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How do we eat meat – the role of structure, mechanics, oral processing, and sensory perception in designing meat analogs

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Abstract. This study provides an overview of over 50 publications exploring the consumers' motives for choosing meat analogs over real meat, how they perceive them, and what can be learned from meat structure, mechanics, oral processing, and dynamic sensory analysis for meat analog design. Meat analogs' sensory perception is their main lack, while ethics, health, and environmental statements might be used to boost their promotion. Methods for meat structure and mechanics' analysis are well established and translated (to some degree) to meat analog's quality analysis. However, limited information is present concerning meat and meat analogs' oral processing and dynamic perception, which can be seen as a chance for future research and improvement.

1. Introduction

A constant meat consumption rise per capita for the past few decades has been recorded in parallel with the population growth [1,2]. Considering these facts, it can be assumed that larger quantities of meat will be required. At the same time, the resources needed for the production of meat on a larger scale need to be increased, even though some of them are limited.

Consumers enjoy meat because of several reasons. A broad group enjoys meat sensory qualities. Meat nutritional value – the content of essential amino acids, high protein content, and B group vitamins – is another crucial element for meat appreciation.

However, a question that may appear is – will there be enough resources (e.g., land and fuels) to produce meat in a sustainable manner in the future, considering the trends mentioned above of meat consumption and population rise [3]? Also, impacts of meat production on climate change should also be considered [4]. Answering this question is undoubtedly tricky, knowing that many factors could impact the outcome in this case. Nonetheless, being prepared for that and having products capable of replicating the eating experience and nutritional value of meat, for the food producers is a comparative advantage.

In recent years, there is a growing number of products aiming to replicate meat products considering the whole experience of meat consumption. These are known as meat analogs, vegetarian meat, or meat substitutes. Some of these products present on the market are specifically designed using the scientific approach. At present, the products of *Beyond Meat* and *Impossible Foods* companies are especially popular. Both of these apply the technology of using plant proteins (pea protein in the case of *Beyond*



Meat and soy protein in the case of *Impossible Foods*) to produce products aiming to mimic burgers, meatballs, sausages, or ground meat. Otherwise, making meat substitutes resembling the appearance of steaks is still challenging due to meat's complexity concerning its structure and mechanical properties that further reflect on the process of eating (oral processing) and sensory perception [5].

Within this literature review, we strive to answer how consumers perceive meat analogs, what are the benefits and drawbacks of meat analogs compared to conventional meat, and what are the lessons learned from meat structure and mechanics, oral processing, and sensory perception that can be translated to meat analogs' improvement.

2. Consumers' attitudes towards meat and meat analogs

Studies covering consumers' meat appreciation indicated the importance of juiciness, tenderness, fibrousness, color, and meat flavor [6], while it was found that tenderness, juiciness, and flavor play the main role for 13 meat products and meat [7]. Some of these properties were identified as the main drawbacks for meat analogs' acceptance.

Consumer perceptions of three different types of burgers (meat-, plant-, and insect-based) under three testing conditions (blind, expected, and informed) were investigated [8]. The results of this study showed lower liking scores for non-meat origin products. They also reveal the weak points in quality for the meat analogs under scrutiny, mostly related to their texture, i.e., juiciness. However, the influence of testing conditions was also revealed, indicating that consumers will perceive plant-based burgers better if they are not aware of their origin. In another study, 46 consumers were interviewed to get insight into their attitudes towards meat analogs, and sensory testing of six dishes containing meat analog products was conducted [9]. Results followed a similar vein, and lack of uniform taste, compactness, dryness, and softness were found. However, consumers also stated positive sides of these products, referring to the health aspect and some sensory properties (tastiness, crispiness, chicken-like texture, or granular texture). Another study invited over 100 subjects to express their impressions of (four) plant-based chicken and (five) plant-based burgers compared to the real products. Again, insufficient satisfaction was seen, mainly because of the texture attributes, e.g., rubbery, insufficiently juicy, firmness, juiciness, greasiness. It is also worth mentioning that in this research, one plant-based burger surprisingly did not differ from a real burger, promising that it is possible to achieve desired plant-based product quality.

Fulfillment of the expectations related to sensory perception is a must for nearly all foodstuffs. In the case of meat and meat analogs, two groups of consumers with different expectations were identified [10]. The first group drivers for choosing meat analogs are the benefits they provide, discussed below. According to [10], this group is willing to compromise the meat-eating experience while respecting the other mentioned values. Otherwise, the group of meat-eaters that highly respect meat-eating experience is ready to accept meat analogs only if they fully resemble real meat or meat products.

2.1. Benefits of the meat analogs

There are several benefits, discussed in the literature, of meat analogs compared to real meat. These are also important drivers for choosing these products, even though there could be drawbacks in sensory quality at the same time. Among the first are ethical issues. Person- and product-related factors in light of the meat analogs' acceptance were investigated [11]. Ethical issues were important for those who already broadly use this kind of product, and at the same time, this group were satisfied with analogs' sensory profile that does not fully resemble real meat. In contrast, the group that rarely consumes meat analogs, referring to the products' sensory attributes as their weakest point, is not much interested in meat ethics.

Since it was found that high meat consumption could lead to a negative impact on health [12,13], it can be hypothesized that some consumers are interested in replacing these products with healthier alternatives, following the consumers' beliefs that were previously confirmed [14]. An illustration of protein yield from different sources (beef, pork, poultry, fish, clean beef, insects, plants) per area of land, and greenhouse gas production from different protein sources (beef, pork, poultry, plants, insects) has been proposed [15], showing the greatest yields of proteins for insect and plant sources per land area,

while, in contrast, animal sources produced significantly lower protein yields. At the same time, it is noticeable that insect- and plant-based protein production will result in much lower emissions of greenhouse gases, indicating advantages of these concerning environmental protection.

Regardless of the research focus, all the papers referenced here dealing with the consumers' perception of meat analogs suggested that the benefits these products have in the environment, ethics, and health, can be a powerful marketing tool, but still, their sensory perception is the main drawback needs to be improved for the meat analogs to be widely accepted.

3. Structure and mechanics of meat and meat analogs

On a macrostructural scale, meat consists of few different entities (muscle, connective, and adipose tissues), forming a composite, discrete, anisotropic material. The muscle tissue microstructure has been investigated in depth before, and it is well known [16,17]. The connective tissue can be classified based on its morphological role (endomysium, perimysium, epimysium). Collagen and elastin are two connective tissue components affecting its mechanical properties. The collagen is predominant in connective tissue compared to elastin. Opposite to elastin, collagen is rigid – it resists tension, while elastin fibers are stretchable. The negative impact of collagen on meat tenderness has been seen with animal maturation [18] due to changes in the insoluble/soluble collagen ratio. In contrast, elastin's influence on meat tenderness is negligible. Intramuscular fat content, i.e., marbling, is a desired meat property, making certain types of meat (e.g., Wagyu and Kobe beef) especially valuable. A positive impact of marbling on tenderness has been advocated [19]. Considering the fats' melting temperature, their lubricative effect, and temperatures used for meat preparation and serving, it can be further hypothesized that higher marbling will also improve perceived juiciness and impact oral processing.

Several different mechanical tests are used for meat quality evaluation [20,21]. One of the oldest and, nowadays, broadly accepted is the Warner-Bratzler shear force test [22], which describes a standard procedure [23]. This test has been used for muscle fiber strength quantification [24], while its results (maximal shearing force) have been correlated with sensorially perceived texture parameters [25]. Texture profile analysis (TPA) is another popular test used for meat texture analysis and prediction that tends to mimic subsequent two chews, in that way providing several parameters (i.e., hardness, springiness, adhesiveness, cohesiveness, chewiness) [26]. Even though these two tests are widely accepted, the literature review suggests a great diversity of applied testing conditions and sometimes their misuse, e.g., reporting the penetration test as the TPA [27]. Thus, the need for a better understanding of mechanical and sensory definitions and the need for standard testing procedures appear. Besides the Warner-Bratzler and TPA tests, tensile and penetration tests also found application for meat mechanical testing. The tensile test has been used to quantify both fiber strength and adhesion between fibers, depending on the direction of applied deformation [28,29]. The penetrometer test also has been used for adhesion measurements [24]. Other biophysical methods also found application for meat quality assessment [30]. Good examples are applications of near-infrared spectroscopy for predicting the beef sensory hardness and tenderness [31] and proton NMR relaxometry for assessing the state of the water in meat [32], which could be a crucial indicator for predicting sensory juiciness.

Meat analogs are structured using several different technologies. Cultivated meat is produced based on the process of muscle cell replication under controlled conditions. This (pilot) product has disadvantages primarily because of the exclusively high costs of production, but also lack of sensory qualities resembling real meat [5]. Poor sensory quality and low acceptance by consumers are issues of insect-based meat analogs [8]. Otherwise, although slightly more expensive than real meat products, meat analogs produced using textured plant-based proteins (e.g., soy, pea, wheat, peanut, or their blends) are already present on the market and accepted to some degree, although their sensory quality needs improvements. A recent review [33] was on plant-based protein processing technologies for meat analogs production. They recognized two classes of methods used for plant protein texturization, i.e., bottom-down strategies focused on resembling meat fibrousness on a macro scale (extrusion, shear cell technology, and freeze texturization), and bottom-up technologies focused on meat microstructure resemblance (spinning technologies, tissue engineering, and fermentation of filamentous fungi).

However, even though some of these technologies are promising, extrusion is the most frequently used technique to produce meat-like products. For the extrusion process, the vegetable flours or their blends are moistened to a certain degree and undergo a combination of pressure, heat, and mechanical shear inside the extruder. As a consequence, protein polymerization occurs, leading to the formation of layered fibers aligned in parallel with the mass flow direction [33].

The recent publications related to the meat analogs' structure and mechanics examinations witness lessons that have been learned from meat analysis. Table 1 denotes methods used for assessing meat analogs' structural and mechanical properties, as well as the purpose of their application and information obtained.

Table 1. Methods used for assessing meat analogs' structure and mechanics

	Method	Analyzed properties	Application
Mechanics	Compression test	Young's modulus Hardness Chewiness	Examinations of the extrusion parameter [34,35] and binding agent influences [36]
	Tensile test	Young's modulus Tensile strength Anisotropic index	Examinations of the extrusion and feed parameter influences [37][38]
	Shearing test	Maximal shearing force Texture index	Comparison of meat analogs and real meat prepared in sous-vide [39], oyster mushroom protein addition influence on meat analog quality [40]
	Puncture	Penetration force	Effect of binding agents on sausage analog quality [35]
	Texture Profile Analysis (TPA)	Springiness, cohesiveness, gumminess, hardness, chewiness	Examinations of the extrusion parameter influences [41]
Structure	Microscopy (light, scanning electron, laser scanning)	Microstructure and anisotropy	Examinations of extrusion parameter influences and blend ratios in feed [34,37,38]
	X-ray microtomography	Structure porosity (air incorporation)	Blend comparisons [37]
	Nuclear magnetic resonance (NMR)	State of the water	Influences of processing parameters and feed [42,43]
	Fourier infrared spectroscopy	Protein secondary structure	Influences of processing parameters and feed [43]

The literature review of 20 papers published during the past 20 years indicates that meat analog structures and mechanics were recently investigated mainly through the impact of the processing factors (e.g., cooking temperature, screw speed, cooling dynamics, feed composition, the addition of binding agents) on their quality. However, several studies are distinguished based on their approach. Recent research dealing with the examination of different moisture and wheat gluten contents applied an original approach in studying retention of volatile flavor substances, microstructure, moisture distribution, and secondary protein structures of meat analogs [43]. For that purpose, the authors used combined gas and mass chromatography, scanning electron microscopy, low-field NMR, and Fourier transform-infrared (FT-IR) spectroscopy. The results have shown the potential for adjusting blends and processing parameters to achieve desired microstructure properties that further impact volatile retention. This study also opens new questions that could be an entrance for future research, e.g., how do these

structures behave during the oral processing, what are the profiles of sensorially perceived volatiles, or their *in-vivo* release. Answering these should further improve meat analog consumption and perception and reduce the gap between real meat and analogs.

Several factors impact obtaining representative samples for meat mechanical testing, e.g., muscle anatomical position, animal breed, sex, age, pre-, and post-mortem factors. To obtain a better image of meat and meat analogs' mechanical properties, a novel method has been presented [44]. It is based on measuring Young's modulus of the sample using a spherical probe of a small diameter (1 mm, corresponding to the muscle bundle diameter) continuously for the area under scrutiny (300 mm²), by conducting the measurements in small steps corresponding to the half of the probe's diameter. The results provide images for a broader understanding of meat/meat analog mechanics related to their structure. That can be a powerful tool in analyzing meat and tailoring meat analogs.

An older study proposed a new method for quantifying the fibrous nature of meat analogs using fluorescence polarization spectroscopy [45]. Another introduced image processing for the same purpose, simplifying the data curation and examination execution [46].

4. Oral processing and sensory perception of meat and meat analogs

Food oral processing and sensory perception are in a tied relationship. As mentioned, previous studies covered sensory attributes' importance for meat and meat products' quality appreciation. It was found that tenderness, juiciness, and flavor play a crucial role. However, less is known about dynamic sensory perception. A few reasons are recognized as the cause for that.

Time-intensity (TI), as one of the oldest dynamic sensory methods, has been applied for meat evaluations. However, since it can be considered a time-consuming method, bearing in mind that one or eventually two attributes can be evaluated simultaneously [47], TI may not be a suitable method for deeper understanding of meat and meat analogs' dynamic sensory perception. Temporal Dominance of Sensations (TDS) and Temporal-Check-All-That-Apply (TCATA) are methods that improved on TI by allowing simultaneous selection of several (dominant or present) attributes at a time. Their parallel application with oral processing for meat revealed new information for bolus formation and sensory perception correlation.

TCATA has found its application for commercial ham evaluation [48], showing that the fibrousness is related to the in-mouth sample fragmentation, while the perceived juiciness was linked to the saliva incorporation. TDS application has been used to assess the influence of cooking [49] and Wagyu beef fattening periods [50] on dynamic sensory perception. The changes in perception during the consumption (from hard or firm at the beginning, through fibrous and juicy, to soft at mastication end) were revealed, which witnesses the expediency of applying TDS for a broader understanding of eating experience.

There is a slightly higher number of publications than dynamic sensory studies covering meat oral processing. It was found that the meat cooking method [49], preparation temperature/time combinations [51], and muscle anatomical position and aging [52] impact oral processing, as well as the correlations between it and mechanical parameters (e.g., shear force). Further investigations showed that harder meat would also be differently orally processed, implicating the differences in bolus properties [53], and hypothetically, sensory perception – in line with the previous explanation. Oral processing is even more complex when considering the individual character of mastication [54], and thus, perception.

To the best of our knowledge, there have not been any studies published on meat analogs' oral processing and dynamic sensory perception (and including comparisons with real meat).

5. Conclusion

Following the literature findings, we underline three main conclusions. Firstly, there is room for meat analogs. However, their sensory perception needs to be significantly improved. Secondly, meat structure and mechanics methods of analysis are well established, even though there are some inconsistencies in the literature. They are a good reference point for examining meat analogs and are already implemented to a certain degree for these products. Thirdly, there is a lack of information about meat and meat analogs' oral processing and dynamic sensory perception due to the limited number of publications,

which also can be recognized as an opportunity for future research. Last but not least, recruitment, training, validation and performance analyses of panels involved in both sensory and oral processing studies have to be performed, as these evaluation tools involve human subjects [55]. Finally, we suggest a holistic approach encompassing different classes of methods discussed herewith, with the aim of improving meat analogs' quality.

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