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Review

A framework for reporting texture profile analysis in cultivated meat research☆

Alice Millbank [a,b], Travis Callue [b], Anna-Marie Stobo [c], Jason M. Thomas [d], Paul D. Topham [a], Mariana Petronela Hanga [e], Jean-Baptiste R.G. Souppez [f], Eirini Theodosiou [a,*]

[a] Aston Institute for Membrane Excellence, Aston University, Birmingham, UK
[b] Rooted Research Collective, St Paul's Place, St Paul's Square, Birmingham, UK
[c] CPI, The Coxon Building, John Walker Road, Sedgefield, County Durham, UK
[d] School of Psychology, Health and Clinical Sciences, Aston University, Birmingham, UK
[e] Department of Biochemical Engineering, University College London, London, UK
[f] Department of Engineering, School of Architecture, Built Environment, Computing and Engineering, Birmingham City University, UK

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ABSTRACT

Cultivated meat could enhance global food security but public acceptance is closely linked to emulating conventional meat texture. Texture profile analysis (TPA) is commonly used to assess the textural properties of meat; however, methodological inconsistency and incomplete reporting limit comparability across cultivated meat studies. This review critically examines 41 studies applying TPA to cultivated meat and fish, identifying substantial variation in sample dimensions, test parameters, sample cooking protocols, and metric selection. Despite this variability, partial convergence was observed in certain practices, including frequent use of strain values of 0.5 and prioritisation of hardness and springiness amongst reported metrics. Building on these observations and established guidance from meat science and polymer testing, we propose the BIOPLATE framework - a reporting-focused checklist designed to improve transparency and cross-study comparability. Adoption of clearer reporting practices will strengthen texture evaluation and support integration into sustainable food systems.

1. Introduction

Cultivated meat has existed in public awareness for some time, with fictional depictions of meat grown outside of the animal body dating back to the 19th century (Lane, 1880), however, the first official meeting of the "In Vitro Meat Consortium" was held over 125 years later (2008) at the Food Research Institute in Norway (Stephens, 2010). Five years later in 2013, the first cultivated meat proof-of-concept was presented to the media (Post, 2014), marking a significant technological breakthrough in the food industry. Products derived from cellular agriculture aim to provide sustainable, ethical, healthy, and widely accepted alternatives to conventional meat, addressing concerns over environmental impact, animal welfare, and public health risks (e.g. zoonotic diseases and antibiotic resistance) (Crippa et al., 2021; United Nations Environment Programme, 2023). They also respond to mounting global pressures; as the world population approaches 10 billion, protein demand is projected to rise significantly, particularly in rapidly growing markets across Asia and Africa (Innova, 2024; United Nations Environment Programme, 2023.

However, the success of cultivated meat ultimately depends on public acceptance. The sensory properties, including texture, in particular, significantly influence how the public perceives the overall quality of food products (Dar & Light, 2014; De Araújo et al., 2022; Reicks et al., 2011). As such, achieving products with the same familiar texture is key. In fact, several sensory perception studies have shown that meat alternatives that best emulate conventional meat texture are far more likely to gain widespread acceptance (Hoek et al., 2011; Konrad et al., 2024; Michel et al., 2021; Schouteten et al., 2016).

Significant progress has been made ex vivo to closely mimic the structure of meat tissue, including the implementation of co-culture techniques (Wang, Zhong, et al., 2024) and the creation of whole cut analogues by assembling cell fibres using tendon-gel integrated bioprinting (Kang et al., 2021). 3D scaffolds can provide a supportive framework for cellular growth and organisation by mimicking the native

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* Corresponding author at: Aston University, Birmingham, B3 7ET, UK.
E-mail address: e.theodosiou@aston.ac.uk (E. Theodosiou).

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extracellular matrix found in living tissue, contributing to the desired texture of cultivated meat (Bomkamp et al., 2022). For partially processed products such as mince or burgers, large-scale stem cell production efforts have focused on improving texture through the use of edible microcarriers (Hanga et al., 2025; Norris et al., 2022; Ogawa et al., 2022). These high surface area-to-volume scaffolds are designed to enhance the efficiency of cell culture as well as the organoleptic (sensory) properties of the final product (Hanga et al., 2025).

Variance in the methodology of creating cultivated meat will affect the structure of the end product in complex ways, impacting both cellular organisation and overall tissue architecture (MacQueen et al., 2019; Yoshida et al., 2025). For example, MacQueen et al. (2019) found that cultivated beef and rabbit prototypes demonstrated notable textural differences compared to their conventional whole cut counterparts, despite exhibiting good microscopic alignment. This was attributed to the lack of densely packed tissue usually seen in conventional meat. Therefore, although advances in cellular agriculture have been made, replicating the complexity found in conventional meat remains a significant challenge, particularly when producing whole cuts. By contrast, finely comminuted products, such as sausages and nuggets, as well as partially processed products, such as mince or burgers, may be easier to replicate. Their conventional production methods, including homogenisation, grinding, and mixing, naturally disrupt muscle fibre alignment and connective tissue structures, reducing the need for cultivated meat to mimic intricate architectures (Berger et al., 2022, 2023).

Accurate textural analysis methods are needed to ensure whole cut, partially processed, and finely comminuted cultivated meat products meet sensory expectations (Hoek et al., 2011; Michel et al., 2021). Several in-depth reviews have outlined the prevalence of mechanical tests employed to objectively assess the texture of conventional meat (Chen & Opara, 2013; Schreuders et al., 2021; Szczesniak & Torgeson, 1965). Amongst the most frequently used techniques (as shown in Fig. 1) are Warner-Bratzler shear force (WBSF; Fig. 1A), texture profile analysis (TPA; Fig. 1B) and tensile testing (Fig. 1C), each offering advantages and disadvantages with varying degrees of reproducibility and alignment with public perceptions (García-Segovia et al., 2014; Paredes et al., 2022; Solomon et al., 2010).

Mechanical properties, including textural properties, are highly directional (St. Pierre & Kuhl, 2024). Therefore, it is key to select a method that will apply forces in a similar manner to those the product will experience during mastication (i.e. compressive forces). WBSF has been widely applied in the textural analysis of both conventional and cultivated meat (Barlocco et al., 2006; Bomkamp et al., 2022; Cavitt et al., 2005; Cierach & Majewska, 1997). However, this method more closely matches the action of cutting meat, meaning it may be less representative of the chewing-related sensations that underpin public sensory perception and acceptance (De Huidobro et al., 2005; Novaković & Tomašević, 2017; Platter et al., 2003). Tensile testing provides valuable information regarding the extensional forces acting on a material, such as breaking strength, which would mimic the tearing of meat (Schreuders et al., 2021). However, it still does not directly replicate the dominant compressive component of mastication, and is therefore less relevant to sensory metrics[1] such as hardness, springiness, or chewiness.

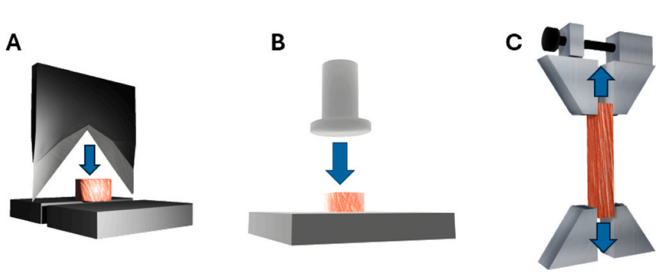

Fig. 1. Schematic drawings of commonly employed mechanical testing methods for both conventional and cultivated meat products: (A) Warner-Bratzler Shear Force (WBSF); (B) Texture profile analysis; (C) Tensile testing. Arrows indicate direction of force. Images created in Blender.

The TPA method has broad applications across whole cuts, partially processed, and finely comminuted meat, as well as analogue products, and TPA equipment is commonly found in food research labs (Bourne & Szczesniak, 1998). TPA applies a double compression force that more closely mimics mastication, evidenced by the strong link between measured properties and public acceptance studies (De Huidobro et al., 2005; Novaković & Tomašević, 2017). The benefit of using TPA to provide a more representative quantification of organoleptic properties in cultivated meat research is evident, therefore TPA is the focus of this review.

In highlighting TPA's potential, it is useful to compare its current lack of formal standardisation with the highly specific guidance available for other materials and mechanical testing methods. For example, the International Organisation for Standardisation (ISO) has developed mechanical testing protocols and testing environments for rigid and semi-rigid materials via tensile and compression testing respectively: ISO 527, ISO 604, and ISO 291 specify conditions such as 23 °C (± 2 °C), 50% (± 10%) relative humidity, uniform cross-sectional area, and standardised strain rates depending on the property being measured (International Organization for Standardization (ISO), 2002; International Organization for Standardization, 2008; International Organization for Standardization (ISO), 2019). Similarly, WBSF testing benefits from detailed standardisation, including precise blade specifications (e.g. 1.1684 mm thickness, 60° V-notch) and defined sample dimensions (e.g. 12.7 mm or 52.4 mm diameter cylinders), which must be followed for the test to qualify as true WBSF (Novaković & Tomašević, 2017). The American Meat Science Association (AMSA) has also published recommendations on cooking procedures and sample sizes for WBSF testing (AMSA, 2015; Chen & Opara, 2013).

In contrast, progress towards such standardisation for TPA test parameters for meat, or indeed any food product, has been extremely limited, despite this shortcoming being highlighted numerous times over decades (Barbut, 2015; Breene, 1975; Chen & Opara, 2013; Dunne et al., 2025 ; Schreuders et al., 2021). One of the few attempts to improve methodological consistency was made by Barbut (2015), who reviewed TPA procedures for meat and highlighted how inconsistencies in strain, displacement rate, and sample geometry hinder comparability between studies. Barbut (2015) proposed general reference conditions and reporting practices to enhance reproducibility, though these were never formalised. Building on this, Novaković and Tomašević (2017) provided quantitative recommendations for TPA test parameters in both whole cut and processed meat. However, despite these efforts, subsequent reviews continued to report methodological inconsistencies, and no formal standards have yet been proposed for the application of TPA to cultivated meat (Dunne et al., 2025; Schreuders et al., 2021).

Specifically, this review critically examines the use of TPA in cultivated meat research. It begins by outlining the approach taken whilst providing an overview of research activity in the field. It then investigates how the double compression method has been applied to assess texture across different cultivated meat formats and, in many cases, to compare them with conventional meat. Key variables are reported, including species, tissue type, scaffold usage, sample conditions (e.g. storage method, cooking state), and test parameters (e.g. strain, displacement rate), as well as reported metrics (e.g. hardness, springiness). Variables were benchmarked against conventional meat literature and existing standards, typical for related mechanical tests, such as ISO

[1] In this review, terms such as "hardness", "springiness", and "chewiness" are referred to as textural metrics or properties, rather than "parameters". This distinction is made to avoid confusion with mechanical or instrumental parameters (e.g. strain, displacement rate) that define the test conditions in TPA.

standards and AMSA guidelines (AMSA, 2015; International Organization for Standardization (ISO), 2019, 2020). This review also identifies methodological commonalities and variation, highlighting areas where standardisation is lacking and relevant test parameters are frequently underreported. Finally, it proposes practical, evidence-based reporting guidance to support standardisation efforts in textural analysis, ultimately facilitating the development of commercially viable cultivated meat products with greater potential for public acceptance.

2. Literature selection approach

To inform this critical review, relevant literature was identified primarily through searches on Web of Science, ScienceDirect, Google Scholar, and PubMed Central. Boolean operators were used to combine and refine search terms. The primary query was ("texture profile analysis" OR "TPA" OR "texture analysis") AND ("cultivated meat" OR "cultured meat" OR "cell-based meat" OR "in vitro meat" OR "clean meat" OR "cultivated fish"). Additional searches incorporated terms such as "meat analogue*", "meat alternative*", and "lab-grown meat", as well as texture-related properties (e.g. "hardness", "chewiness", "springiness") to capture relevant studies that did not explicitly reference TPA. The term "double compression test" was also searched to identify studies referring to the method by its mechanical testing procedure rather than its conventional name.

Searches included full text indexing where available (e.g. ScienceDirect) to maximise coverage beyond titles, abstracts, and keywords. No date restrictions were applied, and only peer-reviewed studies were considered. Studies were selected based on their relevance to the review's focus on textural characterisation of cultivated meat and/or fish, with particular emphasis on those that reported primary TPA data. The literature search was current as of the 14th of January 2026. No eligible studies published prior to 2019 were identified. A total of 41 scientific papers meeting these criteria were identified.

Whilst some broader literature on scaffolding materials and plant-based analogues was also considered to contextualise findings, only studies involving actual cultivated animal cells were included in direct comparisons of mechanical parameters. Studies were excluded if they did not report original data or focused solely on in vitro scaffolds without cellular components. Where available, relevant methodological details were extracted to facilitate critical comparison.

In order to highlight possible commonalities and correlations amongst the various works, exploratory association rule mining (ARM) was applied as a supplement to the discussion of observations in the data, wherein information from the studies was collated, manually standardised, and converted to binary format using one-hot encoding. The Apriori algorithm was implemented in Python to extract association rules from the encoded data. For each rule, key metrics (support, confidence, and lift) were generated to assess frequency, reliability, and strength of the association rules. Rules were further evaluated based on domain relevance and interpretability rather than purely on metrics alone. For a rule of the form $A \rightarrow B$, (where A is the antecedent and B is the consequent):

- $P(A \cup B)$ is the probability that A and B both occur
- $P(B \mid A)$ is the conditional probability of B occurring, given that A occurs
- $P(A)$ is the probability that A occurs
- $P(B)$ is the probability that B occurs

Mathematical definitions of support, confidence, and lift (Zhang et al., 2019) are as follows:

- $\text{Support}(A \rightarrow B) = P(A \cup B)$
- $\text{Confidence}(A \rightarrow B) = P(B \mid A)$
- $\text{Lift}(A \rightarrow B) = P(A \cup B) / (P(A) \times P(B))$

2.1. Temporal and geographical distribution of studies

To provide an overview of research activity in this field, Fig. 2 illustrates the number of publications relevant to this review per year. A clear increase in studies was observed in recent years, particularly from 2022 onwards, bearing in mind that the time of writing for this review was January 2026. This reflects trends in the wider field of textural analysis, as the number of publications relevant to "food texture" were noted to have doubled between 2002 and 2012 (Chen & Opara, 2013). The geographical distribution of studies (based on the institutional affiliation of the first author), indicated that research was primarily concentrated in the People's Republic of China (61%), followed by the Republic of Korea (17%), and the Republic of Singapore (10%). Japan, Israel, the United States of America, Mexico, Spain, and the United Kingdom were attributed to 2% (each) of the reviewed studies.

Research activity was mostly concentrated in countries that regard the diversification of protein sources as both a means to enhance food security and reduce import dependence, and that are also advancing most rapidly towards cultivated meat commercialisation. For instance, Singapore, the first nation to approve and commercialise cultivated meat, continues to expand its regulatory and consumer frameworks as part of a broader food security agenda aimed at reducing reliance on imports and building domestic production capacity (Singapore Food Agency, 2024). China has embedded cultivated meat within its national policy goals (UNDP, 2021), whilst Korea is advancing its own regulatory frameworks (MFDS (Korean Ministry of Food and Drug Safety), 2024).

These temporal and geographical patterns illustrate how research activity in cultivated meat texture analysis has expanded and diversified in recent years. To better understand the biological focus and research priorities underlying these textural studies, the following section examines the diversity of species represented across the literature.

2.2. Range of meat types tested

Fig. 3 categorises the textural studies based on the species of cultivated meat tested, and contrasts with data pertaining to global meat consumption. For the period 2022–2024, OECD/FAO (2025) reported that poultry was the most widely consumed meat in high income countries (with a consumption rate of 21.96 kg per person per year). This was followed closely by pork (21.83 kg) and beef (13.16 kg), with sheep consumed at substantially lower levels (1.02 kg). In upper middle-income countries for the same period, pork was the most consumed (17.36 kg), followed by poultry (13.78 kg), beef (6.81 kg), and sheep (1.84 kg). Amongst the reviewed studies, pork was the most frequently used for textural analysis (49% of all studies), followed by beef (27%) and chicken (10%), whereas no studies used sheep.

Furthermore, meats that are less commonly consumed occasionally appeared in some of the papers reviewed, such as rabbit (5%). In addition, rat-derived cells were used in one study (Tang et al., 2024), which is an unusual choice given the intended applications for cultivated meat. Nevertheless, although it was not explicitly mentioned, this may be attributed to an abundance of pre-existing work on rats as model organisms (Smith et al., 2019). Similarly, Yang et al. (2025)'s use of mouse myoblasts likely reflects their status as a well-established, easy-to-culture skeletal muscle model for proof-of-concept tissue engineering studies (Ikeda et al., 2017).

The focus on pork, despite poultry being more widely consumed globally, could be attributed to both biological and regional socio-economic factors. Porcine cells share a closer genetic proximity to human cells than those of other farmed species, allowing researchers to leverage the extensive stem cell literature derived from human models, which can be more readily applied to cultivated pork development (Xuan et al., 2023). Furthermore, the majority of pork-related studies were conducted in China, where pork represents approximately 60% of national meat production and accounts for nearly half (49%) of global

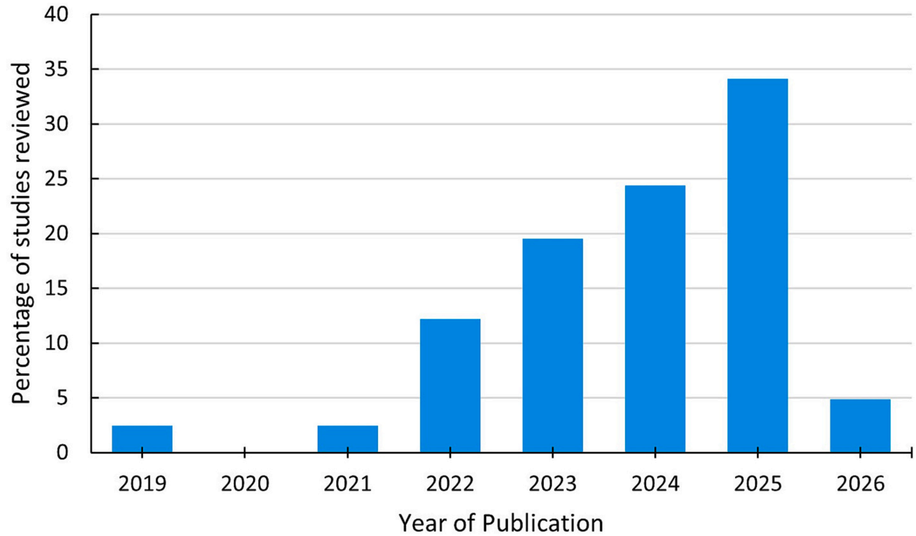

Fig. 2. Percentage of studies (on TPA application to cultivated meat) reviewed herein by year of publication. Nb: literature search was current as of January 14th 2026.

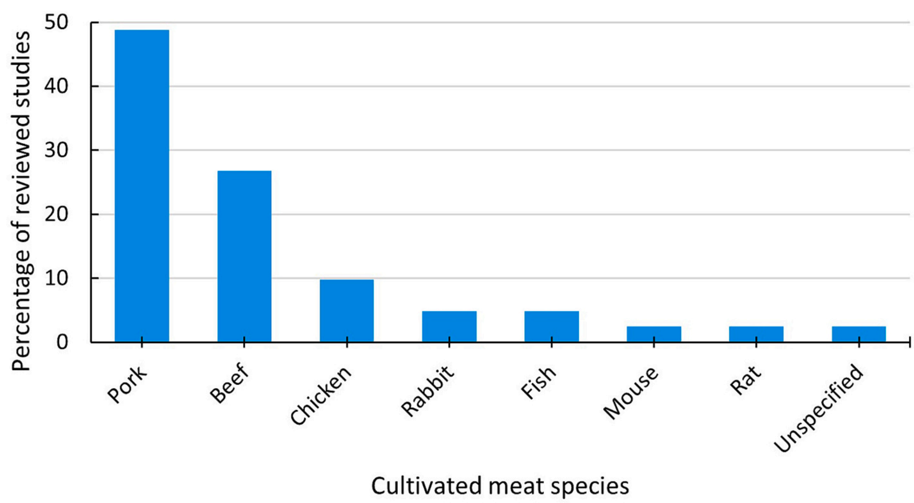

Fig. 3. Variance of cultivated meat species produced across reviewed studies.

pig meat output (OECD and Food and Agriculture Organization of the United Nations, 2024; USDA Foreign Agricultural Service, 2024). Pork holds deep cultural and economic significance in China and remains a dietary staple, with outbreaks such as African swine fever highlighting the vulnerabilities of conventional production systems (OECD and Food and Agriculture Organization of the United Nations, 2025). Accordingly, the development of cultivated pork aligns closely with China's broader ambition to enhance self-reliance and resilience in its food system (UNDP, 2021).

Across the reviewed studies, only 5% focused on fish, whereas the rest examined terrestrial meats, not only highlighting a significant underrepresentation of marine species in cultivated meat TPA research, but in cultivated meat species as a whole. Mentions of cultivated fish technology are absent in recent review texts of cultivated meat (Post, 2014; Stephens & Ellis, 2020), a review of over 100 companies active in, or related to, the cultivated meat space noted only 5 companies focused on cell-based seafood (Mellon, 2020). However, industry activity suggests cultivated seafood is an emerging and expanding category; GFI's alternative protein company database lists 2099 companies (at time of writing), including 284 entries categorised as “cultivated”, of which 79 (28%) are geared towards seafood (Good Food Institute, 2026). Given that TPA is already well established for conventional fish, its broader adoption in cultivated seafood research is critical for benchmarking against conventional products and for guiding texture optimisation in this emerging category (Bruni et al., 2020; Lin et al., 2012; Monteiro et al., 2019; Wang et al., 2019).

This overview highlights how research on cultivated meat texture has evolved across regions and species, reflecting national priorities and broader food system objectives. However, although research activity has expanded rapidly, methodological differences limit direct comparison. The next section therefore explores TPA in detail, outlining its principles, instrumentation, measurable properties, and relevance to cultivated meat texture assessment.

3. Texture profile analysis

3.1. Principles and equipment

TPA first emerged in the 1960s when Dr. Alina Szczesniak introduced the General Foods Texture Profile and General Foods Texturometer, aiming to establish repeatable texture measurements across various food types and laboratories (Brandt et al., 1963; Friedman et al., 1963). The method was soon applied to meat samples and has since been widely adopted in the meat industry, alongside advancements in dedicated texture analysis equipment, such as the TA.XTPlus Texture Analyser (Szczesniak et al., 1963).

Bourne (1968) later adapted TPA for use with universal testing machines (UTMs), following techniques that largely adhered to the original procedures of Friedman et al. (1963). This adaptation made TPA more accessible to researchers without specialised texture analysers. However, dedicated texture analysers appear to be the preferred choice for cultivated meat texture evaluation. 61% of studies reviewed herein used texture analysers from Stable Micro Systems, whilst only one study employed a UTM (Paredes et al., 2022) and one used a rheometer (MacQueen et al., 2019).

TPA allows for quantification of multiple textural properties from a single experiment, providing a broad, information-rich dataset (De Huidobro et al., 2005). The next section describes how the method quantifies these key properties from force-time data, which enable the translation of mechanical responses into sensory-relevant metrics.

3.2. *Quantification of textural properties*

TPA simulates the mastication process by subjecting a sample to two compressive cycles and measuring its response to the applied forces. Each compression cycle captures force-time curves (see Fig. 4) that determine the primary properties (Table 1). These include hardness (F_1), which represents the peak force during the first compression and is indicative of initial bite resistance, and springiness (S), which reflects the sample's ability to recover its shape between cycles. Cohesiveness (C_o) is determined from the energy absorbed across both compressions and describes the internal structural integrity, whilst adhesiveness (A) measures any negative force during withdrawal, signifying stickiness. Additionally, resilience (R) quantifies recovery after deformation and fracturability (F_f) measures the degree to which a solid food sample resists breaking.

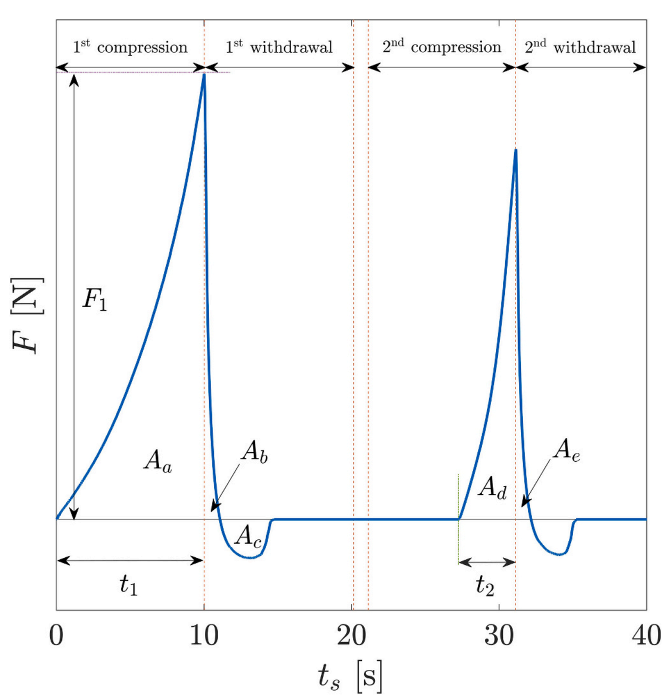

Fig. 4. An example of a force-time curve obtained from TPA, illustrating two compression and withdrawal cycles separated by a 1 s pause. The diagram defines key properties, including hardness (F_1), time points (t_1 and t_2) and areas (A_a, A_b, A_c, A_d and A_e) used to calculate other metrics. Used with permission from Souppez et al. (2025).

Table 1
Summary of primary and secondary textural properties derived from TPA of conventional and cultivated meat samples. Primary properties are directly measured mechanical responses from the double compression test, whilst secondary properties are calculated from primary properties. Definitions and corresponding equations are provided (Rahman et al., 2021; Souppez et al., 2025; Szczesniak, 1963).

Textural Measurement	Definition	Equation	Expressed as / expected units
Hardness	The maximum force required to compress a sample during the first bite, reflecting its stiffness and initial resistance to deformation.	$H = F_1$	Force (Newtons, N)
Adhesiveness	The force required to overcome the attractive forces between the surface of a sample and the surface of another material when the sample is pulled away.	$A = A_c$	Work (Area under force-time curve, N s)
Cohesiveness	The degree to which the sample can be deformed and still maintain its integrity, calculated as the ratio of the area under the force-time curve of the second compression cycle in comparison to the first cycle.	$C_o = \frac{A_d + A_e}{A_a + A_b}$	Ratio (Dimensionless, no units)
Springiness (formerly elasticity)	The ability of a sample to regain its original shape between compression cycles, quantified as the ratio of the time taken to reach maximum force during the second downstroke relative to the first.	$S = \frac{t_2}{t_1}$	Ratio (Dimensionless, no units)
Resilience	The ability of a sample to resist deformation during the initial compression cycle, calculated as the ratio of the area under the curve during the first withdrawal phase to that of the first compression phase.	$R = \frac{A_b}{A_a}$	Ratio (Dimensionless, no units)
Fracturability (formerly brittleness)	The degree to which a sample resists fracture under applied force, which is measured where the peak force falls during the first compression cycle. Only applicable to solid foods.	$F_f = \max(F)$	Force (Newtons, N)
Chewiness	The energy required to disintegrate a solid food sample, calculated as the product of hardness, cohesiveness, and springiness. It	$C_h = \frac{F_1 t_2}{t_1\left(\frac{A_d + A_e}{A_a + A_b}\right)} = HSC_o$	Force (Newtons, N)

(continued on next page)

Table 1 (*continued*)

Textural Measurement	Definition	Equation	Expressed as / expected units
Gumminess	represents the resistance of the sample to breakdown during mastication. The energy required to disintegrate a semi-solid food, calculated as the product of hardness and cohesiveness. It represents the resistance of the sample to breakdown during mastication.	$G = F_1\left(\frac{A_d + A_e}{A_a + A_b}\right) = HC_o$	Force (Newtons, N)

The properties directly calculated from the force-time plot (Fig. 4) also serve as the basis for calculating secondary metrics, which are derived combinations of the primary outputs: chewiness (C_h) integrates hardness, cohesiveness, and springiness to quantify the effort required to break down a solid sample during mastication; gumminess (G) relies on just hardness and cohesiveness to assess the same characteristic in semi-solid foods (Rahman et al., 2021; Szczesniak, 1963).

3.3. TPA metrics for meat and cultivated meat

3.3.1. Trends in reported metrics for cultivated meat studies

Although Table 1 summarises several commonly reported TPA properties, notable inconsistencies remain in how these properties are interpreted, calculated, and reported. The choice of which metrics to report ultimately lies with individual researchers, and debate continues regarding which properties are most appropriate for different food categories (St. Pierre & Kuhl, 2024). This places responsibility on researchers to understand how each metric functions within the context of their study. Not all TPA properties are universally applicable, and using metrics that are not appropriate for meat can lead to misleading or uninformative results. Each food category exhibits characteristic textural attributes, and the choice of metrics should reflect this. Meat texture has been cited as comprising hardness, gumminess, resilience, cohesiveness, springiness and adhesiveness (Novaković & Tomašević, 2017), though this list is neither exhaustive nor standardised. Fig. 5 provides a visual representation of the coverage of these TPA metrics across the reviewed literature, illustrating the relative frequency with which each property was reported.

Hardness is strongly related to sensory texture in bovine meat (De Huidobro et al., 2005) and effectively differentiates burger-style products (Souppez et al., 2025). It is the most widely measured TPA metric in cultivated meat studies, appearing in 95% of cases, reflecting its established sensory relevance and commercial importance (De Huidobro et al., 2005; Szczesniak et al., 1963). However, because hardness is highly sensitive to sample geometry, compression rate, and strain (limiting its reliability as a comparative metric across studies), Dunne et al. (2025) and St. Pierre and Kuhl (2024) propose modulus as a more robust comparative metric. Although not typically reported in TPA, modulus can be calculated directly from existing datasets, since the stress can be ascertained by dividing the force (hardness) by the cross-sectional area of the sample, and strain is equal to the degree of displacement (Dunne et al., 2025; Richbourg et al., 2022). A metric derived from a simple stress-strain plot, therefore, offers clearer interpretation and reduces inconsistencies in TPA reporting, particularly given the sensitivity of meat texture measurements to test conditions (Mittal et al., 1992). Despite these advantages, modulus has not yet been adopted in cultivated meat TPA studies. Nevertheless, there is little downside to additionally reporting modulus where feasible, as it may support clearer cross-study comparisons.

Chewiness is also linked to sensory texture (De Huidobro et al., 2005) and is frequently reported alongside hardness, with both metrics measured in 88% of studies. Both metrics are particularly effective for differentiating burger-style meat products, reinforcing their importance as outcome-orientated metrics for structured and processed cultivated meat formats (Souppez et al., 2025). Chewiness often appears together with gumminess (56% of studies), although the two metrics were

Fig. 5. The percentage of studies that reported each TPA property, highlighting the most and least commonly assessed metrics.

originally intended for different material classes (chewiness for solid foods and gumminess for semi-solids), meaning both may not be meaningful for the same sample.

Springiness, measured in 85% of studies, reflects a product's ability to recover its shape after compression (Szczesniak, 1963). It is influenced by fat, protein, and moisture content, making it useful for comparing raw and cooked meat and for tracking changes during ageing (Bulgaru et al., 2022; Mabrouki et al., 2023; Souppez et al., 2025; Wee et al., 2018). Therefore, as advancements continue in the downstream bioprocessing of cultivated meat, springiness may become an increasingly important factor to consider. Adhesiveness is similarly influenced by protein and fat levels, making both metrics valuable for analysing ingredient composition (Le Foll et al., 2024; Wambui et al., 2017). Furthermore, springiness and adhesiveness can be viewed as valuable additional descriptors when evaluating the texture of co-cultured meats that incorporate both fat and muscle cells. Despite this, all three studies that analysed co-cultured cultivated meat prototypes measured springiness, yet none assessed adhesiveness (Guan et al., 2025; Lee et al., 2024; Murugan et al., 2024).

Cohesiveness appeared in 73% of studies, making it one of the more commonly reported metrics. Resilience, adhesiveness, and fracturability were rarely measured, with the latter appearing in only 4% of cultivated meat studies. This is understandable, as fracturability describes the force required to break rather than deform a sample (Szczesniak, 1963) and is more applicable to brittle foods, such as jerky or dry-cured meats (Smith, 1991). Its occasional appearance may reflect reliance on default instrument macros rather than intentional metric selection.

3.3.2. Terminology and units

In addition to differences in the selection of reported properties, variability was also observed in the terminology and units used to describe TPA outputs. Multiple terms are sometimes used interchangeably across the literature to describe similar mechanical concepts, which can introduce ambiguity when definitions are not explicitly stated. For example, legacy terminology (e.g. elasticity) continues to appear alongside more widely adopted TPA terms (e.g. springiness), and in some cases alternative descriptors are used that appear to map onto established parameters. In such instances, providing clear definitions or equations would support interpretability and reduce potential confusion across studies.

Variation was also noted in how TPA metrics were quantified and reported. A small subset of studies, for example, described hardness as stress rather than force, standardising the measured force by sample cross-sectional area. Whilst both approaches are valid, reporting stress requires the associated sample geometry to be specified to ensure comparability across studies. In addition, variability was evident for other TPA metrics. In several cases, units were omitted entirely, or alternative representations (e.g. energy-based units or dimensionless notation) were used. Such differences are not inherently incorrect, provided the calculation method is clearly defined and supported by sufficient methodological detail.

Springiness provides a further example of definitional variability. Whilst commonly expressed as a ratio derived from either time or distance during the recovery phase of the TPA test, only a minority of studies explicitly stated which definition was applied. Both approaches quantify elastic recovery behaviour, and no clear advantage of one over the other is evident; however, explicit reporting of the calculation method would improve transparency. The time-based calculation appears to have more traction in existing literature (Johnson, 2023; Rahman et al., 2021; Souppez et al., 2025; Szczesniak, 1963), as well as from key instrument manufacturers (Stable Micro Systems, n.d.-c), suggesting a degree of informal convergence.

3.3.3. Influence of species, tissue type, and composition on metric suitability

It has been demonstrated that textural profiles vary across species, tissue types, and even between breeds within the same species (Tu et al., 2025). Thus, rather than attempting to establish a universal set of criteria applicable to all cultivated meat studies, it may be more realistic to promote the consistent use of a small core set of TPA metrics, alongside additional properties reported as appropriate for specific product formats. In this review, the most defensible core set comprises the primary metrics (hardness, springiness, and cohesiveness) which also enable calculation of commonly used secondary metrics. To further support interpretability and comparability, studies could also provide force-time curves, allowing readers to contextualise derived parameters and assess curve features that may not be captured by summary metrics alone.

Beyond this core set, the selection of additional texture properties should be guided by tissue composition and intended meat format. For example, fat contributes to texture, juiciness, and mouthfeel in conventional meat, and its controlled inclusion in cultivated meat prototypes is expected to significantly influence measurable properties (Frank et al., 2016; Sarıçoban et al., 2009). Importantly, fat can behave as a semi-solid food component (Chen & Opara, 2013; Kealy, 2006; Novaković & Tomašević, 2017), which may affect the relevance and interpretation of certain TPA outputs, particularly those linked to mastication behaviour and the mechanical response of solid versus semi-solid foods (e.g. chewiness and gumminess, respectively; Rahman et al., 2021; Szczesniak, 1963). In this context, adhesiveness may represent a useful additional descriptor for fat-containing cultivated meat prototypes, given its relevance to mouth-coating and fat-related sensory attributes (Kealy, 2006; Godoi et al., 2019; Gonçalves et al., 2022). By contrast, hardness, springiness, cohesiveness, and resilience are broadly relevant across both solid and semi-solid foods (O'Sullivan, 2020; Gonçalves et al., 2022; Rashidi et al., 2016;Xu, Tao & Shivkumar, 2016; Yang et al., 2023).

Across the reviewed literature, 56% of the studies focused exclusively on muscle-based constructs, whereas only 7% investigated adipose tissue alone, 10% undifferentiated tissues and 5% co-culture systems in isolation. A further 15% of studies examined mixed tissue categories, most commonly combining muscle with adipose or undifferentiated components. One study also reported bone tissue differentiation (Jaime-Rodríguez et al., 2025), an unexpected choice given that off-the-bone meat, whilst discussed in conceptual models (van Mensvoort, 2014), was not the study's apparent aim.

Tissue type was reported in 95% of studies, often with detailed information on cell origin and composition. Within individual tissue categories, hardness and springiness remained near-universal, and chewiness was also frequently included, indicating that tissue composition (and the implied solid versus semi-solid nature of the sample) has not yet strongly shaped TPA metric selection. A notable gap is the inconsistent reporting of adhesiveness in adipose-focused and co-culture studies, despite its relevance to fat containing formats and the strong link between fat content and perceived meat quality (Frank et al., 2016; Xu et al., 2025). As cultivated fat becomes increasingly used to enhance mouthfeel, juiciness, and overall sensory performance in structured and hybrid products (Mellon, 2020), adhesiveness may become an increasingly valuable supplementary metric for capturing fat-enhanced textural effects.

A notable finding is the relatively high reporting of gumminess in muscle-based studies, despite the metric traditionally being associated with semi-solid foods. This may be reasonable in the context of cultivated meat and fish, as many muscle-derived foods, particularly fish fillets and other high-moisture tissues, can exhibit soft, gel-like mechanical behaviour, and many cultivated meat constructs rely on scaffolds with semi-solid characteristics (e.g. hydrogels or decellularised extracellular matrix), which may make gumminess a relevant descriptor (Carter & Bhattarai, 2013; Zamproni et al., 2021; Kim, Kim, Lee, Jang, et al., 2025). Indeed, 96% of studies reporting gumminess used scaffolds, though this should be interpreted cautiously given the limited number of scaffold-free studies. Gumminess may also appear simply because it is provided as a default output in instrument software (Kim,

Kim, Lee, Kim, et al., 2025), or because some prototypes are intended to resemble comminuted or restructured meat formats, where soft-solid to semi-solid mechanical behaviour makes the metric more appropriate than for steak-like structures.

In contrast to tissue type, species choice may influence which texture properties are emphasised due to inherent differences in tissue composition (Dransfield et al., 1984). Chewiness was reported particularly consistently in pork studies, whereas cohesiveness was more frequently reported in beef studies, though these patterns may reflect study design or reporting practices rather than species-specific differences. For example, cohesiveness may be especially informative for restructured or scaffold-supported constructs, where internal bonding strength is a key design consideration (Rahman et al., 2021). However, few studies clearly described the intended product format (e.g. "burger-like"; Yen et al., 2023), limiting interpretation of these trends.

In addition, the characteristics of the conventional reference samples also influence the comparability of cultivated and conventional meat measurements. In conventional meat, anatomical location strongly affects texture. For example, hardness in raw Atlantic salmon is significantly higher in the tail than in other regions (Jonsson et al., 2001; Sigurgisladottir et al., 1999), and beef texture varies substantially by cut (Ricardo-Rodrigues et al., 2024). However, most studies provided little or no information about the anatomical origin of their conventional comparators, limiting the interpretability of cross-system comparisons.

3.4. Structural organisation, degree of processing, and comparative benchmarking

It is also understood that textural profiles should be tailored not only across different food groups but also within format categories; for instance, finely comminuted, partially processed, and whole cut meat products, each display distinct mechanical behaviours. An approximate understanding of the sample's physical characteristics is therefore essential, as TPA yields more meaningful results when tailored to the specific meat matrix being analysed (Bourne & Szczesniak, 1998). In more processed or comminuted matrices, mechanical behaviour is influenced by the strength of internal bonding and the interactions of water within the matrix, rather than by aligned fibrous structures (Aguilera, 2019). In such cases, metrics such as adhesiveness (linked to surface properties and moisture content), gumminess (used to characterise semi-solid foods), and cohesiveness (reflecting the strength of internal bonding) are particularly informative (Bourne, 2002; Chen & Opara, 2013; Szczesniak, 1963). For example, Souppez et al. (2025) found that beef burgers typically exhibit higher cohesiveness than plant-based burgers, which are often perceived as more "mushy".

It is often unclear whether cultivated meat prototypes tested via TPA are intended to emulate whole cuts, partially processed products, or finely comminuted textures. Although the overwhelming majority of studies (88%) incorporated scaffolds, several of which produced three-dimensional structures, this does not necessarily imply an intention to mimic whole cut architecture, as some constructs may instead be designed for subsequent processing. In addition, microcarrier- and disc-based systems, where adherent cells are expanded on suspended microcarriers or larger disc-shaped carriers to increase available attachment surface area, are typically used to enhance proliferation for producing more processed or comminuted meat formats (Hanga et al., 2025), yet these approaches were represented in only 12% of the TPA studies analysed.

Nevertheless, most studies benchmarked cultivated meat samples directly against conventional whole cuts (e.g. beef steak or yellow croaker fillet) rather than more processed counterparts, reflecting either an aspiration towards whole cut replication or limited clarity in sample characterisation. In this context, metrics such as hardness, springiness, cohesiveness, and chewiness are well suited to capturing bite resistance and overall textural perception (Szczesniak, 1963), which likely explains why these were the most frequently measured properties across the studies analysed (Fig. 5).

Paredes et al. (2022) compared a cultivated frankfurter (species unspecified) against conventional frankfurters (species unspecified), partially processed turkey, and whole cut chicken, thereby offering a valuable comparative scale across processing levels. Selection of an appropriate comparative sample appears to be an area for optimisation, as 41% of studies did not include a conventional counterpart of the same species analysed in parallel. Whilst benchmarking against existing literature can be informative, TPA outputs are highly sensitive to test configuration and sample history, meaning that direct side-by-side testing under identical conditions provides a stronger internal reference and reduces confounding due to methodological and biological variability. Zhou et al. (2025) compared cultivated meat solely with plant-based analogues, which provides context within the wider alternative protein landscape; nonetheless, inclusion of a conventional comparator would have provided additional value.

Scaffolds themselves play a substantial role in defining the mechanical properties of cultivated meat. The majority (64%) of scaffold-using studies also analysed blank scaffolds, an important step in isolating the contribution of structural materials to overall texture. This distinction is essential for determining whether measured mechanical properties originate primarily from the scaffold itself or from cellular activity and tissue maturation. In addition to contributing to the textural properties of the final product, scaffolds also influence cell attachment, proliferation, and differentiation (Ahmad et al., 2021; Valdoz et al., 2021). For example, stiffer matrices can promote myogenic differentiation, whereas softer scaffolds may favour adipogenic lineages; both of which directly impact texture through changes to the tissue matrix (Ahmad et al., 2021; Valdoz et al., 2021; Yang et al., 2013).

Standardising the inclusion and reporting of blank scaffold controls would therefore enable clearer attribution of textural changes to either biological or material factors. This approach would also provide a more rigorous foundation for cross-study comparisons, ensuring that TPA data reflect genuine tissue development rather than artefacts of scaffold composition. In turn, this could help prioritise which mechanical properties to target during scaffold development, accelerating optimisation efforts and enhancing the design of scaffolds tailored to specific textural outcomes.

3.5. Post-culture maturation and storage conditions

Following scaffold-mediated tissue development, further maturation steps are sometimes employed to enhance the resemblance of cultivated meat to conventional counterparts, particularly considering the biochemical transformations that occur after animal slaughter. In conventional systems, these post-mortem biochemical changes transform muscle into meat, driving maturation and influencing texture (Juárez et al., 2012). Muscle fibres initially stiffen due to the depletion of adenosine triphosphate (ATP), the energy source that powers cells. However, over time, enzymes such as calpains break down structural proteins, softening the meat (Abril et al., 2023; Zhang et al., 2009). The ageing process that often follows allows the meat to regain tenderness. Since reproducing the effects of rigor mortis ex vivo is challenging, there will be implications for emulating the precise texture-influencing processes. None of the studies reviewed explicitly mention maturation steps, although Song et al. (2022) specify that differentiated adipocytes were "maintained in growth medium for 2 days", whilst Lou et al. (2024) reported that the stacked muscle bundles were wrapped and kept at 37 °C for 12 h to allow crosslinking. Similarly, Li et al. (2026) reported crosslinking their samples with transglutaminase - also referred to as 'meat glue' which has been speculated to have potential use in cultivated meat production models (Callue, 2020) - for 2 h at 40 °C. A more complex treatment can be found in the work of Chng et al. (2025), whose samples were subjected to a freeze-thaw cycle before undergoing heat treatment (separate from cooking).

Storage methods also greatly influence the texture of both cultivated and conventional meat. Freezing, for example, induces structural changes such as air pockets in the meat, which can reduce hardness and enhance tenderness perception (Pieniazek et al., 2018). Moreover, storage can impact hydration levels, structure, microbial growth, and protein stability (Cao et al., 2023; Liu et al., 2022; Orkusz et al., 2024). Yet, as with maturation, storage practices were rarely reported. Nevertheless, as tissue culture conditions and the durations of proliferation and differentiation were reported, it is reasonable to assume that most samples were tested immediately following the stated culture period to avoid confounding the effects of these developmental stages. However, greater transparency regarding the storage and handling of comparative reference samples would help account for potential confounding variables and better contextualise any observed differences between cultivated and reference samples.

3.6. Cooking states, methods, and environmental conditions

The cooking process is a well-established determinant of meat texture, yet preparing samples for texture analysis introduces additional challenges due to the wide variety of cooking methods available to researchers. Different cooking techniques generate distinct heat transfer profiles and levels of moisture retention, whilst also influencing muscle protein denaturation, fibre breakdown, and connective tissue solubilisation, all of which can substantially alter textural outcomes (Alfaifi et al., 2023). For example, deep-frying at 120–140 °C versus pan-frying at 140 °C for 1 min per side will produce different degrees of moisture loss, with direct consequences for measured texture (Hall et al., 2019).

Empirical studies demonstrate that these effects are readily captured by common TPA metrics. Abd Rashid et al. (2021) showed that hardness can effectively differentiate between cooking methods, with roasted meat exhibiting greater hardness than boiled meat, likely due to increased moisture loss and the toughening of muscle fibres (Kaur et al., 2020). Similarly, Perez-Palacios et al. (2019) reported that sous vide cooking induced time-dependent changes in pork loin texture: shorter cooking durations reduced hardness and chewiness, whereas prolonged cooking increased these attributes. Vasanthi et al. (2007) further highlighted that cooking temperature and time significantly influence adhesiveness and other textural properties in buffalo meat. Consequently, standardising the cooking technique or, at the very least, recording it, is essential in order to draw meaningful comparisons.

Amongst the studies reviewed, 56% analysed only raw samples (with the assumption that samples were raw unless otherwise stated), 15% tested only cooked samples, and 27% examined both states allowing for direct comparison between states and indicating an awareness of thermal effects (Table 2). Nevertheless, raw testing continues to dominate the literature, likely because it introduces fewer confounding variables. It also demonstrates the field's current focus on baseline mechanical characterisation rather than consumer-ready texture, reflecting the developmental stage of the cultivated meat sector, in which prototypes are primarily evaluated as research materials rather than finished food products. It may also be attributed to the fact that TPA is noted to outperform WBSF in the prediction of sensory evaluation when applied to raw meat (Novaković & Tomašević, 2017), and the quality of data obtained by both TPA and WBSF on cooked meat has been described as sub-par in quality (De Huidobro et al., 2005). However, since most people do not eat raw meat, as commercialisation advances, the inclusion of cooked state analyses will become increasingly important for assessing consumer-relevant texture and product performance, as well as standardisation of cooking methods, including time, temperature, and technique.

Reporting of cooking and post-cooking conditions remains inconsistent: of the studies that reported cooking, 83% specified the cooking method, though only 61% provided both temperature and duration (Table 2). Moreover, most studies did not clarify whether cooked samples were tested immediately or first allowed to cool to room temperature before testing - a variable that can substantially influence measured texture through differences in moisture redistribution and protein relaxation (Bertola et al., 1994; Kaur et al., 2020). When analysing plastics, environmental conditioning is recommended for 4 h prior to testing samples, to be held at 23 ± 2 °C and 50 ± 10% humidity (International Organization for Standardization (ISO), 2008). To date, there is no established best practice for the cooling period between cooking and texture testing. Measurements should ideally be conducted at a defined and controlled temperature. Many conventional meat and meat analogue studies therefore opted to test samples after cooling to room temperature (Souppez et al., 2025) or to a consumer-relevant serving temperature (Özcan & Bozkurt, 2015), rather than immediately post-heat. This latter approach aligns with sensory evaluation protocols, which frequently recommend a brief cooling or equilibration period before assessment (AMSA, 2015).

To add to this, environmental conditions are rarely detailed in the studies; some refer to "ambient conditions" or "room temperature", only 22% explicitly specify a temperature and only 5% report humidity levels. One study recorded a room temperature of 15 °C, whereas the highest reported room temperature was 25 °C, demonstrating a considerable variation that could influence textural measurements (Johnson, 2023; Rheology Lab, n.d.). Such variation is particularly relevant for cultivated meat incorporated into hybrid formulations, where lipid components (e.g. coconut oil) can undergo phase transitions close to room temperature, substantially altering mechanical response with small temperature changes (Chaleepa et al., 2010). Moreover, as discussed, cooling rates and cooking-induced differences in heat distribution can alter meat texture (Alfaifi et al., 2023; Drummond et al., 2015), implying that uncontrolled environmental factors may compound variability in post-cooking texture measurements. At minimum, researchers should report testing environment conditions, including ambient temperature, humidity, and cooling time, to improve reproducibility in cultivated meat texture analysis.

3.7. Shape and dimensions of samples

Having examined the influence of cooking and environmental conditions on texture, another source of variability lies in the geometry of the sample. Due to the various production methods used to create ex vivo meat, the ability to form standardised shapes can be challenging. The process of culturing may yield non-uniform samples or delicate structures that are difficult to handle and may not lend themselves to precise trimming. This could potentially introduce a non-uniform stress distribution (unless stress is controlled) and uneven sample buckling (Barbut, 2015; Novaković & Tomašević, 2017). This issue is not limited to cultivated meat, as conventional meat samples also present the same challenges. In these cases, it is common to set a standard height for the sample and differences in cross-sectional area are accounted for by assuming the force during compression is proportional to the cross-sectional area (Peleg, 1977). However, this assumption does not always hold true, especially in food materials where the mechanical behaviour can deviate from ideal predictions. As Peleg (1976) demonstrated, mechanical measurements may not be comparable if specimen dimensions differ, or excessive deformation arises from inappropriately high strain or displacement rates. Additionally, properties such as hardness and adhesion are highly affected by probe contact area since area is not included in their calculations.

Given these considerations, it is recommended that efforts be made to standardise sample shape and dimensions in cultivated meat research wherever possible. In the reviewed samples, a variety of shapes and sizes were used (Table 3). Cylindrical samples were the most common shape, employed by 39% of all studies (47% of studies that reported shape). However, only 69% of these studies provided clear details about both the diameter and height of the cylindrical samples. Cylindrical shapes are commonly used in textural analysis, largely due to the popularity of tools such as cork borers, which are designed to extract cylindrical

Table 2
Sample characteristics and preparation conditions for cultivated meat samples tested by TPA in the reviewed studies, including storage and maturation (where applicable), sample state (raw or cooked), cooking method, cooking temperature and duration, and environmental conditions. NR = not reported. NA = not applicable.

Study	Species	Storage and Maturation	Sample State	Cooking Method	Cooking Temperature (°C)	Cooking Duration (mins)	Ambient Temperature (°C)	Humidity
(Baeghbali et al., 2026)	Beef	NR	Raw	NA	NA	NA	NR	NR
(Chen et al., 2024)	Pork	NR	Raw	NA	NA	NA	NR	NR
(Chen, Bassey, Zhu, & Zhou, 2023)	Pork	NR	Raw	NA	NA	NA	NR	NR
(Chen, Li, Chen, Shao, Chen, Fan, Liu, Tang, et al., 2023)	Chicken	NR	Cooked	Fried	140	2	NR	NR
(Chng et al., 2025)	Pork	NR	Cooked	Fried	150	3	NR	NR
(Kim, Kim, Lee, Jang, et al., 2025)	Beef	NR	Both	Grilled	NR	NR	NR	NR
(Ding et al., 2023)	Pork	NR	Raw	NA	NA	NA	NR	NR
(Guan et al., 2023)	Pork	NR	Both	Deep fried	120–140	4	25	NR
(Guan et al., 2025)	Pork	NR	Both	Oven baked	105	5	25	NR
(Lee, Kim, et al., 2024)	Beef	NR	Both	Sous vide	NR	NR	NR	NR
(Jaime-Rodríguez et al., 2025)	Pork	NR	Cooked	Warming rack	180	10	18–20	NR
(Jiang et al., 2025)	Pork	NR	Cooked	NR	NR	NR	NR	NR
(Kim, Kumari, et al., 2024)	Chicken	NR	Raw	NA	NA	NA	NR	NR
(Li et al., 2026)	Chicken	NR	Raw	NA	NA	NA	NR	NR
(Liu et al., 2023)	Pork	NR	Raw	NA	NA	NA	20	NR
(Lou et al., 2024)	Yellow croaker fish	The stacked muscle bundles were wrapped up and kept at 37 °C for 12 h to allow crosslink	Raw	NA	NA	NA	NR	NR
(Kim, Kim, Lee, Kim, et al., 2025)	Beef	NR	Both	Grilled	180	10	NR	NR
(Lee, Park, et al., 2024)	Beef	NR	Cooked	Grilled	180	10	NR	Ambient
(MacQueen et al., 2019)	Beef Rabbit	NR	Both	NR	NR	NR	23	NR
(Mi et al., 2025)	Pork	NR	Raw	NA	NA	NA	NR	NR
(Murugan et al., 2024)	Pork	NR	Both	Fried	80	1	NR	NR
(Paredes et al., 2022)	NR	Stored at 4 °C, never frozen. Moisture content carefully preserved. Kept for 1 h at room temperature before testing.	Both	NR	NR	NR	NR	NR
(Park et al., 2024)	Beef	NR	Cooked	Microwaved	NR	4	NR	Ambient
(Song et al., 2022)	Pork	The differentiated ADSC (adipocytes) were maintained in growth medium for 2 days	Raw	NA	NA	NA	NR	NR
(Tanaka et al., 2022)	Beef	Cultivated beef is assumed to have been stored in phosphate-buffered saline	Both	Boiled	85–90	1.5	NR	NR
(Tang et al., 2024)	Rat	Beef was stored in air 4 °C until needed, then prewarmed at room temperature for 2 h	Raw	NA	NA	NA	Room temperature	NR
(Tang et al., 2025)	Chicken	NR	Raw	NA	NA	NA	NR	NR
(Wang, Zhuang, et al., 2024)	Beef	NR	Raw	NA	NA	NA	NR	NR
(Wang et al., 2025)	Beef	NR	Raw	NA	NA	NA	NR	NR
(Wu et al., 2024)	Pork	NR	Raw	NA	NA	NA	NR	NR
(Wu et al., 2025)	Pork	NR	Raw	NA	NA	NA	25	NR
(Chen et al., 2023)	Rabbit	NR	Raw	NA	NA	NA	NR	NR
(Huang et al., 2025)	Pork	NR	Raw	NA	NA	NA	NR	NR
(Yang et al., 2025)	Mouse	NR	Cooked	Fried	180	5	NR	NR
(Yen et al., 2023)	Beef	Cultivated meat prototypes were stored at 4 °C	Both	Fried	Layered - 150, 250 Burger - 250	Layered - 5, 1 Burger - 6	NR	NR
(Huang et al., 2025)	Rainbow trout	NR	Raw	NA	NA	NA	Room temperature	NR
(Zheng et al., 2021)	Pork	NR	Raw	NA	NA	NA	20	NR
(Zheng et al., 2022)	Pork	NR	Raw	NA	NA	NA	20	NR
(Zheng, Shi, Zhu, Ding & Zhou, 2022)	Pork	NR	Raw	NA	NA	NA	15	NR
(Zhou et al., 2025)	Pork	NR	Raw	NA	NA	NA	NR	NR
(Zhu et al., 2023)	Pork	NR	Both	Fried	NR	0.5	NR	NR

Note: Cooking conditions are summarised in general terms (e.g. fried, baked, grilled) as reported by the original authors, since specific techniques, times, and temperatures varied widely across studies. The term “grilling” varies across cultures and may refer to broiling (heat from above), open-flame grilling, or pan-frying. One study (Kim, Kim, Lee, Kim, et al., 2025) described grilling but also cited the use of a frying pan, indicating that the method was likely pan-frying.

Table 3
Geometry and dimensions of cultivated meat samples by species, where “d” is diameter, “h” is height, “l” is length and “w” is width. Where orientation was not reported (NR), the longest dimension was assumed to lie horizontally, as upright slender geometries (e.g. 6 × 6 × 10 mm) are mechanically unstable under compression.

Study	Species	Tissue	Shape	Dimensions (mm; l x w x h for prism and d x h for cylinder)
(Baeghbali et al., 2026)	Beef	NR	Rectangular prism	20 × 20 × 4
(Chen et al., 2024)	Pork	Muscle	Cylinder	NR
(Chen, Bassey, Zhu, & Zhou, 2023)	Pork	Muscle	Cylinder	NR
(Chen, Li, Chen, Shao, Chen, Fan, Liu, Ding, et al., 2023)	Chicken	Muscle	Cylinder	2 × 4
(Chng et al., 2025)	Pork	Undifferentiated	Rectangular prism	15 × 15 x NR
(Kim, Kim, Lee, Kim, et al., 2025)	Beef	Muscle	Cube	10 × 10 × 10
(Ding et al., 2023)	Pork	Muscle	NR	NR
(Guan et al., 2023)	Pork	Muscle	Rectangular prism	10 × 10 × 5
(Guan et al., 2025)	Pork	Co-culture	Cube	10 × 10 × 10
(Le Foll et al., 2024)	Beef	Muscle	Cylinder	NR
(Jaime-Rodríguez et al., 2025)	Pork	Muscle and bone	Rectangular prism	15 × 15 × 10
(Jiang et al., 2025)	Pork	NR	Rectangular prism	20 × 20 × 15
(Kim, Song, et al., 2024)	Chicken	Undifferentiated	Cube	10 × 10 × 10
(Li et al., 2026)	Chicken	Adipose	Cylinder	15 × 15
(Liu et al., 2023)	Pork	Adipose	Rectangular prism	10 × 10 × 1
(Lou et al., 2024)	Fish	Muscle	Rectangular prism	8 × 5 × 3
(Kim, Kim, Lee, Jang, et al., 2025)	Beef	Muscle	Cylinder	20 × 5–6
(Lee, Kim, et al., 2024)	Beef	Co-culture	NR	NR
(MacQueen et al., 2019)	Beef, Rabbit	Muscle and undifferentiated	Cylinder	10 × 1.5
(Mi et al., 2025)	Pork	Muscle	NR	NR
(Murugan et al., 2024)	Pork	Muscle and co-culture	Cylinder	NR
(Paredes et al., 2022)	NR	NR	Cylinder	8 x NR
(Park et al., 2024)	Beef	Muscle	NR	NR
(Song et al., 2022)	Pork	Adipose	Rectangular prism	6 × 6 × 1
(Tanaka et al., 2022)	Beef	Muscle	Cylinder	11–15 × 1.4–2.3
(Tang et al., 2024)	Rat	Muscle	Cube	20 × 20 × 20
(Tang et al., 2025)	Chicken	Muscle and adipose	NR	NR
(Wang, Zhong, Munawar, Zan & Zhu, 2024)	Beef	Muscle	NR	NR
(Wang et al., 2025)	Beef	Muscle	Cultivated meat: cylinder, Conventional meat: rectangular prism	NR
(Wu et al., 2024)	Pork	Muscle	Cylinder	NR
(Wu et al., 2025)	Pork	Muscle and Adipose	Rectangular prism	20 × 20 × 5
(Chen et al., 2023)	Rabbit	Muscle	NR	NR
(Huang et al., 2025)	Pork	Muscle	Sphere	NR
(Yang et al., 2025)	Mouse	Muscle	Cylinder	4 × 1.5
(Yen et al., 2023)	Beef	Undifferentiated	Cylinder	Layered: 8 × 4; Burger-like: 18–20 × 20
(Huang et al., 2025)	Fish	Muscle	Rectangular prism	NR
(Zheng et al., 2021)	Pork	Muscle	Cylinder	5 × 5
(Zheng et al., 2022)	Pork	Muscle	Rectangular prism	6 × 6 × 1
(Zheng, Shi, Zhu, Ding & Zhou, 2022)	Pork	Muscle and undifferentiated	Rectangular prism	6 × 6 × 10
(Zhou et al., 2025)	Pork	Undifferentiated	Cube	10 × 10 × 10
(Zhu et al., 2023)	Pork	Muscle	Cylinder	NR

samples from materials (Stable Micro Systems, n.d.-a; Stable Micro Systems, n.d.-b; Peleg, 1977). This shape provides the advantage of uniformity in analysis, and measurement of area in contact with the probe, which are important for stress and adhesion. Furthermore, cylindrical samples are relatively easy to produce, and their dimensions can be controlled with a high degree of precision (Peleg, 2019).

Rectangular prisms were used in 32% of all studies, 92% of which provided explicit dimensions; however, only two employed identical sizes and both of these studies originated from the same research group. Some consistency was observed amongst cubic samples, with three out of the four studies using cubes of uniform dimensions (10 × 10 × 10 mm). One study tested a cylindrical sample of cultivated meat alongside a rectangular prism of conventional beef, although the shape and dimensions were not clearly specified (Wang et al., 2025). Almost half (44%) of the reviewed studies failed to report both the shape and complete dimensions (i.e. reported only one of these two or reported neither) of the samples tested. Improved reporting and greater harmonisation of sample preparation would substantially strengthen comparability across studies.

In the absence of consistent reporting, it becomes difficult to determine whether differences in measured texture arise from biological factors or simply from variations in sample geometry. To address this, prior research has explored optimal specimen ratios and configurations for compression testing. Mittal et al. (1992) suggested using cylindrical samples with a diameter-to-length ratio of 1:5 for compression tests, as this ratio is believed to maintain consistency in deformation behaviour during compression. However, this slender geometry would likely be unsuitable for soft biological materials, such as finely comminuted or partially processed meat products, since they are prone to deformation or collapse under their own weight.

Given these considerations, researchers may wish to trial cylindrical samples with a diameter-to-height ratio of approximately 1:1 for cultivated meat texture analysis, where feasible. These geometries can offer improved mechanical stability for soft, hydrated materials and align with the practical use of cork borers for reproducible sample preparation. A diameter of approximately 10 mm is both commonly used in the existing literature and compatible with standard cork borer sizes and may therefore represent a sensible starting point. When cylindrical geometries are not possible due to material limitations or sample fragility, alternative shapes may be used but should be clearly described and appropriately justified. In all cases, accurate reporting of sample dimensions is essential, as this will serve as the contact area and can be used for further calculations (e.g. stress, modulus, adhesion with respect to contact area).

3.8. Instrumental parameters

3.8.1. Terminology and reporting consistency

The shape and structure of a sample determine how it deforms, but the instrumental settings dictate how that behaviour is captured and quantified. Szczesniak (1975) first emphasised the importance of developing defined texture methods, whilst Breene (1975) and Voisey (1975) demonstrated how strongly test conditions influence measured outcomes. Parameters such as degree of deformation, displacement rate, and probe geometry directly affect the force-time curve and the textural properties derived from it.

Across the reviewed literature, instrumental parameters were generally reported, but the terminology used to describe them was often inconsistent or ambiguous. In TPA, double compression tests are defined by a displacement rate and a target strain, yet these were frequently described using varied phrasing rather than explicit parameter names (e.g. "compression at X mm s^{-1}", "X% of original height", "compression ratio", or "maximum deformation"). Although such descriptions are usually interpretable from context, inconsistent terminology complicates data extraction and cross-study comparison.

Probe configuration was another further area where clearer reporting is needed. Standard TPA uses flat-ended probes larger than the sample's cross-sectional area to ensure bulk compression rather than localised penetration. However, some studies provided conflicting information about probe size, sample dimensions, and test descriptions, making it unclear whether measurements reflected true double-compression TPA or penetration-style tests. Whilst penetration tests can yield valuable information about local mechanical resistance or structural heterogeneity, they probe different material responses than bulk compression and are not mechanically equivalent to TPA (Schreuders et al., 2021). Explicit reporting of probe geometry relative to sample dimensions is therefore important to enable accurate interpretation of the measurement mode.

3.8.2. Variability in TPA instrumental parameters

Building on the terminology inconsistencies outlined above, it is also important to consider how these key instrumental parameters were implemented in practice. Strain is particularly influential, and recommended values vary because TPA can be used to measure fracture behaviour, elastic recovery or plastic deformation. It is important, therefore, that method design matches the property being targeted.

In conventional meat research, Mittal et al. (1992) proposed a strain of 0.75 for meat products based on systematic comparison across processing levels, whilst more recently, Barbut (2015) recommended 0.75 for both processed and whole cut meat, and Bernardo et al. (2022) suggested that strains between 0.6 and 0.75 yield the most reliable textural data for fish. Within the cultivated meat literature reviewed here, strain was often unreported (Table 4); when stated, 0.5 was most common (56% of studies), likely reflecting the fragility of cultivated meat constructs, with 0.75 used less frequently (22% of studies).

Avoiding fracture is essential when relating TPA outputs to sensory attributes, as failure during the first compression compromises the second and reflects the behaviour of a partially destroyed structure, which can distort derived parameters such as springiness and cohesiveness. Researchers are therefore encouraged to test multiple strain levels, visually inspect samples and select the highest strain that does not induce failure for subsequent measurements, in line with ISO 604 (International Organization for Standardization (ISO), 2002). Given that a strain of 0.5 was most commonly reported across the reviewed literature, this value may represent a pragmatic starting point for future studies.

Displacement rate also strongly affects textural outcomes, as higher speeds reduce relaxation time and increase measured force (Bernardo et al., 2022; Novaković & Tomašević, 2017). When testing meat textures, the applied displacement rate should be carefully considered to replicate the sensory evaluation of the meat. Note that force driven experiments are possible, however this is not recommended due to the potential for variable strain to be applied, particularly where deviations in sample size may be a factor. Mittal et al. (1992) advocated for relatively slow rates (~0.167–0.333 mm s^{-1}), whilst Bernardo et al. (2022) suggested a slightly broader range of 0.5–2.0 mm s^{-1}, aligning closely with AMSA's recommendation of 100 mm min^{-1} (equivalent to 1.67 mm s^{-1}; AMSA, 2015).

Although higher speeds often correlate better with sensory data, true bite speeds vary widely, with reported values ranging from 1 to 173 mm s^{-1} (Hansdottir & Bakke, 2004; Novaković & Tomašević, 2017), making replication impractical. Within the reviewed cultivated meat literature, a displacement rate of 1 mm s^{-1} was the most frequently reported (46% of studies). Nevertheless, substantial variability remained across the literature, with some studies employing considerably higher displacement rates ($\geq$ 5 mm s^{-1}) under specialised testing conditions. This variability could suggest that displacement rate is selected pragmatically rather than based on a universally applicable standard. Accordingly, whilst 1 mm s^{-1} is commonly used, it should not be interpreted as an optimal or broadly transferable condition. Instead, rate selection should be justified based on sample properties (e.g. size, structure, mechanical behaviour), and, where possible, evaluated for rate-dependence when characterising new material formats.

Pause duration was unreported in most studies (68%), despite its relevance to time-dependent metrics such as springiness and cohesiveness (Rosenthal, 2010). Very long pauses allow full sample recovery and can render these values meaningless, whilst industry practice typically uses one second as an acceptable pause time, roughly matching chewing frequency (1.1–1.5 chews per second) (Sánchez-Ayala et al., 2013). Given its influence on recovery-related parameters, pause duration should be explicitly reported, and its optimisation for meat products merits further investigation.

Finally, probe geometry and material can also influence the forces applied during TPA, and therefore affect the reliability and comparability of results. Amongst studies that reported cylindrical probes (the standard geometry for TPA) diameters varied widely, from 5 mm to 115 mm. Where both probe size and sample dimensions were provided, the probe was usually larger than the sample's contact area, supporting a more even distribution of compressive force during testing (Stable Micro Systems, 2025). However, in the few cases where the probe was smaller than the sample, and despite the method being described as TPA, the deformation was likely more localised and mechanically distinct from bulk compression. Additionally, 34% of studies did not report enough detail to determine the probe-to-sample size relationship, limiting confidence in how comparable their measurements are to standard TPA practice.

One factor that was not specifically stated is the probe's material of construction. Probes may be made from stainless steel, aluminium or acrylic, yet many studies simply reported using a P/50 probe and a Stable Microsystems instrument, which implies a stainless steel probe (Stable Micro Systems, n.d.-d). Probe material is particularly important for adhesiveness measurements, as adhesiveness is an interfacial property (Michalski et al., 1997). Stainless steel is a common default in food texture testing, but material choice should still be reported and, where

Table 4
Summary of TPA instrument settings used and metrics measured in selected cultivated meat studies. NR = not reported.

Study	Properties Calculated	Displacement Rate (mm s^{-1})	Strain	Pause (s)	Number of Replicates
(Baeghbali et al., 2026)	Chewiness Gumminess Cohesiveness Hardness Resilience Springiness	NR	0.5	5	3
(Chen et al., 2024)	Hardness Resilience Chewiness	1	0.5	NR	$n = 3$, 5 repeats
(Chen, Bassey, Zhu, & Zhou, 2023)	Hardness Springiness Chewiness	1	0.5	NR	NR
(Chen et al., 2023)	Hardness Cohesiveness Chewiness Gumminess	NR	0.5	NR	3
(Chng et al., 2025)	Hardness Chewiness Springiness Cohesiveness	2	0.5	NR	3
(Kim, Kim, Lee, Kim, et al., 2025)	Hardness Gumminess Chewiness Springiness Cohesiveness	3	0.5	NR	≥ 3
(Ding et al., 2023)	Hardness Cohesiveness Springiness Chewiness	1	0.5	NR	≥ 3
(Guan et al., 2023)	Hardness Springiness Chewiness	1	0.75	5	3
(Guan et al., 2025)	Hardness Cohesiveness Springiness Resilience Chewiness Gumminess	1	0.75	5	≥ 3
(Lee, Park, et al., 2024)	Cohesiveness Springiness Resilience Adhesiveness Firmness	0.1	0.5	5	≥ 3
(Jaime-Rodríguez et al., 2025)	Cohesiveness Chewiness Gumminess	2	0.5	NR	NR
(Jiang et al., 2025)	Hardness Gumminess Chewiness	2	0.5	5	2
(Kim, Song, et al., 2024)	Hardness Cohesiveness Springiness Chewiness Gumminess	1.7	NR	NR	5
(Li et al., 2026)	Hardness Adhesiveness Springiness Cohesiveness Gumminess Chewiness Resilience	0.1	NR	NR	NR
(Liu et al., 2023)	Hardness Springiness Cohesiveness Gumminess Resilience Chewiness	1	0.75	NR	NR
(Lou et al., 2024)	Hardness Cohesiveness Springiness Resilience Chewiness Gumminess	1	0.5	NR	3

(continued on next page)

Table 4 (*continued*)

Study	Properties Calculated	Displacement Rate (mm s^{-1})	Strain	Pause (s)	Number of Replicates
(Kim, Kim, Lee, Jang, et al., 2025)	Hardness Chewiness Gumminess	NR	0.5	NR	3
(Le Foll et al., 2024)	Hardness Cohesiveness Springiness	NR	0.4	NR	3
(MacQueen et al., 2019)	Hardness	NR	0.25	180	NR
(Mi et al., 2025)	Hardness Chewiness Cohesiveness Springiness	1	0.5	NR	NR
(Murugan et al., 2024)	Hardness Cohesiveness Springiness Chewiness	2	0.5	5	5
(Paredes et al., 2022)	Hardness Cohesiveness Springiness Resilience Chewiness	3	0.5	1	≥ 6
(Park et al., 2024)	Hardness Cohesiveness Springiness Adhesiveness Brittleness Gumminess	NR	NR	NR	NR
(Song et al., 2022)	Hardness Cohesiveness Springiness Chewiness Gumminess	1	0.75	NR	6
(Tanaka et al., 2022)	Hardness Cohesiveness Springiness Chewiness Adhesiveness Brittleness Elastic modulus	40	NR	NR	Cell sheet = 4 Beef = 6
(Tang et al., 2024)	Hardness (“durometer”) Springiness (“resilient”) Cohesiveness Chewiness (“masticatory”)	1	0.5	5	NR
(Tang et al., 2025)	Hardness Springiness Cohesiveness Gumminess Chewiness Resilience	0.1	0.5	5	NR
(Wang, Zhuang, Munawar, Zan & Zhu, 2024)	Hardness Springiness Chewiness Gumminess	1	0.75	NR	NR
(Wang et al., 2025)	Hardness Cohesiveness Springiness Resilience Chewiness Gumminess	5	NR	NR	NR
(Wu et al., 2024)	Hardness Springiness Resilience Chewiness	1	0.5	NR	3
(Wu et al., 2025)	Springiness Chewiness Gumminess Hardness	1	0.75	5	NR
(Chen et al., 2023)	Hardness Cohesiveness Springiness Resilience Chewiness Gumminess	NR	0.5	NR	3
(Huang et al., 2025)	Hardness Springiness Cohesiveness Gumminess	1	0.5	NR	NR

(*continued on next page*)

Table 4 (*continued*)

Study	Properties Calculated	Displacement Rate (mm s^{-1})	Strain	Pause (s)	Number of Replicates
	Chewiness Resilience				
(Yang et al., 2025)	Hardness Cohesiveness Springiness Gumminess Chewiness Resilience	1	0.5	NR	NR
(Yen et al., 2023)	Hardness Cohesiveness Springiness Chewiness Adhesiveness	0.83	0.5	0	3
(Huang et al., 2025)	Hardness Springiness Gumminess Chewiness Resilience	1	NR	NR	NR
(Zheng et al., 2021)	Hardness Cohesiveness Springiness Chewiness	1	0.85	NR	5
(Zheng, Chen, et al., 2022)	Hardness Springiness Chewiness Gumminess	1	0.75	NR	NR
(Zheng, Shi, et al., 2022)	Hardness Springiness Chewiness Gumminess	1	0.75	NR	NR
(Zhou et al., 2025)	Hardness Cohesiveness Springiness Chewiness	NR	0.5	3	8
(Zhu et al., 2023)	Hardness Cohesiveness Springiness Resilience Chewiness Gumminess	NR	0.75	NR	3

possible, standardised, especially when adhesiveness is of interest.

3.9. Replication and statistical considerations

The number of replicates used in compression testing varies across published guidance and the cultivated meat literature. The AMSA (2015) recommends conducting at least ten replicates for textural analysis, whereas the most common number of minimum replicates used in the reviewed studies is three (with 39% of all studies stating either the use of 3 replicates, or using the number three as their minimum replicate number). Another 41% of studies in the review did not report the number of replicates.

Meat samples, whether conventional or cultivated, are often heterogeneous in texture (Boots et al., 2021). Variability in meat's composition, such as differing amounts of fat, muscle, connective tissue, and/or the inclusion of scaffolding materials, can lead to inconsistent textural property measurements. A larger number of replicates helps to account for heterogeneity, by ensuring that the textural measurements are representative of the entire sample and not biased by specific regions. This is particularly important for cultivated meat, where sample uniformity can be a challenge due to spatial variations in cell proliferation and differentiation across scaffolding, for example. However, this must be weighed against feasibility for the specific field; the process of generating a cultivated meat construct is both costly and labour-intensive, and thus 10 replicates may be unattainable as a standard minimum (Cai et al., 2024; Hauser et al., 2024; Hubalek et al., 2022).

Rather than prescribing a universal minimum number of replicates, this review emphasises the importance of transparent reporting of replication. Where feasible, testing a sufficient number of replicates to capture material heterogeneity is desirable, and existing mechanical testing standards such as ISO 604, which specifies a minimum of five specimens for compression testing, may provide a pragmatic reference point (International Organization for Standardization (ISO), 2002).

4. Summary of methodological commonalities

Having examined the influence of individual TPA parameters, it is useful to step back and consider broader patterns across the literature. Several recurring methodological patterns are evident across the literature, reflecting frequently adopted experimental approaches within current cultivated meat TPA studies. Importantly, these commonalities should not be interpreted as best practice or optimal conditions, but rather as frequently adopted approaches that may provide useful reference points for future studies.

Table 5 summarises parameters that were most commonly reported or cited across the dataset. Parameters were included where they:

(i) were reported or reasonably inferable in ≥50% of studies;

(ii) exhibited a most frequently used value or condition, indicating frequently adopted experimental conditions; and.

(iii) represented either a potentially standardisable methodological variable (e.g. strain, sample shape) or an experimental design factor that materially affects outcomes and cross-study comparability (e.g. cooking

Table 5
Frequently reported conditions / cited values for TPA parameters.

Parameter	Value	Studies reporting this value (%)	Studies reporting any value (%)
Strain	0.5	56	85
Cooking state (raw, cooked, or both)	Raw	56	100
Sample shape	Cylinder	39	83
Number of replicates	3	34	56

state, number of replicates).

With regard to criterion (i) of the inclusion criteria for Table 5, pause duration was most commonly cited as 5 s, but this parameter was unreported in 68% of studies, and is therefore not included amongst commonly reported practices. Since properties like springiness and cohesiveness are time-dependent, inconsistent or unreported pause durations significantly affect result interpretation (Rosenthal, 2010). For several other influential parameters (e.g. sample dimensions), reporting was highly inconsistent or absent. Where no clear reporting trends were observed, guidance is therefore informed primarily by wider texture analysis literature and by the known mechanical implications of these parameters, rather than by frequency of use alone.

Where probe geometry was reported, a flat-ended cylindrical probe was used in the majority of studies, consistent with standard practice for uniaxial compression testing and with the intended mechanics of TPA. Several studies did not explicitly state probe shape, likely reflecting the implicit assumption of a flat compression plate, whilst only one study specified a non-cylindrical probe (spherical). Given the widespread use of flat-ended cylindrical probes, probe shape itself is not treated as a distinguishing methodological variable and is therefore not included in Table 5. In contrast, probe dimensions are more consequential, as probe diameter must be considered relative to sample geometry to ensure uniform compression and valid strain calculation. Although a probe diameter of 50 mm was most frequently reported, no corresponding convergence in sample diameter was observed. Probe diameter in isolation is therefore not interpreted as a consistent reporting trend and is likewise excluded from Table 5.

Encouragingly, most studies used comparative samples of the same species as their cultivated counterparts, minimising biological confounding variables. In contrast, environmental conditioning parameters (e.g. temperature and humidity) were rarely reported, despite their well-established influence on the mechanical behaviour of hydrated and biological materials, limiting the interpretability and cross-study comparability of reported results.

Many other parameters showed a wide range of variance in their cited values or were excessively underreported. This further highlights incomplete reporting of experimental parameters as a longstanding issue with studies utilising TPA that impacts comparability of data (Breene, 1975). Fig. 6 illustrates the proportion of reviewed studies reporting key experimental parameters. Promisingly, the majority of studies report biological information, as well as some instrumental parameters, including sample shape and dimensions, displacement rate, and strain. However, comprehensive reporting across all relevant parameters remains uncommon.

The geographical distribution of the reviewed studies also warrants consideration, with 61% originating from China. This raises the valid question of whether observed trends might simply reflect repeated methodologies from particularly active research groups. However, our analysis indicates that these studies stem from four distinct groups, with no single group accounting for more than 8% of the total dataset. Therefore, the observed reporting patterns are unlikely to be solely driven by a single laboratory or research group.

4.1. BIOPLATE reporting framework

These observations indicate that cultivated meat TPA is currently characterised by recurring methodological patterns alongside substantial variability and incomplete reporting across studies. Whilst a fully standardised protocol is not realistic at this stage, the reporting trends identified here, together with established guidance from conventional meat science and polymer testing, provide a useful foundation for defining shared reporting expectations and reasonable starting points for future studies. To aid recall and implementation, this guidance is summarised using the mnemonic BIOPLATE, which should be understood as a structured checklist of key considerations rather than a mandatory testing specification.

B: Biological information.

Report the biological origin of the material, including species, cell type(s), and tissue type, as well as the intended product category (e.g. finely comminuted, partially processed, or whole cut analogue). Where feasible, provide background information on biological source material and reference samples (in supplementary materials if necessary),

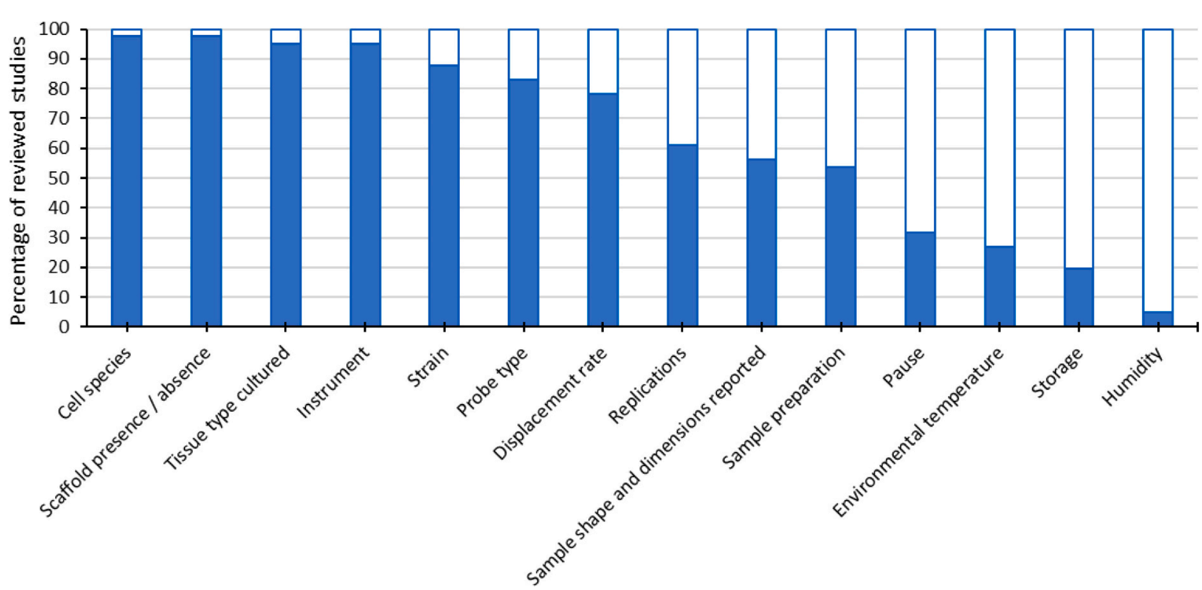

Fig. 6. Experimental parameters versus the percentage of studies (reviewed herein) that reported them. A value of 100% indicates that the experimental parameter was reported in all reviewed studies.

including donor age, sex, breed, anatomical site, and post-mortem timing (where applicable).

I: Interpretation.

Explicitly describe how reported TPA metrics are interpreted within the context of the specific product, material state, and experimental comparison being made. Authors should clarify how individual metrics relate to mechanical behaviour and, where relevant, sensory perception.

O: Operational test parameters.

Report key instrumental parameters, including probe dimensions (ensuring the probe is larger than the sample), pause duration, probe material (particularly where adhesiveness is assessed), displacement rate, and strain.

A strain of ~0.5 was most frequently reported across the reviewed studies and may serve as a useful starting point; however, alternative values should be clearly justified where used. Nevertheless, strain should be selected experimentally to remain below fracture when deformation-based properties (e.g. springiness, cohesiveness, chewiness) are of interest. Fracture behaviour, where relevant, should be investigated using designs appropriate to that objective.

Where feasible, particularly for more heterogeneous samples, the use of 5–10 replicates may improve confidence in reported measurements. Where material availability is limited, a minimum of three replicates could still be performed and clearly reported.

P: Physical geometry and dimensions.

Cylindrical samples are commonly used in cultivated meat TPA studies, and the widespread use of cork borers may make this a practical sample shape where feasible. Although reported sample dimensions vary widely across the literature, the use of approximately equal diameter-to-height ratios may reflect practical constraints associated with soft, hydrated samples and limited material availability, whilst also supporting more uniform compression behaviour. Regardless of geometry, accurate measurement and reporting of the sample area in contact with the probe are essential for valid strain calculation and for standardising adhesion-related measurements.

L: Listed cooking protocol (where applicable).

TPA may be conducted on raw or cooked samples depending on study aims. From a consumer perspective, cooked samples are often most relevant; however, substantial variability in cooking methods currently limits the ability to define best practice. At present, more consistent comparison is afforded by raw sample testing. Where cooking is included, raw measurements should ideally be reported alongside cooked results to support interpretation, and cooking protocols should be described in sufficient detail to enable replication and comparison. Researchers may look to established meat science guidance (e.g. AMSA, 2015) as a reference point for designing and reporting cooking procedures.

A: Ambient and sample conditions.

Report any relevant sample condition variables, such as sample processing steps, maturation or ageing, and the time interval between harvest and testing. Storage conditions, thawing methods, ambient testing conditions, and sample temperature should be reported wherever possible, including for conventional meat comparators.

T: Texture metrics and derivation.

Based on observed trends across the literature and the mechanical relevance of individual parameters, hardness, springiness, and cohesiveness are recommended as a core metric set for cultivated meat TPA studies. These primary outputs of the double compression test form the basis for calculating commonly reported secondary metrics such as chewiness and gumminess. Additional TPA properties may be reported where justified by the study objective, product format, or material behaviour; in such cases, authors should clearly articulate the rationale for their inclusion. Clear definitions and calculation methods could be reported alongside metrics to reduce ambiguity. Where secondary metrics are reported, the underlying primary properties should also be provided to support transparency and comparability.

Where feasible, representative force-time curves or raw datasets may be made available in supplementary materials or upon reasonable request, particularly where non-standard metrics or fracture behaviour are discussed. Consideration may also be given to reporting modulus alongside hardness where stress-strain relationships can be robustly defined and sample geometry is well controlled.

E: Experimental comparators.

Where feasible, benchmark cultivated samples against appropriate conventional equivalents tested under identical conditions. Where scaffolds are used, inclusion of both cell-seeded constructs and corresponding acellular scaffolds may aid mechanical interpretation by providing a baseline reference. Such comparisons should be included where practical and clearly justified.

5. Conclusion

This review demonstrates that TPA is a widely adopted and potentially powerful tool for characterising cultivated meat texture, offering multiple sensory-relevant metrics from a single double compression experiment. Across 41 cultivated meat and fish studies, substantial variability was identified in both the reporting and implementation of key TPA variables, including biological context, sample geometry, test parameters, cooking state, and metric selection.

Despite this variability, several reporting trends were observed, including cylindrical sample geometries and frequent use of strains of 0.5. In addition, hardness and springiness were prioritised amongst reported metrics. Whilst these observations should not be interpreted as universally optimal testing conditions, the consistent reporting of a core set of metrics and the use of geometries compatible with uniform compression may provide useful reference points for improving transparency and cross-study comparability in cultivated meat TPA. Building on these observations, and informed by established guidance from conventional meat science, polymer testing, and other mechanical characterisation, we propose the BIOPLATE framework as a reporting-focused checklist for cultivated meat TPA studies. This framework is intended to support clearer methodological reporting, encourage justification of experimental choices, and improve transparency and interpretability across the field.

Future work would benefit from further validation of these proposed reporting considerations through inter-laboratory studies, as well as addressing underreported but influential parameters such as storage/handling history, sample conditioning, cooking protocols, and pause duration. Finally, stronger integration of instrumental texture metrics with sensory evaluation will be essential as cultivated meat approaches commercialisation, enabling more reliable, human-perceived texture benchmarking and supporting translation into industrial and regulatory settings.

CRediT authorship contribution statement

Alice Millbank: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation. **Travis Callue:** Writing – review & editing, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation. **Anna-Marie Stobo:** Writing – review & editing, Data curation. **Jason M. Thomas:** Writing – review & editing. **Paul D. Topham:** Writing – review & editing, Supervision. **Mariana Petronela Hanga:** Writing – review & editing, Supervision. **Jean-Baptiste R.G. Souppez:** Writing – review & editing, Supervision, Conceptualization. **Eirini Theodosiou:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare no conflicts of interest relevant to the content of this publication.

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Data availability

Data will be made available on request.

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Glossary

Confidence: A value pertaining to Association Rule Mining (ARM) data mining, ranging from 0 to 1, denoting the frequency with which a consequent (outcome) appears when an antecedent (condition) is present, i.e. the likelihood that the relationship is significant.

Conventional meat: Food products composed, entirely or partially, of muscle and/or fat tissue directly harvested from a slaughtered animal(s) of any species.

Cultivated meat: Muscle and/or fat tissue produced in vitro from isolated animal stem cells for the purpose of being used (whether solely or as a component in a final product) for human consumption, or as a development of the biotechnology applied to that end. Also known as lab-grown, cultured, or cell-based meat. In the interest of brevity, the term cultivated meat is used throughout this review to refer to both cultivated terrestrial meat and cultivated fish products.

Deformation: The absolute physical change in a sample's height during compression, typically expressed in millimetres (mm). In the texture analysis literature, it is often referred to as the "deformation level" or "compression level" and may be described as "the sample was compressed to 0.5 mm".

Deformation rate: The measured rate at which sample deformation occurs, influenced by displacement rate. Often used interchangeably with strain rate in uniaxial testing.

Displacement rate: The predetermined speed at which the crosshead travels during compression in TPA, also referred to as crosshead speed.

Finely comminuted products: Meat products, cultivated or conventional, that exhibit minimal or no intact muscle structure. In conventional meat, this typically results from mechanical processing (e.g. mincing, emulsification) to produce a uniform, paste-like matrix for products such as sausages, hot dogs, or nuggets. In cultivated meat, a similar texture may arise either from post-processing or from the inherent lack of tissue organisation in undifferentiated or scaffold-free constructs, even without extensive processing.

Lift: A value pertaining to ARM analysis denoting the probability that an association rule is meaningful versus a result of random chance, i.e. degree of significance. A value of 0 would indicate that there is no chance that an observed rule results from meaningful association. A value of 1 indicates the rule is equally as likely to result from random chance than from meaningful association. Values higher than 1 indicate increasing likelihood that a rule is a result of meaningful association.

Microcarriers: Microscopic scaffolds with diameters typically ranging from 100 to 500 μm, used in suspension cultures of adherent cells (e.g. bioreactor cultures) and favoured for higher surface area-to-volume ratios and scalability than other scaffold morphologies (Dagès, 2024; Rafiq, Coopman, Nienow and Hewitt, 2016).

Partially processed products: Meat products, cultivated or conventional, that retain some degree of structural organisation but are not intact whole muscle cuts. In conventional meat, this typically includes shredded, minced or ground formats where muscle fibres are fragmented but still contribute to texture (e.g. mince, pulled meat, burgers). In cultivated meat, partially processed formats may be produced by harvesting structured constructs and mechanically breaking them down, or by assembling less organised biomass into a cohesive matrix. These products may incorporate added fat and/or binders to improve cohesion, shaping, and mouthfeel.

Scaffolds: Structures on which adherent cells may attach, proliferate, and differentiate. Key functions of a scaffold include the facilitation of oxygen, nutrient, and waste exchange whilst also contributing to the final product's texture, flavour, and nutritional profile.

Support: A value pertaining to ARM analysis, ranging from 0 to 1, denoting the frequency with which an association rule is observed across the entire dataset i.e. the prevalence of the relationship.

Strain ε: The relative deformation of a sample under direct loading, calculated as the change in length Δx divided by the original length x. In TPA, strain reflects the sample's compression during each cycle. Although it is a dimensionless ratio, it may also be described in literature as "the sample was compressed by X%", where the percentage represents the strain value (e.g. "compressed by 75%" corresponds to a strain of 0.75).

Whole cut analogues: Cultivated meat constructs designed to emulate whole cut conventional meat products such as steak, pork chop, salmon fillet, or chicken breast, necessitating the use of scaffolding or advanced structuring techniques and co-culture of multiple tissues alongside the muscle (such as fat and connective tissue).