked as S, two types of methylcellulose : Emulan 2 ATFL (Amco Sp. z o.o) marked as E and Methocel MX (International Flavours & Fragrances IFF) marked as MX, and soy protein isolate (Exeller Polska sp. z o.o.) marked as BS. Seitan and soy protein isolate were added at 3 g per 100 g of the plant-based portion, with emulsions in a 1:2:3 ratio (additive:oil:water). Emulan 2 ATFL was used at 3 g per 100 g, with a 3:10:8 emulsion ratio, while Methocel MX was applied at 0.3 g per 100 g, with a 1:10:22 ratio. A mixed sample (marked as MIX) contained all four additive emulsions on appropriate level (1/4 of dosage for each). A control sample (C) was prepared without additives.

To prepare the emulsions, structure-forming additives were combined with the appropriate amount of oil and homogenized using a SilentCrusher M homogenizer (Heidolph Instruments GmbH & Co. KG, Germany) for about one minute at 20.000 rpm. Then, the specified amount of water was added, and homogenization was repeated for approximately one minute under the same conditions until a uniform emulsion was obtained. The produced emulsions were stored under refrigeration until they were applied to the burgers.

The plant batter was divided into six parts, to five of them the emulsions were added at the appropriate level. The last portion of the batter was left unchanged (control – C). Batters were mixed in a Kenwood mixer to spread the emulsions. The prepared plant batters were combined with the previously prepared meat batter in a 1:1 ratio and mixed until the ingredients were evenly combined using a Kenwood mixer. The final batters were portioned into 100 g parts, from which burgers were formed using a round mould (maintaining the same height to standardize the batters arrangement in the mould). The formed and portioned burgers were subjected to thermal treatment in a RATIONAL convection-steam oven (Aktiengesellschaft, City, Germany) at a temperature of 160°C and 60% humidity for approximately 14 minutes until a temperature of 70°C was reached at the geometric centre of the burgers. After thermal treatment, burgers were left to cool down, covered with aluminium foil to reduce moisture loss, and stored under refrigeration (4-6°C). After 24 hours of storage, all hybrid burger variants were subjected to further analysis.

The study was conducted in three series of measurements. Each series involved the production of six hybrid burger variants, with six burgers prepared per variant in each series. Each parameter was measured three times per series, ensuring statistical reliability.

Methods

Thermal processing yield and surface reduction measurements

The thermal processing efficiency of the produced hybrid burgers was determined by measuring the sample's mass before thermal treatment and after 24 hours of refrigerated storage. The yield was calculated in relation to the weight before thermal processing and expressed in %.

For the reduction in the surface area of the burgers due to thermal treatment determination, burgers were photographed on graph paper before and after thermal treatment. The images were analysed using computer image analysis (ImageJ, Version 1.51 23 April 2018) to determine the product's surface area (in cm^2) and its change in relation to the surface area before thermal processing and expressed in %.

Colour parameters measurement

Colour parameters were measured 24 hours after burgers production using a CR200 Konica Minolta colourimeter with a D65 light source and a 2° observer (Konica Minolta, Japan) in the CIE L*a*b* system. Before the measurements, the device was calibrated using a white standard (Y: 95.2 x: 0.3159, y: 0.3326). L*, a* and b* colour parameters were measured on the surface of the hybrid burgers and their freshly cut with a knife cross-section. Additionally, the absolute colour difference colour ΔE between product variants was calculated using the formula:

ΔE=√(ΔL^(*2)+Δa^(*2)+Δb^(*2))

Where:

- ΔL* - difference in average L* values between samples,
- Δa* - difference in average a* values between samples,
- Δb* - difference in average b* values between samples.

The results were interpreted according to the criteria presented by Mokrzycki and Tatol [2011], where 0<ΔE<1 – colour difference is not noticeable, 1<ΔE<2 – the colour difference is noticeable only to an experienced observer, 2<ΔE<3.5 – the colour difference can be noticed by an inexperienced observer, 3.5<ΔE<5 – clear difference between colours, ΔE>5 – the observer perceives two distinct colours.

Water activity measurement

For water activity (aw) analysis, the entire burger was homogenized, and homogenised. The entire burger was homogenised for water activity (aw) analysis, and the sample was taken for measurement. The water activity (aw) of hybrid burger samples was measured at 23°C ± 1°C using the AquaLab Series 3 water activity meter (METER Group, Inc., USA), following the user manual instruction.

Proximate chemical composition analysis

The proximate chemical composition of the hybrid burgers was determined 24 hours after burgers production using a FoodScan 2® device (Foss Analytical, Denmark) using near-infrared transmission spectroscopy (NIR) at a wavelength of 850-1050 nm. Measurements were conducted according to the Polish Standard [PN-A-82109:2010].

Texture parameters measurement

Texture parameters were measured 24 hours after burgers production using a Zwicki 1120 device (Zwick GmbH & Co., Germany) following the user manual instructions. The conducted tests included penetration and shear force tests. The measurement was taken at 22-23°C on "cold samples" and also performed on "warm samples", meaning after reheating (in a convection-steam oven at 160°C and 60% humidity) the burgers samples to a temperature of 70°C achieved at the geometric centre . Penetration force was measured on whole burgers with a diameter of 75 mm and a thickness of approximately 20 mm using a flat-tipped probe with a diameter of 13 mm. The head speed was 50 mm/min, and the pre-test force was 0.2 N. The penetration force was recorded at a depth of 10 mm.

Shear force was measured on hybrid burger samples cut into rectangular blocks measuring 75x10x10 mm. This measurement was conducted using a Warner-Bratzler flat blade. The head speed was 50 mm/min, and the pre-test force was 0.2 N. The maximum shear force was recorded at the point of the complete sample cut.

Sensory evaluation

After producing all variants of the hybrid burgers, a sensory evaluation was conducted 24 hours after production. The evaluation was performed on trained panelteam consistinged of 8 individuals. Samples were prepared for each variant of the hybrid burgers. Before the sensory evaluation, the burgers samples were rethermally treated in a convection-steam oven to reach aheated to temperature of 70°C. at the geometric centre of the product. The following attributes were assessed: colour, aroma, tenderness, juiciness, taste, and overall acceptability. Sensory evaluation was performed using the scaling method. Hedonic acceptability of the Aattributes was rated on a scale from 1 to 9, where 9 represented the most desirable perception of a given attribute, where 1 meant "I do not like it" and 9 meant "I like it the most" [Baryłko-Pikielna, Matuszewska 2009].

Statistical analysis

The final results of all tests were reported as mean values and standard deviations obtained from three series for each variant. To determine the significant differences between the mean values of the studied parameters of the hybrid burgers produced, a One-Way ANOVA and t-test were conducted. Significant differences were calculated using Tukey's HSD posthocpost hoc test.

A Student's t-test was also performed to compare the texture parameters of the hybrid burgers measured while cold and warm. Analyses were performed using StatSoft Statistica 13.0 (TIBCO Inc., Palo Alto, CA, USA) at a significance level α = 0.05.

Results and Discussion

Thermal processing yield and surface reduction

The use of plant-based ingredients can help reduce cooking losses. The thermal processing yield of the produced hybrid burgers was approximately 90%. The addition of Methylcellulose – Emulan 2 ATFL significantly ($p \le 0.05$) increased the cooking yield of hybrid burgers compared to those with addition of Seitan (Table 1). The Significantly the highest ($p \le 0.05$) reduction in surface area, compared to other burger variants, was observed in the variant with MX variant of hybrid burgers. The smallest surface reduction during thermal treatment was noted for the E and BS burgers variants (Table 1).

The results of this study align with previous findings on thermal processing yield in hybrid and plant-based burgers. Zhang et al. [2024] reported lower cooking losses in plant-based burgers (20.1%) compared to beef burgers (37.5%), which is consistent with the high thermal yield (88.4–90.9%) observed in the present study. Similarly, Fadiloglu et al. [2023] found that buckwheat flour increased the yield of oven-baked beef burgers, while plant oils slightly reduced it. In this study, methylcellulose (Emulan 2 ATFL) improved cooking yield, likely due to its water-binding capacity, whereas seitan slightly decreased yield, suggesting differences in moisture retention mechanisms among plant-based additives. Soltanizadeh and Ghiasi-Esfahani [2015] demonstrated that *Aloe Vera* reduced cooking losses by up to 11% in low-meat beef burgers by enhancing water retention. While *Aloe vera* was not tested here, a similar effect was observed with methylcellulose, which helped preserve burger mass during heat treatment. Additionally, surface reduction in this study ranged from 9.8% to 14.2%, with the lowest shrinkage in samples containing Emulan 2 ATFL and soy protein isolate, further supporting the role of hydrocolloid-based additives in maintaining product structure during thermal processing.

Zhang et al. [2024] showed that sous-vide processing at 70°C followed by grilling led to a 20.1% loss in plant-based burgers compared to a 37.5% loss in beef burgers, highlighting lower cooking losses in plant-based materials. Fadiloglu et al. [2023] found that the thermal yield of oven-baked beef burgers with added buckwheat flour and walnut or safflower oils ranged from 71.09 to 78.77%, with the highest yield observed with buckwheat flour alone. The addition of oils slightly decreased the yield of burgers, suggesting that the binding capacity between meat proteins and plant oils may affect yield outcomes. Soltanizadeh and Ghiasi-Esfahani [2015] reported that adding *Aloe vera* enhanced yield in low-meat beef burgers, likely due to its water retention properties, which minimized cooking losses by up to 11% compared to control samples. Diameter reduction was also significantly minimized, from 16% without *Aloe vera* to just 2% in burgers with a 5% addition of Aloe vera.

Colour parameters measurement

The lightness parameter value (L*) was similar for all burger variants. No significant ($p > 0.05$) differences ($p > 0.05$) were observed either on the surface or on the cross-section of burgers. Similarly, redness (a*) and yellowness (b*) parameters showed consistent values across samples, both on the surface and cross-section of burgers (Table 1). The use of structure-forming additives did not affect the colour parameters of hybrid burgers. Notably, the calculated absolute colour difference (ΔE) was below 1 between most variants, indicating that colour differences were imperceptible to the human eye. The only exception was the control sample (C), which had no structural additives. Differences between the control and the experimental variants were minor but perceptible to experienced observers (ΔE between 1 and 2 for most comparisons, and ΔE = 2.3 for the control C vs. MX variant; (Table 2).

The results of this study showed no significant differences in the colour parameters (L*, a*, b*) of hybrid burgers with different structure-forming additives. This is consistent with findings by Kamani et al. [2019], who reported that the incorporation ofincorporating soy protein isolate and wheat gluten in meat products did not significantly alter colour perception. Similarly,

Table 1. Thermal processing yield, surface reduction, L*, a* and b* colour parameters, and water activity of hybrid burgers (mean ± standard deviation).

Parameter	Hybrid burgers variants					
	C	S	E	MX	BS	MIX
Thermal Processing Yield [%]	$90.4^{ab} \pm 0.42$	$88.4^{a} \pm 0.55$	$90.9^{b} \pm 0.08$	$89.1^{ab} \pm 0.82$	$90.3^{ab} \pm 0.39$	$89.9^{ab} \pm 0.75$
Surface reduction [%]	$11.8^{b} \pm 0.3$	$12.8^{bc} \pm 0.7$	$9.8^{a} \pm 0.3$	$14.2^{d} \pm 0.4$	$9.8^{a} \pm 0.3$	$13.5^{dc} \pm 0.7$
L* - surface	$45.92^{a} \pm 1.73$	$45.30^{a} \pm 2.32$	$45.40^{a} \pm 2.14$	$45.51^{a} \pm 2.85$	$45.45^{a} \pm 1.98$	$45.73^{a} \pm 2.39$
a* - surface	$10.87^{a} \pm 1.10$	$11.13^{a} \pm 1.73$	$10.93^{a} \pm 1.80$	$11.19^{a} \pm 1.48$	$10.97^{a} \pm 1.33$	$11.14^{a} \pm 1.63$
b* - surface	$11.61^{a} \pm 1.71$	$9.95^{a} \pm 2.63$	$9.91^{a} \pm 2.13$	$9.37^{a} \pm 2.42$	$9.71^{a} \pm 2.20$	$9.95^{a} \pm 2.33$
L* - cross section	$49.11^{a} \pm 1.05$	$49.57^{a} \pm 1.70$	$48.21^{a} \pm 1.37$	$48.81^{a} \pm 1.68$	$49.70^{a} \pm 1.62$	$48.70^{a} \pm 0.74$
a* - cross section	$11.66^{a} \pm 1.09$	$11.46^{a} \pm 1.33$	$11.74^{a} \pm 1.16$	$11.78^{a} \pm 1.42$	$11.03^{a} \pm 1.32$	$11.20^{a} \pm 0.69$
b* - cross section	$12.50^{a} \pm 1.97$	$12.26^{a} \pm 1.93$	$12.06^{a} \pm 1.89$	$12.05^{a} \pm 1.99$	$11.68^{a} \pm 1.43$	$11.74^{a} \pm 1.34$
Water activity (a_w)	$0.967^{a} \pm 0.005$	$0.973^{a} \pm 0.004$	$0.972^{a} \pm 0.005$	$0.972^{a} \pm 0.003$	$0.970^{a} \pm 0.004$	$0.966^{a} \pm 0.005$

a-d: Means with different superscript letters within the same row differ significantly at $p \le 0.05$.
Meaning of hybrid burger variants abbreviations: C – Control; S – Seitan; E – methylcellulose Emulan; MX – methylcellulose Methocel; BS – soy protein isolate; MIX – a mixture of all additives.

Table 2. Absolute colour difference (ΔE) between variants of hybrid burgers.

Variant	*C*	*S*	*E*	*MX*	*BS*	*MIX*
C	-	1.8	1.8	2.3	2.0	1.7
S	1.8	-	0.2	0.6	0.3	0.4
E	1.8	0.2	-	0.6	0.2	0.4
MX	2.3	0.6	0.6	-	0.4	0.6
BS	2.0	0.3	0.2	0.4	-	0.4
MIX	1.7	0.4	0.4	0.6	0.4	-

Meaning of hybrid burger variants abbreviations: C – Control; S – Seitan; E – methylcellulose Emulan; MX – methylcellulose Methocel; BS – soy protein isolate; MIX – a mixture of all additives.

Profeta et al. [2021] found that plant-based meat alternatives often exhibit colour characteristics comparable to hybrid formulations, as their composition allows for controlled pigmentation and uniform appearance.

In findings of Fadiloglu et al. [2023], who reported that the partial replacement of beef fat with safflower and walnut oils resulted in darker burgers due to the colour of the plant-based oils. The lack of significant differences in colour parameters between hybrid burger variants indicates that the selected structure-forming additives, including seitan, soy protein, and methylcellulose, can be effectively incorporated into formulations without compromising the visual quality of the product. This finding underscores the feasibility of integrating plant-based components into hybrid products, addressing consumer demand for meat reduction [Ziegler et al. 2020].

Water activity

No differences (p>0.05) in water activity were observed between hybrid burger variants (Table 1), indicating that the applied structure-forming additives did not affect moisture availability in the formulations. However, the high aw values, exceeding 0.85, suggest that the burgers may be susceptible to microbial spoilage without additional preservation measures [Rifna et al. 2022].

These results align with findings by Elgasim and Al-Wesali [2000], who reported water activity values between 0.93 and 0.95 in beef patties containing soy protein and Samh flour (Mesembryanthemum forsskalei Hochst), depending on the type and percentage of plant-based additives used. While plant-based ingredients have been shown to absorb and bind water through mechanisms such as hydration, surface energy interactions, and molecular diffusion [Kyriakopoulou et al. 2019, Chandler & McSweeney 2022], no such effect was observed in this study.

To improve the shelf life of hybrid burgers while maintaining sensory quality, strategies such as the use of water-binding agents, modified atmosphere packaging, or advanced preservation techniques should be considered. These measures could help balance product stability with consumer appeal, ensuring both safety and quality [Kyriakopoulou et al. 2019, Rifna et al. 2022].

No significant (p>0.05) differences were observed between water activity of hybrid burger variants (Table 1). These results indicate a consistent water-binding capacity across formulations, ensuring the desired juiciness and texture. However, the high aw values, typical for products with high moisture availability, exceed 0.85, making the burgers susceptible to microbial spoilage without additional preservation measures [Rifna et al. 2022].

These results align with findings by Elgasim and Al-Wesali [2000], who investigated the water activity of beef patties containing soy protein and Samh flour (Mesembryanthemum forsskalei Hochst). In their study, water activity ranged from 0.93 to 0.95 depending on the type and percentage of the plant-based additive used.

The ability of plant-based ingredients to influence water activity stems from their capacity to absorb and bind water through mechanisms such as hydration, surface energy interactions, and molecular diffusion within their structure [Kyriakopoulou et al. 2019; Chandler and McSweeney 2022]. This binding determines water availability in the food matrix, impacting texture and shelf life. Strategies such as using water-binding agents, modified atmosphere packaging, or advanced preservation techniques could be explored for improved shelf life. These measures would help balance sensory appeal with microbial stability, ensuring the hybrid burgers meet quality and safety standards [Kyriakopoulou et al. 2019; Rifna et al. 2022].

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Proximate composition analysis

The proximate composition of hybrid burgers is primarily influenced by the selection of raw materials and the applied thermal treatment methods [Chandler, McSweeney 2022]. Plant-based ingredients contribute to variations in macronutrient content, while processing conditions of beef affect moisture retention, fat content, and overall nutritional properties [Modzelewska et al. 2022]. The raw materials and thermal treatment methods significantly influence the chemical composition of hybrid burgers [Chandler, McSweeney 2022; Modzelewska et al. 2022]. In our study, no significant differences (p>0.05) were observed between hybrid burger variants in terms of protein, fibre, sugar, ash and salt contents (Table 3). However, fat content differed significantly, with the highest levels observed in E burgers variants due to the oil required for its emulsification. These variations in fat content directly influenced the energy values of the hybrid burgers, which ranged from 703 to 824 kJ (168–197 kcal). Burgers without structure-forming additives were characterized by the lowest fat and energy values (p≤0.05), highlighting the role of additives in determining the nutritional profile of hybrid products (Table 3).

Table 3. Nutritional composition of hybrid burgers (mean ± standard deviation).

Nutrient [g/100 g]	Hybrid burgers variants					
	C	S	E	MX	BS	MIX
Protein	16.82^{a} ± 0.03	15.71^{a} ± 0.28	15.55^{a} ± 0.23	16.17^{a} ± 0.48	16.37^{a} ± 0.20	16.14^{a} ± 0.60
Fiber	3.68^{a} ± 0.88	3.53^{a} ± 0.69	2.81^{a} ± 0.21	3.33^{a} ± 0.39	4.09^{a} ± 0.66	3.76^{a} ± 0.34
Sugars	0.88^{a} ± 0.02	2.10^{a} ± 0.36	2.46^{a} ± 0.64	1.27^{a} ± 0.71	0.72^{a} ± 1.08	1.60^{a} ± 0.98
Ash	2.50^{a} ± 0.36	2.16^{a} ± 0.07	2.06^{a} ± 0.29	2.04^{a} ± 0.29	1.77^{a} ± 0.16	1.93^{a} ± 0.20
Salt	1.33^{a} ± 0.21	1.77^{a} ± 0.14	1.74^{a} ± 0.15	1.49^{a} ± 0.07	1.32^{a} ± 0.17	1.70^{a} ± 0.18
Fat	10.01^{a}± 0.41	12.05^{ab} ± 0.77	13.28^{b}± 0.59	11.44^{ab} ± 0.54	12.20^{ab} ± 0.53	12.05^{ab} ± 0.58
Energy value [kJ]	703^{a} ± 23	781^{bc} ± 28	824^{c} ± 22	750^{ab} ± 30	779^{bc} ± 23	781^{bc} ± 28

a-b: Means with different superscript letters within the same row differ significantly at p≤0.05.

Meaning of hybrid burger variants abbreviations: C – Control; S – Seitan; E – methylcellulose Emulan; MX – methylcellulose Methocel; BS – soy protein isolate; MIX – a mixture of all additives.

Soltanizadeh and Ghiasi-Esfahani [2015] reported similar to our finding of protein and fat levels in low-meat burgers with *Aloe vera*, while De Marchi et al. [2021] found no significant differences in protein and fat content between meat and plant-based burgers. These findings underline the potential of hybrid products to balance the nutritional benefits of plant and animal ingredients. Hybrid formulations can improve nutritional quality by combining animal proteins with plant-derived components like fibre. Furthermore, hybrid products address evolving consumer demands for healthier, more sustainable food options. Reducing meat content aligns with sustainability goals, such as lowering carbon footprints and supporting greener food production systems. This approach diversifies the meat industry's offerings and supports flexitarian diets, which provide essential amino acids and fatty acids while promoting environmental and health benefits. Thus, hybrid burgers represent a promising innovation in line with current sustainable and health-conscious eating trends [Kyriakopoulou et al. 2019; Grasso, Jaworska 2020; Chandler, McSweeney 2022; Grasso, Goksen 2023].

Texture Parameters

Texture is a critical quality attribute of meat products, influencing consumer perception and acceptance [Kyriakopoulou et al. 2019, Grasso & Jaworska 2020, Grasso & Goksen 2023]. The study revealed texture parameters of hybrid burgers depending on the structure-forming additives and the temperature at which the analysis was conducted (cold or warm samples). No significant differences (p>0.05) were observed in penetration force values for cold samples. Similarly, there were no significant differences in shear force , regardless of the temperature of samples (cold or warm). The highest penetration force value among warm samples was observed in the E burger variant containing Emulan 2 ATFL, while the lowest was recorded in the S variant containing Seitan (Table 4).

A paired t-test (p>0.05) comparing cold and warm samples indicated significant differences in both penetration (except E variant) and shear forces (except E and BS variantvariants) (Table 4). Burgers analysed when warm demonstrated lower values

Table 4. Texture parameters of hybrid burgers: penetration and shear force (mean ± standard deviation).

Parameter	Hybrid burgers variants					
	C	S	E	MX	BS	MIX
Penetration Force (warm) [N]	4.40^{Xab} ± 0.54	3.16^{Xa}± 0.69	4.88^{Xb} ± 0.99	3.77^{Xab} ± 0.78	3.77^{Xab} ± 0.40	4.27^{Xab} ± 0.59
Penetration Force (cold) [N]	8.08^{Ya} ± 1.33	6.64^{Ya} ± 1.17	5.98^{Xa} ± 0.96	6.46^{Ya} ± 0.72	6.76^{Ya} ± 1.02	7.06^{Ya} ± 1.14
Shear Force (warm) [N/cm^2]	2.40^{Xa} ± 0.32	2.41^{Xa} ± 0.95	3.50^{Xa} ± 1.18	2.22^{Xa} ± 0.43	3.68^{Xa} ± 0.79	2.97^{Xa} ± 0.80
Shear Force (cold) [N/cm^2]	5.19^{Ya} ± 1.14	3.74^{Ya} ± 0.20	3.93^{Xa} ± 0.83	3.75^{Ya} ± 0.50	4.15^{Xa} ± 0.95	3.85^{Ya} ± 0.49

a-b: Means with different superscript letters within the same row differ significantly at p≤0.05.
X-Y: Means with different superscript letters within the same column differ significantly at p≤0.05.

Meaning of hybrid burger variants abbreviations: C – Control; S – Seitan; E – methylcellulose Emulan; MX – methylcellulose Methocel; BS – soy protein isolate; MIX – a mixture of all additives.

of texture parameters, indicating softer consistency and easier chewability than cold samples. These findings align with general trends in texture changes during cooling, where the protein and fat matrix solidifies, resulting in firmer products [Chen, Rosenthal 2015]. Despite these variations, the study found no substantial improvement in texture attributable to the structure-forming additives tested, suggesting their limited impact at the concentrations applied.

Studies by Soltanizadeh and Ghiasi-Esfahani [2015] demonstrated that *Aloe vera* increased compression force but reduced shear force in low-meat burgers due to competition between *Aloe vera* and myofibrillar proteins for water binding. Similarly, Fadiloglu et al. [2023] observed that substituting animal fats with saffron and walnut oils softened the texture of beef burgers by replacing saturated fats with unsaturated counterparts. These studies highlight the potential of functional additives to modify textural properties through different mechanisms.

Sensory evaluation

Consumer acceptance of plant-based meat analogues remains a significant challenge due to their often inferior sensory attributes compared to traditional meat products. Hybrid products, combining animal and plant-based ingredients, have the potential to bridge this gap, delivering acceptable sensory qualities while reducing meat content [Grasso, Jaworska 2022]. In our study, sensory evaluation of hybrid burgers was conducted by trained panelists using the scaling method and demonstrated. It demonstrated comparable ratings across all variants and attributes, including colour, aroma, juiciness, tenderness, flavour, and overall acceptability. Scores are presented in Table 5. Importantly, no significant differences ($p>0.05$) were observed between burger variants, suggesting that the inclusion of structure-forming additives such as Seitan, Emulan 2 ATFL, Methocel MX, or Soy Protein Isolate, at the tested concentrations, did not negatively influence sensory properties.

The absence of significant differences in the sensory quality of hybrid burger variants aligns with findings from other studies on meat analogues and low-meat products. For example, Kamani et al. [2019] reported no significant differences in texture perception when replacing meat with soy protein isolate and gluten in sausages. Similarly, Fadiloglu et al. [2023] observed that including buckwheat flour and plant oils in beef burgers maintained or improved sensory attributes, demonstrating the potential of functional plant-based ingredients to enhance meat product quality. These findings reinforce that well-designed formulations combining plant and animal components can maintain acceptable sensory profiles.

Interestingly, certain additives, such as Methocel MX and Seitan, were associated with slightly higher scores for specific attributes, such as juiciness and overall desirability, though these differences were insignificant (Table 5). This suggests that structural additives might play a subtle role in enhancing specific sensory qualities. However, these effects appear to depend on the concentration and combination of ingredients used, emphasizing the need for further optimization in hybrid burger formulations to maximize consumer satisfaction.

These findings represent a preliminary sensory assessment conducted by trained specialists, indicating that the tested hybrid burgers were generally acceptable in terms ofregarding sensory quality. While the results suggest that the inclusion of structural additives did not negatively impact sensory perception, further research is recommended to evaluate consumer acceptance on a larger, more diverse panel. Future studies should focus on assessing preferences and overall acceptability among a broader group of consumers to better and optimize hybrid burger formulations accordingly.

Table 5. Sensory evaluation of hybrid burgers (mean ± standard deviation).

Attribute	Hybrid burgers variants					
	C	S	E	MX	BS	MIX
Colour	$7.6^a \pm 0.5$	$7.6^a \pm 0.5$	$7.8^a \pm 0.5$	$7.9^a \pm 0.4$	$8.0^a \pm 0.5$	$7.9^a \pm 0.5$
Aroma	$7.7^a \pm 0.4$	$8.1^a \pm 0.3$	$7.8^a \pm 0.6$	$7.7^a \pm 0.3$	$7.8^a \pm 0.5$	$7.9^a \pm 0.4$
Tenderness	$7.3^a \pm 0.3$	$7.1^a \pm 0.1$	$7.1^a \pm 0.2$	$7.3^a \pm 0.4$	$7.1^a \pm 0.1$	$7.1^a \pm 0.1$
Juiciness	$7.2^a \pm 1.0$	$7.6^a \pm 0.2$	$7.2^a \pm 0.2$	$7.8^a \pm 0.3$	$7.5^a \pm 0.1$	$7.4^a \pm 0.2$
Taste	$7.3^a \pm 0.2$	$7.4^a \pm 0.3$	$7.0^a \pm 0.3$	$7.4^a \pm 0.6$	$7.4^a \pm 0.3$	$7.5^a \pm 0.2$
Overall Acceptability	$7.3^a \pm 0.8$	$7.6^a \pm 0.1$	$7.1^a \pm 0.2$	$7.6^a \pm 0.5$	$7.3^a \pm 0.1$	$7.4^a \pm 0.2$

a-b: Means with different superscript letters within the same row differ significantly at $p\leq0.05$.

Meaning of hybrid burger variants abbreviations: C – Control; S – Seitan; E – methylcellulose Emulan; MX – methylcellulose Methocel; BS – soy protein isolate; MIX – a mixture of all additives.

Conclusions

This study evaluated the influence of selected plant-based ingredients and structural additives on the sensory, textural, and nutritional properties of hybrid meat burgers. The findings provide partial support for the hypothesis that the appropriate selection and optimization of plant-based components can enable the production of hybrid products with high consumer acceptability while maintaining desirable sensory and nutritional qualities. Although all burger variants were well-accepted by the sensory panel, the anticipated optimization of texture was not fully achieved.

The results demonstrated that structural additives can positively influence thermal processing yield and cooking losses, with methylcellulose (Emulan 2 ATFL) improving both cooking yield and penetration force of warm samples. Conversely, the addition of seitan reduced the thermal processing yield and penetration force of warm samples. Despite these functional differences, none of the structural additives significantly affected burger colour, as only experienced observers could visually differentiate the samples. Nutritional analysis revealed that the inclusion of methylcellulose (Emulan 2 ATFL) increased fat content and energy value without impacting other nutritional parameters.

Among the tested additives, methylcellulose (Emulan 2 ATFL) showed the most promising functional effects, enhancing thermal processing yield and textural properties. This research highlights the potential of hybrid burgers as a viable and sustainable alternative to traditional meat products, capable of meeting consumer demands for sensory quality while reducing meat content. However, achieving optimal texture remains a technological challenge. Addressing this limitation will require further exploration of structural additives, higher dosages, and alternative plant-based components.

Future studies should focus on refining formulations to enhance textural properties and overall quality, while simultaneously evaluating the impact of innovative natural ingredients on sensory and functional parameters. By overcoming these challenges, hybrid burgers could solidify their position in the food industry as a solution that aligns with consumer preferences for sustainable, innovative, and high-quality food products.

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