Exploring Metabolomics Guided Authentication of Plant-Based Meat Alternatives Supporting Regulatory Standards and Consumer Health Protection

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Abstract: The global demand for plant-based meat alternatives has accelerated in response to rising environmental concerns, shifting dietary preferences, and the pursuit of healthier food systems. However, the authenticity, safety, and quality assurance of these products remain central challenges in meeting consumer expectations and regulatory requirements. Metabolomics, a systems-level analytical approach that profiles the complete set of metabolites in a biological sample, has emerged as a powerful tool for authenticating plant-based meats. Through advanced spectroscopic and chromatographic techniques, coupled with bioinformatics-driven data integration, metabolomics enables the identification of product-specific biomarkers, detection of adulterants, and verification of ingredient sourcing. This review critically examines the application of metabolomics in the authentication of plant-based meat alternatives, focusing on its role in supporting regulatory frameworks, safeguarding consumer health, and enhancing transparency within the food supply chain. Key areas of emphasis include the detection of compositional discrepancies, allergen monitoring, nutritional profiling, and the prevention of fraudulent practices. Furthermore, the paper highlights the challenges of standardizing metabolomics protocols, ensuring reproducibility across laboratories, and integrating omics-based data into international regulatory standards. By situating metabolomics within the broader context of food authenticity and public health, this review underscores its transformative potential in strengthening consumer confidence and advancing sustainable food innovation.

Keywords: *Metabolomics; Plant-Based Meat Authentication; Food Safety Regulation; Consumer Health Protection; Omics-Based Food Analysis.*

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I. INTRODUCTION

➢ *Background on Plant-Based Meat Alternatives*

Plant-based meat alternatives have emerged as innovative food products designed to replicate the sensory, nutritional, and functional attributes of conventional meat, catering to the growing global demand for sustainable diets. Their rapid rise is attributed to increasing awareness of the environmental burdens of livestock production, including greenhouse gas emissions, water scarcity, and land degradation (Curtain & Grafenauer, 2019). These products, often developed from soy, wheat gluten, legumes, and more recently pea protein and mycoprotein, are engineered to simulate meat's texture and flavor using extrusion technologies, binding agents, and flavor enhancers (Joshi & Kumar, 2015).

The appeal of plant-based meat extends beyond environmental sustainability; it aligns with consumer preferences for healthier diets by offering lower saturated fat and cholesterol levels compared to animal-derived meat. Nutritional fortification with vitamins, minerals, and essential amino acids further enhances their dietary profile. For instance, fortification with vitamin B12 or iron is common to bridge nutritional gaps, ensuring equivalence to traditional meat products (Curtain & Grafenauer, 2019).

At the same time, the "flexitarian" consumer segment—individuals who reduce but do not eliminate meat consumption—has driven retail expansion of plant-based products globally. This group prioritizes both environmental stewardship and health benefits, creating a substantial market niche. The background of plant-based meat alternatives is therefore situated at the intersection of technological innovation, sustainability imperatives, and evolving consumer food choices (Joshi & Kumar, 2015).

➢ *Importance of Authenticity, Safety, and Consumer Trust*

Authenticity and safety represent critical pillars in the acceptance of plant-based meat alternatives, directly influencing consumer trust and regulatory alignment. Authenticity concerns encompass accurate labeling, verifiable ingredient sourcing, and assurance that products conform to declared nutritional and compositional standards (van der Weele et al., 2019). Given the increasing complexity of formulations and processing techniques, risks of mislabeling or adulteration are heightened, particularly where manufacturers attempt to replicate meat characteristics with additives or less costly protein blends.

Food safety is another dimension of consumer protection, as plant-based alternatives may still pose risks through contamination, allergen presence, or microbial instability if not rigorously controlled (Aschemann-Witzel & Peschel, 2019). For instance, wheat- or soy-based analogues raise concerns for individuals with gluten sensitivity or soy allergies. Inadequate regulation of these risks could erode consumer confidence, hindering market adoption.

Consumer trust, however, extends beyond technical assurance; it also relies on transparency in sustainability claims and ethical positioning. Misrepresentation of environmental or health benefits can lead to skepticism, undermining long-term loyalty. Studies suggest that consumers are more likely to embrace plant-based meats when they perceive manufacturers as honest about both advantages and limitations (van der Weele et al., 2019). Thus, authenticity, safety, and trust are interdependent: robust verification mechanisms foster regulatory compliance, which in turn reinforces consumer confidence and sustains the legitimacy of plant-based meat markets (Aschemann-Witzel & Peschel, 2019).

➢ *Scope and Objectives of the Review*

This review focuses on exploring how metabolomics can serve as a scientific and regulatory framework for authenticating plant-based meat alternatives, thereby ensuring safety, quality, and consumer health protection. It examines the technological principles of metabolomics, its application in detecting adulteration, verifying nutritional integrity, and monitoring allergens, while also considering its alignment with regulatory standards. The objectives are to critically evaluate current research, highlight best practices in omics-based authentication, identify gaps in standardization, and outline future opportunities for integrating metabolomics into global food safety systems. By doing so, the review seeks to bridge scientific innovation with consumer trust and policy development in the plant-based meat sector.

➢ *Structure of the Paper*

The paper is organized into six major sections to provide a coherent and systematic discussion of the topic. Following the introduction, the second section presents an overview of metabolomics in food authentication, including analytical platforms and data interpretation. The third section examines specific applications of metabolomics in authenticating plant-based meat alternatives, with a focus on biomarker discovery, adulteration detection, and nutritional profiling. Section four discusses regulatory standards and consumer health protection, emphasizing how metabolomics can reinforce transparency and compliance. Section five addresses current challenges and outlines future perspectives for advancing metabolomics-guided authentication. Finally, the paper concludes with a synthesis of findings and implications for industry, regulators, and consumers.

II. METABOLOMICS IN FOOD AUTHENTICATION

➢ *Concept and Principles of Metabolomics*

Metabolomics is the comprehensive study of small-molecule metabolites within biological systems, capturing the dynamic biochemical state of cells, tissues, or whole organisms. It operates on the principle that metabolites serve as downstream products of gene expression and protein activity, thus reflecting real-time physiological and biochemical processes (Fiehn, 2002) as shown in figure 1. By mapping the metabolome, researchers can uncover subtle differences in metabolic fingerprints that arise from environmental conditions, genetic variation, or compositional changes in food products. This characteristic makes metabolomics particularly powerful for food authentication, where even minor deviations in product composition can be detected.

The conceptual foundation of metabolomics is holistic: rather than focusing on individual compounds, it adopts a systems-level approach, integrating high-throughput analytical tools with multivariate data analysis (Nicholson et al., 1999). Through this framework, plant-based meat alternatives can be differentiated from animal-derived products, verified for authenticity, and assessed for quality consistency. For example, metabolomics can distinguish protein sources such as soy or pea by identifying unique metabolic markers. Furthermore, it enables early detection of adulteration, whether intentional substitution with cheaper proteins or contamination with non-declared additives. The principles of metabolomics thus extend beyond chemical analysis, emphasizing pattern recognition, biomarker discovery, and reproducibility to ensure integrity in complex food matrices.

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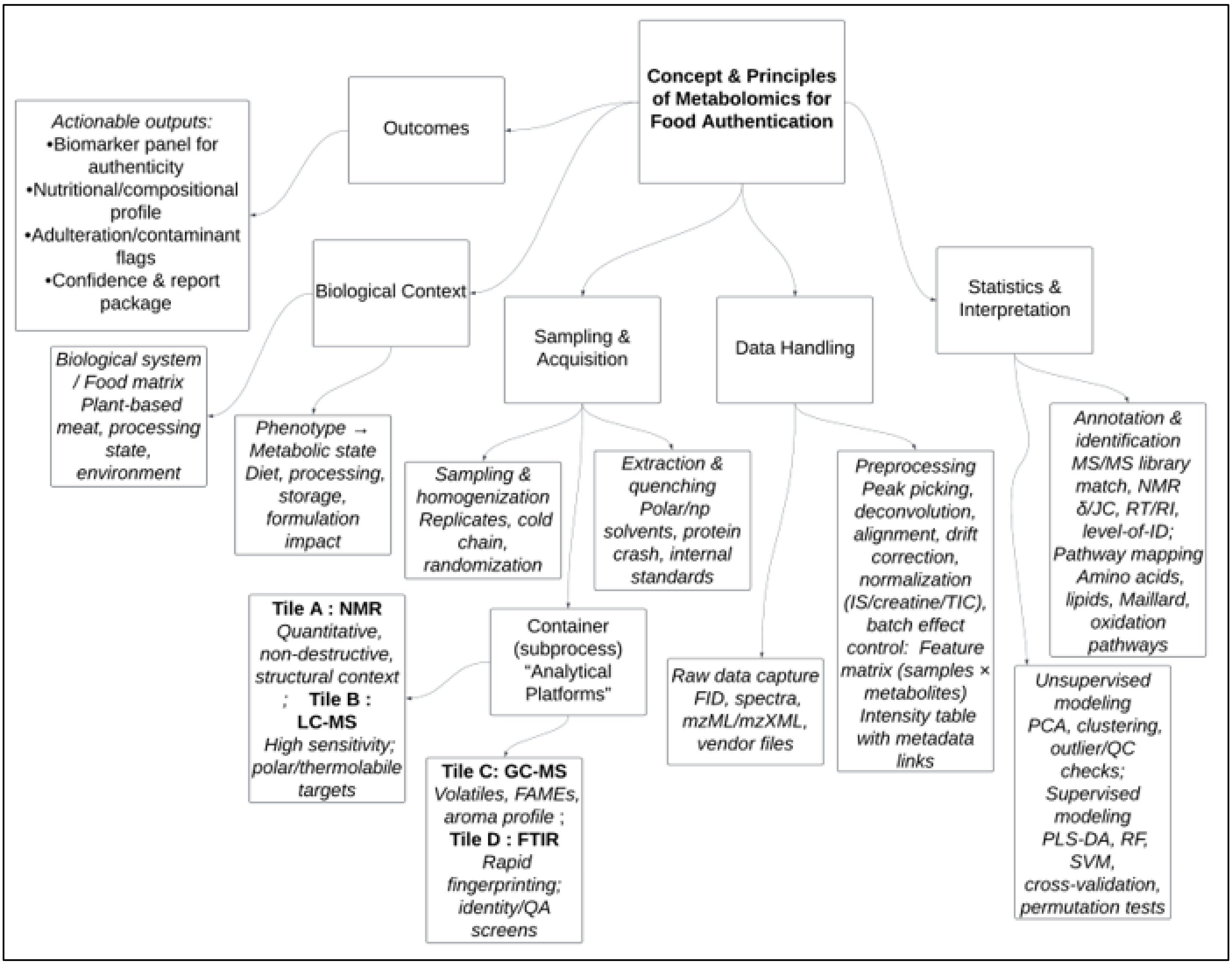

Fig 1 Diagram Illustration of Workflow of Metabolomics for Food Authentication from Sample Analysis to Validated Biomarker Identification.

Figure 1 provides a visual summary of the complete analytical pipeline, illustrating how metabolomics transforms raw biological data into actionable insights for verifying food authenticity. It begins with the biological system or food matrix, representing plant-based meat samples influenced by environmental and processing conditions. Samples undergo extraction and homogenization before analysis using four major analytical platforms—NMR, LC-MS, GC-MS, and FTIR—each capturing different metabolite classes. The generated raw data is processed through data preprocessing and normalization to form a structured feature matrix, which undergoes multivariate statistical modeling (PCA, PLS-DA, machine learning) to identify distinctive metabolic patterns. The diagram then connects these statistical outputs to biological interpretation, where identified metabolites are mapped to pathways such as lipid oxidation or amino acid degradation, revealing biochemical signatures of authenticity or adulteration. Parallel quality control lanes ensure reproducibility through pooled samples and calibration checks, while metadata governance supports traceability and regulatory compliance. The process culminates in actionable outputs—biomarker panels, compositional verification reports, and adulteration alerts—used by regulators and manufacturers to confirm food integrity. Overall, the diagram integrates analytical chemistry, bioinformatics, and quality assurance to depict how metabolomics systematically converts complex chemical data into verified evidence for food authentication and safety.

➢ *Analytical Platforms (NMR, LC-MS, GC-MS, FTIR)*

Metabolomics relies on advanced analytical platforms to generate comprehensive metabolic profiles, with nuclear magnetic resonance (NMR), liquid chromatography-mass spectrometry (LC-MS), gas chromatography-mass spectrometry (GC-MS), and Fourier-transform infrared spectroscopy (FTIR) being the most widely applied. Each technique offers unique strengths suited to food authentication. NMR is highly reproducible and non-destructive, enabling quantitative detection of metabolites across broad chemical classes (Emwas et al., 2019) as presented in table 1. LC-MS provides high sensitivity and resolution for polar and thermolabile compounds, making it effective for profiling amino acids, organic acids, and phytochemicals in plant-based meats.

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GC-MS remains the gold standard for volatile and semi-volatile metabolites, including flavor compounds critical for mimicking sensory properties of animal meat (Scalbert et al., 2014). Its ability to detect fatty acid methyl esters and aroma compounds ensures robust evaluation of authenticity claims. Complementing these approaches, FTIR spectroscopy offers rapid, low-cost fingerprinting of complex food matrices, distinguishing plant-protein formulations from potential adulterants through vibrational spectra.

The integration of these platforms enhances coverage of the metabolome, improving detection sensitivity and reliability. For instance, combining LC-MS and NMR provides both high-resolution identification and quantitative robustness. In authenticating plant-based meat alternatives, such multimodal approaches allow comprehensive profiling of proteins, lipids, and secondary metabolites, enabling accurate verification against regulatory standards. These tools collectively ensure that compositional claims are validated, safeguarding consumer trust and health protection.

Table 1 Summary of Analytical Platforms for Metabolomics in Food Authentication

Platform	Key Features	Applications in Plant-Based Meat	Limitations
NMR	Non-destructive, highly reproducible, quantitative	Global metabolic fingerprinting; quantification of amino acids, organic acids, and sugars	Lower sensitivity compared to MS; costly instrumentation
LC-MS	High sensitivity, broad metabolite coverage	Detects polar/thermolabile compounds; amino acids, phytochemicals, vitamins	Complex data analysis; risk of ion suppression
GC-MS	Gold standard for volatile/semi-volatile compounds	Detection of flavor/aroma metabolites; fatty acid methyl esters	Requires derivatization; limited for non-volatile metabolites
FTIR	Rapid, low-cost, simple fingerprinting	Distinguishes plant proteins from adulterants; quality control	Lower resolution; less specific compared to MS/NMR

➤ *Bioinformatics and Data Interpretation in Metabolomics*

Bioinformatics is indispensable in metabolomics, as high-throughput techniques generate massive datasets requiring advanced computational tools for interpretation. Data analysis typically involves preprocessing, peak detection, normalization, and annotation, followed by multivariate statistical modeling to identify metabolite patterns associated with authenticity and quality (Patti et al., 2012). These workflows enable differentiation between authentic plant-based meats and products containing adulterants or mislabeled protein sources by detecting subtle shifts in metabolic signatures.

Statistical approaches such as principal component analysis (PCA) and partial least squares discriminant analysis (PLS-DA) are widely applied to reduce dimensionality and highlight biomarkers that drive compositional variation. Machine learning algorithms are increasingly incorporated to enhance classification accuracy and predictive power, particularly in distinguishing between plant protein matrices like soy, pea, or wheat (Johnson et al., 2016).

Beyond pattern recognition, bioinformatics facilitates pathway-level interpretation, linking observed metabolite differences to underlying biochemical processes. This mechanistic perspective is critical for regulatory compliance, as it enables verification not only of compositional integrity but also of metabolic stability under processing conditions. For example, identifying pathways linked to lipid oxidation or Maillard reaction products provides insights into flavor authenticity and shelf-life prediction. By integrating statistical rigor with biological context, bioinformatics transforms raw metabolomics data into actionable evidence for food authentication, ultimately supporting consumer health and regulatory enforcement.

III. AUTHENTICATION OF PLANT-BASED MEAT ALTERNATIVES

➤ *Biomarker Discovery for Plant-Based Formulations*

Biomarker discovery is a central application of metabolomics in authenticating plant-based meat formulations, as it enables the identification of specific metabolites that differentiate unique protein sources. Plant proteins such as soy, pea, or mung bean generate distinct metabolic signatures that can be traced using high-resolution mass spectrometry and nuclear magnetic resonance. These biomarkers not only validate compositional claims but also serve as molecular identifiers to monitor processing effects, shelf-life, and nutritional stability (Checa & Mayr, 2020).

Metabolomics-driven biomarker panels are increasingly designed to capture bioactive compounds, such as isoflavones in soy-based formulations or legumin-derived peptides in pea protein. Such markers provide regulators and producers with reliable tools to verify authenticity and prevent fraudulent labeling. Additionally, metabolomics allows for the discovery of secondary metabolite markers, including phenolic compounds, which enhance traceability across supply chains.

In plant-based meat innovation, biomarkers are also essential for mimicking animal meat characteristics, as they can identify metabolic pathways involved in flavor precursors like amino acids and lipid oxidation products. These insights facilitate formulation optimization, ensuring sensory equivalence while maintaining nutritional integrity (Wishart, 2020). By establishing robust biomarker panels, metabolomics offers a scientific basis for regulatory enforcement and consumer assurance, making biomarker discovery a cornerstone for advancing authentication in plant-based formulations.

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➢ *Differentiation from Animal-Based Products*

Differentiating plant-based meat alternatives from animal-based products is critical for authenticity, regulatory compliance, and consumer transparency. Metabolomics provides a powerful platform for distinguishing metabolic signatures unique to plant-derived versus animal-derived proteins. Plant-based formulations exhibit higher levels of phytochemicals, polyphenols, and specific amino acid ratios, while animal meats are characterized by metabolites such as carnosine, creatine, and taurine, which are absent in plant matrices (Clarke et al., 2020) as represented in figure 2.

Advanced LC-MS and NMR-based profiling have demonstrated clear clustering of plant versus animal products in multivariate statistical models, allowing reliable classification even in highly processed samples. For instance, metabolic fingerprints can reveal lipid class differences, with plant alternatives typically showing higher unsaturated fatty acid content, contrasting with the saturated profiles dominant in animal meat (Okpanachi, et al., 2025).

Such differentiation is not merely academic but has direct regulatory implications, especially where mislabeling or cross-contamination is suspected. Consumer trust depends on transparency, and metabolomics enables regulators to substantiate claims of “100% plant-based” or “free from animal derivatives” with biochemical evidence (Pedrosa, et al., 2021). Furthermore, differentiation extends to functional attributes such as digestibility, where metabolic profiling identifies distinct breakdown products between plant and animal proteins (Onyekan, et al., 2025). In this way, metabolomics bridges compositional verification with health relevance, supporting informed dietary choices and ensuring authenticity in an increasingly competitive food market.

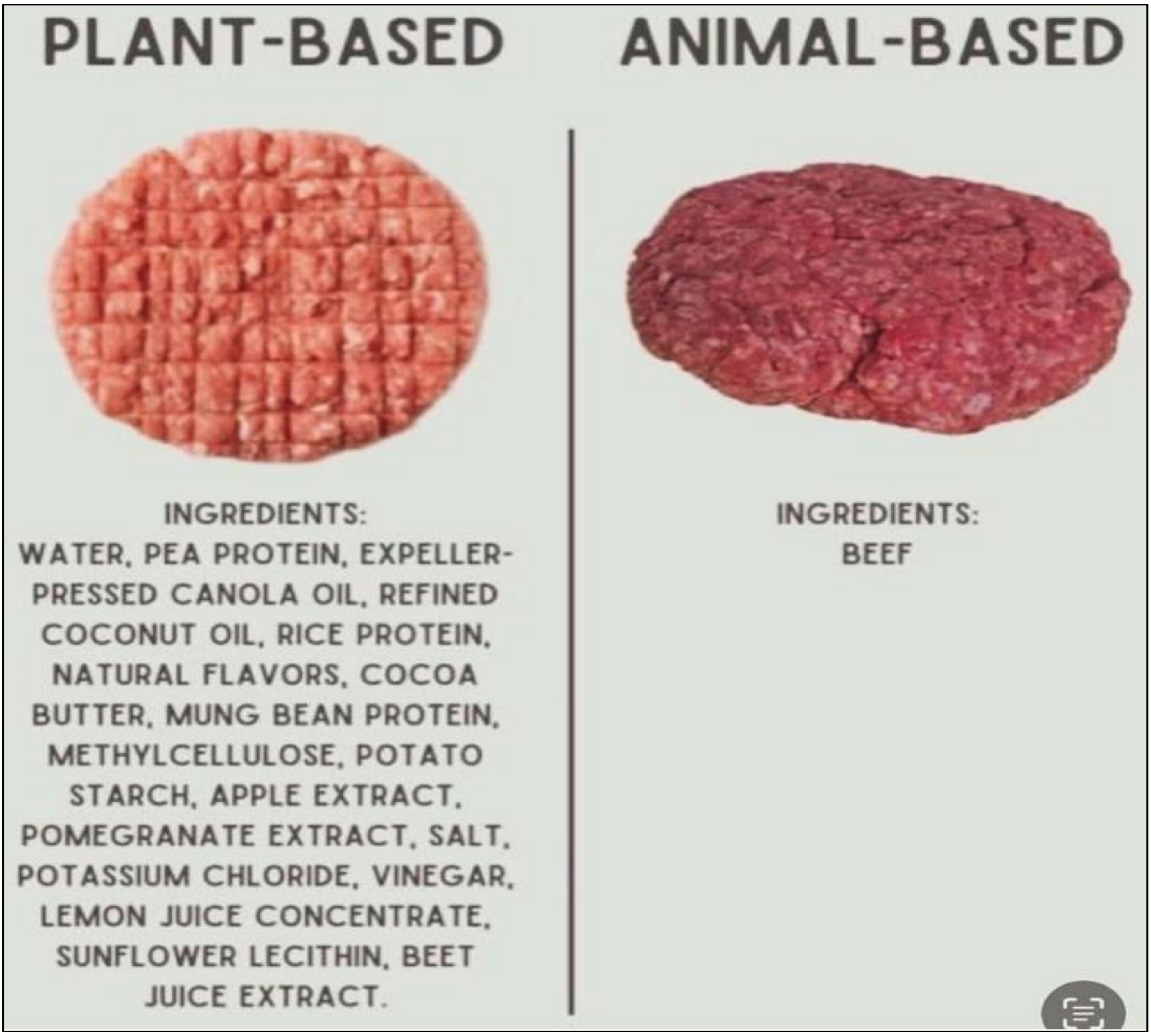

Fig 2 Picture of Metabolomic Differentiation of Plant-Based and Animal-Based Burgers Highlighting Distinct Biochemical Signatures Despite Visual Similarity (Foo, A. Nd).

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Figure 2 illustrates the compositional differences central to *3.2 Differentiation from Animal-Based Products*, contrasting a plant-based burger patty with an animal-based beef patty. The plant-based product is formulated from a complex mixture of pea protein, mung bean protein, rice protein, vegetable oils, starches, extracts, and additives such as methylcellulose and beet juice extract, designed to mimic the taste, texture, and appearance of beef. In contrast, the animal-based counterpart consists solely of beef muscle tissue, which naturally contains metabolites such as creatine, taurine, carnosine, and heme iron compounds unique to animal physiology. From a metabolomics perspective, these differences create distinct metabolic fingerprints: plant-based alternatives exhibit higher levels of phytochemicals, polyphenols, and unsaturated fatty acids derived from legumes and oils, while beef demonstrates signatures of animal-derived amino acids, saturated fats, and muscle-specific metabolites. Analytical platforms like LC-MS and NMR can capture these biochemical profiles, allowing regulators and researchers to differentiate products beyond visual similarity. This metabolic distinction is crucial for verifying authenticity, ensuring correct labeling, and protecting consumers from misrepresentation, as visually the two products are designed to appear nearly identical despite their fundamentally different biochemical origins.

➢ *Detecting Adulteration and Substitution*

Adulteration and substitution remain pressing concerns in the plant-based meat sector, where fraudulent practices may involve the replacement of premium ingredients with cheaper alternatives or the addition of undeclared compounds to enhance texture and flavor. Metabolomics provides an advanced analytical strategy to detect these practices by uncovering subtle deviations in metabolic profiles. Sophisticated techniques such as LC-MS and FTIR, when combined with multivariate statistical analysis, can identify adulterants at trace levels, ensuring that even minimal substitutions are uncovered (Ellis et al., 2022).

Metabolite fingerprinting has proven effective in distinguishing authentic pea or soy protein from mixtures adulterated with fillers such as starches or low-cost proteins. Furthermore, isotopic metabolomics approaches can validate geographical origin and production method, adding an additional layer of authenticity. Such applications are especially valuable in supply chains where ingredient transparency is limited, and the risks of fraudulent substitution are heightened (Haider, et al., 2024).

The consumer health implications of adulteration are significant, as undisclosed allergens or toxins may enter the food system through deceptive practices. By leveraging biomarker panels and predictive models, metabolomics not only safeguards authenticity but also enhances consumer protection (Ononiwu, et al., 2023). The adoption of these methods in regulatory frameworks ensures accountability across the supply chain, mitigating both economic fraud and potential public health hazards.

➢ *Nutritional and Compositional Profiling*

Nutritional and compositional profiling through metabolomics plays a vital role in validating the health claims of plant-based meat alternatives. Unlike traditional proximate analysis, metabolomics provides high-resolution insights into amino acids, fatty acids, vitamins, and secondary metabolites, offering a comprehensive nutritional fingerprint (García-García et al., 2020) as presented in table 2. This level of detail ensures that products marketed as nutritionally equivalent to animal meat truly meet compositional benchmarks for protein quality, micronutrients, and bioactive compounds.

Metabolomic profiling highlights key differences in nutrient composition, such as higher levels of unsaturated fatty acids and phytosterols in plant-based meats compared to animal counterparts. Additionally, fortification strategies, including the addition of iron, vitamin B12, or omega-3 fatty acids, can be evaluated for bioavailability and metabolic stability (James, et al., 2025). By assessing the impact of processing on nutrient retention, metabolomics also informs product development, ensuring that nutritional quality is preserved from raw material to finished product (Zhang et al., 2023).

From a consumer health perspective, accurate nutritional profiling is essential for regulatory compliance, particularly where products are marketed as healthier or more sustainable alternatives. By integrating nutritional biomarkers with authenticity metrics, metabolomics strengthens the scientific foundation for consumer trust (Ijiga, et al., 2025). Ultimately, comprehensive profiling ensures that plant-based meat alternatives not only replicate sensory attributes but also deliver verified nutritional benefits, aligning with both public health goals and regulatory standards.

Table 2 Summary of Nutritional and Compositional Profiling of Plant-Based Meat Alternatives

Aspect	Role of Metabolomics	Examples	Significance
Protein quality	Identifies amino acid composition and peptide biomarkers	Differentiating soy, pea, and wheat proteins	Ensures nutritional equivalence to animal proteins
Lipid profiling	Characterizes fatty acid and sterol content	Unsaturated fatty acids, phytosterols	Supports health claims and cardiovascular benefits
Micronutrients	Evaluates bioavailability of vitamins/minerals	Iron, B12, omega-3 fortification	Validates fortification strategies
Processing impact	Assesses nutrient retention post-processing	Maillard reaction products, lipid oxidation	Ensures nutritional stability and safety

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IV. REGULATORY STANDARDS AND CONSUMER HEALTH PROTECTION

➢ *Current Food Authentication Regulations*

Food authentication regulations are designed to safeguard consumers from fraudulent practices, protect public health, and ensure fair trade across global markets. Regulatory bodies such as the European Food Safety Authority (EFSA), the U.S. Food and Drug Administration (FDA), and Codex Alimentarius Commission have progressively emphasized authenticity as a core component of food safety frameworks (Khan et al., 2021). These regulations mandate accurate labeling, enforce standards for ingredient sourcing, and require systematic monitoring for contaminants, allergens, and adulterants.

The emergence of plant-based meat alternatives presents unique regulatory challenges due to the complexity of formulations and their claims of nutritional equivalence to animal meat. Regulatory standards now extend beyond basic labeling to include nutritional verification, compositional integrity, and allergen disclosure (Idika, & Ijiga, 2025). Furthermore, global trade integration has heightened the importance of harmonized authentication protocols to prevent mislabeling and fraud in cross-border supply chains (Spink et al., 2020).

To address these vulnerabilities, regulations increasingly adopt a risk-based approach, focusing on transparency and accountability throughout the supply chain. Plant-based products are particularly subject to fraud risks, including protein substitution and misrepresentation of sustainability claims. Thus, current regulatory landscapes emphasize traceability systems, standardized testing methods, and proactive fraud prevention mechanisms. These frameworks create the foundation upon which metabolomics can be integrated, offering higher sensitivity and specificity in validating the authenticity of plant-based meats and enhancing consumer protection.

➢ *Integration of Metabolomics in Regulatory Frameworks*

The integration of metabolomics into regulatory frameworks is transforming how food authentication and safety are enforced. Traditional regulatory tools often rely on targeted chemical analysis or DNA-based methods, which, while useful, lack the capacity to capture the full complexity of food matrices. Metabolomics, with its systems-level coverage of metabolites, provides regulators with a robust approach to verify product authenticity, detect adulteration, and ensure nutritional compliance (García-Cañas et al., 2020) as presented in table 3.

One of the key advantages of metabolomics is its ability to provide untargeted screening, enabling regulators to identify novel adulterants or unknown contaminants. Regulatory agencies are increasingly considering metabolomic datasets as admissible evidence for compliance verification (Enyejo, et al., 2024). For example, fingerprinting plant-based meat alternatives against standardized metabolomic profiles can provide legally defensible authentication data. This improves traceability and ensures consistent enforcement across jurisdictions (Li, et al., 2021).

Additionally, metabolomics supports the validation of health and sustainability claims, aligning with evolving consumer expectations and policy priorities. By integrating metabolomics into regulatory pipelines, agencies can monitor compositional equivalence, fortification efficacy, and potential allergenicity with unprecedented accuracy. However, harmonization of methodologies and databases is essential to ensure reproducibility across laboratories. As metabolomics becomes standardized, its integration within regulatory frameworks will reinforce consumer trust while strengthening global food safety governance.

Table 3 Summary of Integration of Metabolomics in Regulatory Frameworks

Dimension	Contribution of Metabolomics	Regulatory Benefits	Challenges
Authentication	Provides untargeted metabolic fingerprints	Legally defensible verification of plant-based claims	Standardization of methods needed
Safety monitoring	Detects unknown adulterants and contaminants	Enhances risk assessment beyond targeted testing	Variability across labs
Nutritional claims	Validates compositional equivalence	Strengthens enforcement of health/sustainability labeling	Need for harmonized datasets
Trade compliance	Creates reference profiles for international use	Facilitates cross-border authenticity checks	Integration with existing systems

➢ *Monitoring Allergens, Toxins, and Contaminants*

Monitoring allergens, toxins, and contaminants is a critical dimension of food safety where metabolomics offers distinct advantages over traditional assays. Plant-based meat alternatives often incorporate protein-rich ingredients such as soy, wheat, or legumes, which are among the most common allergens worldwide. Metabolomics enables precise detection of allergenic peptides and cross-reactive compounds, even in highly processed products, ensuring compliance with allergen labeling regulations (Rao & Dixon, 2020).

Beyond allergens, metabolomics also provides powerful tools for detecting chemical contaminants, including pesticide residues, heavy metals, and industrial toxins that may enter raw materials during cultivation or processing. Advanced LC-MS and GC-MS metabolomic workflows have proven capable of identifying these compounds at trace levels, thereby enhancing consumer protection and regulatory enforcement (Zhang et al., 2021).

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Mycotoxins present another critical hazard, especially in legume-based protein sources vulnerable to fungal contamination. Metabolomic profiling allows simultaneous detection of multiple mycotoxins and their metabolic derivatives, providing a more comprehensive assessment than conventional targeted assays (Enyejo, et al., 2024). Moreover, metabolomics contributes to proactive risk assessment by tracking metabolic pathways involved in toxin biosynthesis, thereby predicting potential contamination risks before they fully manifest. By offering high sensitivity and predictive insights, metabolomics supports regulatory objectives of ensuring allergen safety, toxin monitoring, and contaminant control in plant-based meat alternatives.

➢ *Ensuring Transparency and Traceability in Supply Chains*

Transparency and traceability are essential to maintaining consumer confidence in plant-based meat alternatives, especially as supply chains expand across global markets. Omics-driven tools, particularly metabolomics, provide molecular-level traceability by linking products to their raw material origins through unique metabolic fingerprints. These fingerprints serve as verifiable authenticity markers, ensuring that claims regarding plant protein sources, production methods, and geographical origins are substantiated (Menezes et al., 2020) as shown in figure 3.

Global supply chains introduce vulnerabilities, including substitution, mislabeling, and contamination risks. Metabolomics allows regulators and industry stakeholders to establish product-specific databases, enabling rapid comparison of commercial samples against reference profiles. This capability supports real-time verification of authenticity throughout distribution, reducing the likelihood of fraud and enhancing accountability (Ribeiro et al., 2022).

Additionally, transparency involves not only origin verification but also the ability to communicate product integrity to consumers. By integrating metabolomics data with blockchain-enabled platforms, producers can deliver verifiable information on ingredient sourcing, sustainability practices, and compliance with safety standards (Babatuyi, et al., 2024). Such integration strengthens consumer trust and positions metabolomics as a cornerstone of transparent supply chain governance. Ultimately, these measures reinforce both regulatory oversight and market credibility, ensuring that plant-based meat alternatives remain trustworthy and safe across diverse markets.

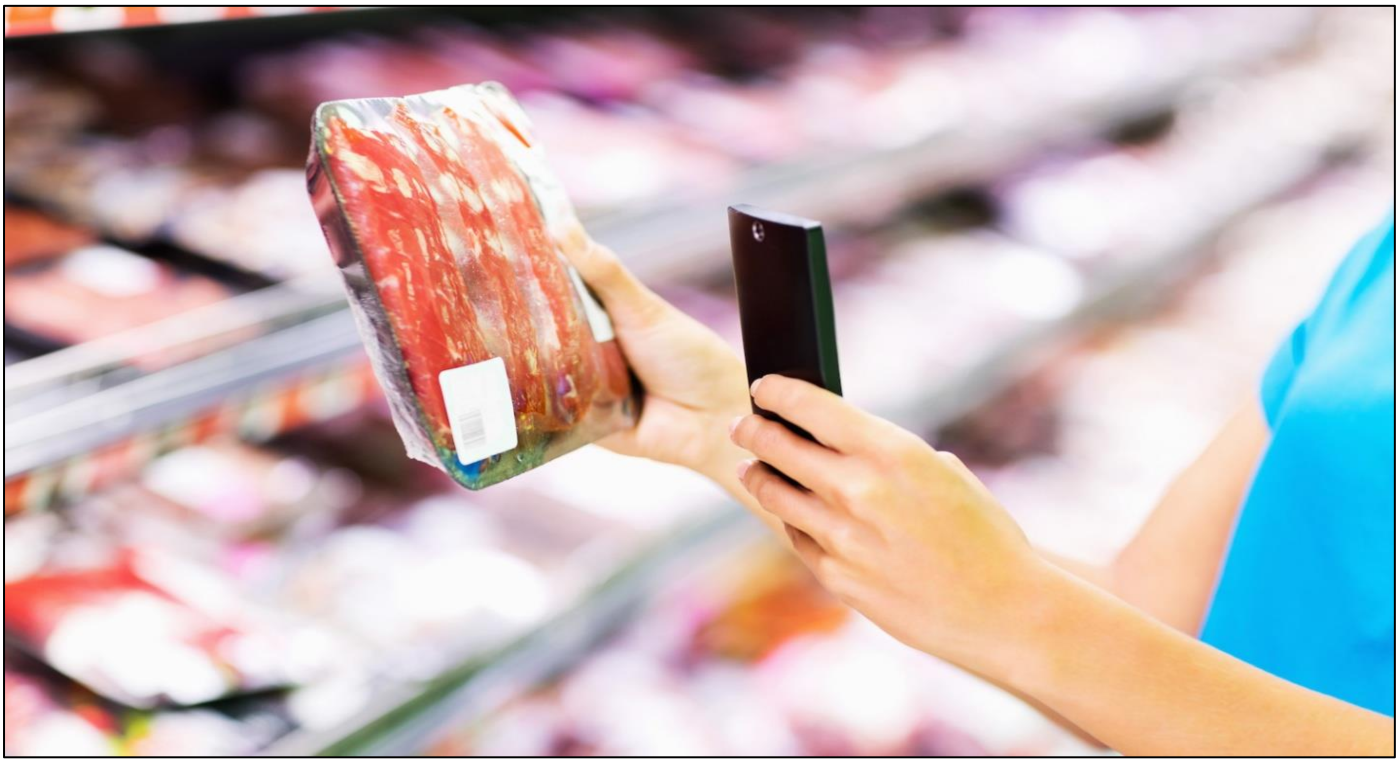

Fig 3 Picture of Metabolomics-Enabled Digital Traceability Enhancing Transparency and Consumer Trust Across Food Supply Chains (Foodtank, 2021).

Figure 3 shows a consumer scanning the barcode of a packaged food product in a retail environment, visually representing the concept of *4.4 Ensuring Transparency and Traceability in Supply Chains*. The act of digitally verifying a product's information exemplifies how modern authentication technologies—enhanced by metabolomics—support end-to-end transparency in food systems. Through the integration of metabolomic data with digital traceability tools such as QR codes and blockchain platforms, each product can be linked to a verified biochemical profile that authenticates its composition, origin, and processing history. This molecular-level verification ensures that plant-based meat alternatives, for instance, can be traced back to their raw material sources and validated against reference metabolomic databases to confirm authenticity and quality. Furthermore, the combination of consumer-facing scanning technology and

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metabolomic data enhances real-time accountability by allowing users to access detailed information about ingredients, allergens, and sustainability certifications. From a regulatory perspective, this integrated approach establishes a digital chain of custody, reducing opportunities for fraud, mislabeling, or contamination within globalized supply networks. The image effectively captures the intersection between consumer empowerment and scientific verification, emphasizing how metabolomics-driven traceability fosters a transparent, trustworthy, and data-driven food ecosystem.

V. CHALLENGES AND FUTURE PERSPECTIVES

➢ *Standardization and Reproducibility of Metabolomics Data*

Standardization and reproducibility remain critical challenges in metabolomics, particularly in regulatory contexts where plant-based meat authentication requires consistent results across laboratories. Variability in sample preparation, instrument calibration, and data processing often leads to discrepancies in metabolite identification, undermining the reliability of authentication outcomes (Dunn et al., 2021). For instance, differences in extraction solvents or chromatographic conditions can significantly alter metabolic profiles, making cross-laboratory comparisons difficult.

To address this, consensus-driven protocols and standardized reference materials are being developed to harmonize workflows (Awotiwon, et al., 2024). International initiatives are promoting benchmark datasets and spectral libraries, which serve as quality assurance tools to validate metabolite identification. These resources are essential when metabolomics data is applied in food regulation, where reproducibility determines the admissibility of findings for legal enforcement (Broadhurst et al., 2020).

Additionally, computational reproducibility is enhanced through open-source bioinformatics platforms that mandate transparent reporting of data preprocessing pipelines. Reporting standards, such as the Metabolomics Standards Initiative (MSI), have been adapted to encourage consistent metadata documentation (Atalor, 2024). For plant-based meat alternatives, ensuring reproducibility is vital for verifying nutritional equivalence, detecting adulterants, and maintaining consumer trust. Without robust standardization, metabolomics cannot fully deliver on its promise as a regulatory tool for global food authentication.

➢ *Technological and Infrastructural Limitations*

Despite its transformative potential, metabolomics faces technological and infrastructural barriers that hinder its widespread adoption in food authentication. High-resolution analytical platforms such as LC-MS and NMR require substantial investment, both in instrumentation and in maintaining controlled laboratory environments. This creates disparities between well-resourced institutions and smaller regulatory laboratories, limiting accessibility in low- and middle-income countries (Roberts & Koulman, 2020) as represented in figure 4.

Technical limitations also arise from incomplete metabolite libraries and databases, which constrain accurate identification. Many food-derived metabolites remain uncharacterized, making authentication of complex plant-based formulations particularly challenging. Instrument sensitivity and stability further affect the ability to detect low-abundance metabolites, especially when evaluating trace adulterants or contaminants (Rinschen et al., 2019).

Infrastructure constraints extend to skilled personnel, as metabolomics requires expertise in analytical chemistry, bioinformatics, and statistics. The shortage of trained analysts restricts the pace at which metabolomics can be embedded into regulatory pipelines (Atalor, & Enyejo, 2025). Furthermore, the large volumes of high-dimensional data demand advanced computational resources, which are often unavailable outside of specialized research centers.

For plant-based meat authentication, these limitations can delay verification timelines and reduce regulatory responsiveness (Akindote, et al., 2024). Addressing technological gaps through capacity-building, collaborative platforms, and investment in open-access metabolomic databases will be essential to overcome infrastructural bottlenecks and democratize the application of metabolomics in global food systems.

Figure 4 provides a comprehensive visualization of the major barriers hindering the large-scale application of metabolomics in regulatory and industrial contexts. At the center lies the hub *"Metabolomics Implementation Challenges,"* symbolizing the convergence of four key constraint domains—technological, infrastructural, computational, and human resource limitations. The technological branch highlights issues such as high costs of advanced analytical platforms like LC-MS and NMR, limited sensitivity for low-abundance metabolites, and incomplete spectral databases that constrain metabolite identification. The infrastructural branch depicts unequal access to laboratory facilities, weak cold-chain logistics compromising sample stability, and inconsistent calibration systems that undermine reproducibility. The data management branch emphasizes computational strain from high-throughput metabolomics, insufficient cloud infrastructure, and non-standardized pipelines leading to fragmented analyses. Meanwhile, the human resource branch underscores the shortage of trained analysts, minimal interdisciplinary collaboration, and the absence of continuous professional development programs. Arrows connecting these branches to the central hub illustrate their interdependence—technological limitations exacerbate data bottlenecks, while inadequate training perpetuates analytical variability. The diagram concludes with a bottom panel summarizing the overall impact: delayed analyses, inconsistent validation, and reduced regulatory confidence in metabolomics-based food authentication. Collectively, it conveys that addressing these interconnected barriers is critical for advancing reliable, standardized, and globally accessible metabolomics frameworks.

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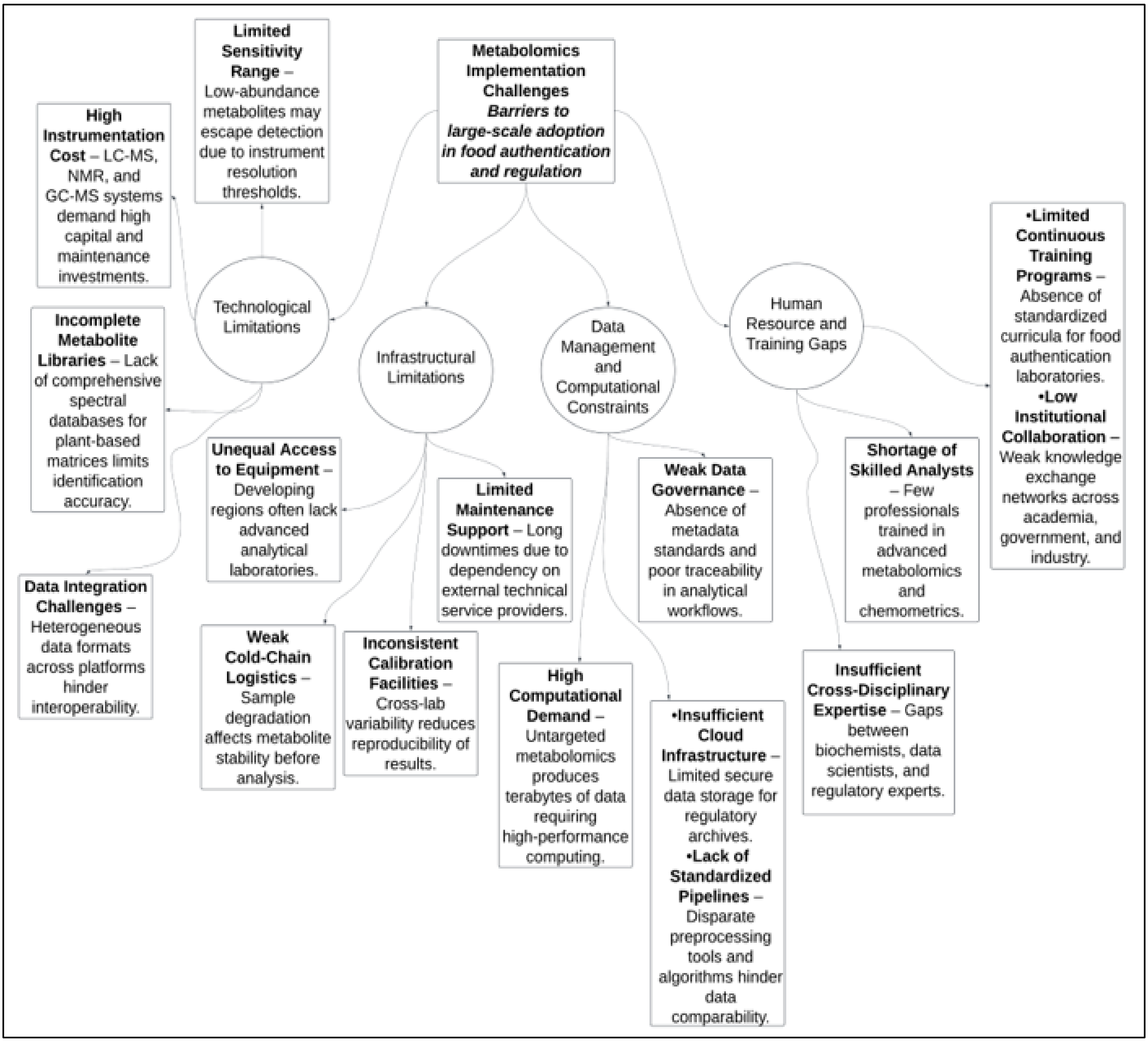

Fig 4 Diagram Illustration of Key Technological and Infrastructural Barriers Limiting Large-Scale Implementation of Metabolomics in Food Authentication Systems.

➢ *Ethical and Policy Considerations*

The integration of metabolomics into food authentication frameworks raises important ethical and policy considerations. Ethical issues primarily revolve around transparency, consumer autonomy, and equitable access to authenticated food systems. Omics technologies generate complex datasets, and the interpretation of these findings for regulatory purposes requires careful communication to avoid misrepresentation or consumer misunderstanding (Kumar, et al., 2022) as presented in table 4. Policy challenges include the protection of proprietary formulation data when plant-based meat producers undergo regulatory testing. Companies may be reluctant to share metabolomic fingerprints if they perceive risks to intellectual property (James, 2022). This necessitates the development of policies that balance confidentiality with public health priorities. Moreover, disparities in access to advanced technologies across regions raise concerns about global equity, as weaker infrastructures may struggle to implement metabolomics-based regulations (Shah et al., 2020).

Another dimension is the ethical use of sustainability claims. If metabolomics is used to validate environmental or nutritional labeling, misleading or selective disclosure could undermine consumer trust. Policy frameworks must therefore ensure that metabolomics data is not only scientifically rigorous but also communicated in ways that empower consumers to make informed choices (Idika, et al., 2021). By embedding ethical safeguards and inclusive policies, regulators can harness metabolomics to promote consumer health while maintaining fairness in food systems.

Table 4 Summary of Ethical and Policy Considerations in Metabolomics-Guided Authentication

Issue	Description	Implications	Policy Needs
Transparency	Communication of metabolomics data to consumers	Risk of misinterpretation or confusion	Clear labeling standards
Intellectual property	Proprietary metabolomic fingerprints from manufacturers	Reluctance to share formulation data	Policies balancing confidentiality and safety
Equity of access	Disparities in access to metabolomics infrastructure	Developing countries face adoption challenges	Capacity building and technology transfer
	Verification of eco-labeling using metabolomics	Potential misuse of selective data	Ethical disclosure frameworks

➢ *Future Research Directions in Metabolomics-Guided Authentication*

Future research in metabolomics-guided authentication will likely focus on integrating multi-omics approaches to enhance the precision and reliability of food verification. Combining metabolomics with proteomics, transcriptomics, and genomics can provide a holistic understanding of plant-based meat formulations, capturing interactions between nutrient composition, metabolic stability, and health outcomes (Misra et al., 2021). Such integrated approaches will enable the development of biomarker panels that simultaneously assess authenticity, nutritional quality, and safety.

Another promising direction involves real-time and portable metabolomics platforms. Miniaturized NMR and MS devices, coupled with artificial intelligence-driven analytics, could allow regulators and producers to conduct on-site authentication at different stages of the supply chain (Amebleh, et al., 2021). This would dramatically improve responsiveness in detecting adulteration or contamination.

Future research must also expand reference metabolomic databases by systematically cataloging plant-based protein sources and their processing derivatives. Such repositories will provide the foundation for standardization and cross-regional comparability (Ulaszewska et al., 2020). Furthermore, predictive modeling using machine learning will enhance the detection of emerging fraud patterns, enabling proactive regulation.

Finally, translational research should explore the policy and consumer dimensions of metabolomics adoption. Investigating how metabolomics data influences consumer perception, trust, and purchasing behavior will be crucial in ensuring its role not only as a regulatory tool but also as a driver of sustainable and transparent food systems.

VI. CONCLUSION

➢ *Summary of Key Findings*

The review highlights metabolomics as a transformative approach for authenticating plant-based meat alternatives, offering robust solutions to challenges of safety, labeling accuracy, and consumer trust. Key findings demonstrate that metabolomics enables comprehensive biomarker discovery, allowing regulators and manufacturers to identify specific metabolic fingerprints of raw materials such as soy, pea, and wheat. These biomarkers not only differentiate plant-based proteins from animal-derived counterparts but also detect adulteration and substitution with high sensitivity. Analytical platforms such as NMR, LC-MS, GC-MS, and FTIR have been shown to complement each other, providing both breadth and depth in metabolite coverage, while bioinformatics tools enhance data interpretation through multivariate models and predictive analytics.

The findings also highlight that metabolomics extends beyond chemical authentication by enabling nutritional and compositional profiling, ensuring plant-based meats deliver equivalent or superior health benefits compared to animal products. Furthermore, metabolomics demonstrates significant value in monitoring allergens, toxins, and contaminants, strengthening consumer protection and regulatory enforcement. Current regulatory frameworks are evolving to integrate metabolomics data, though standardization and reproducibility remain challenges that must be addressed. Overall, the study confirms that metabolomics is uniquely positioned to bridge the gap between scientific innovation, industry needs, and regulatory oversight, ensuring the authenticity and integrity of plant-based meat alternatives in a rapidly expanding global market.

➢ *Implications for Regulatory Authorities and Industry*

The findings of this review carry significant implications for both regulatory authorities and the plant-based food industry. For regulators, metabolomics represents an advanced, scientifically rigorous tool that can enhance the enforcement of food authentication laws. By incorporating metabolomics-based protocols, agencies can transition from reliance on targeted, single-analyte tests toward comprehensive, systems-level verification capable of identifying known and unknown adulterants. This shift supports the development of harmonized global standards, critical for cross-border trade in plant-based products. Regulators must also adapt policies to ensure data reproducibility and inter-laboratory comparability, promoting trust in metabolomics as a legally defensible tool for coampliance monitoring.

For industry stakeholders, metabolomics provides actionable insights into quality assurance and product innovation. By integrating metabolomic profiling into production pipelines, manufacturers can validate ingredient sourcing, monitor nutritional equivalence to animal meat, and optimize formulations for improved taste and health outcomes. Additionally, metabolomics can serve as a differentiator in highly competitive markets, enabling producers to substantiate claims such as "clean label," "allergen-free," or "sustainably sourced." Importantly, the technology offers companies the ability to proactively detect risks in supply chains, reducing the likelihood of costly recalls or reputational damage. Thus, metabolomics is not merely a regulatory requirement but also a strategic tool that enhances transparency, strengthens consumer trust, and supports innovation across the plant-based meat industry.

➤ *Prospects for Consumer Health and Sustainable Food Innovation*

Metabolomics-guided authentication opens promising prospects for advancing consumer health and driving sustainable food innovation. From a health perspective, metabolomics ensures that plant-based meat alternatives meet their nutritional claims, offering consumers products that are not only authentic but also beneficial to well-being. Comprehensive profiling allows manufacturers to validate fortification strategies, such as the addition of iron, vitamin B12, or omega-3 fatty acids, and confirm bioavailability through metabolic signatures. Furthermore, metabolomics enhances consumer safety by detecting allergens and contaminants with precision, thereby preventing exposure to potentially harmful compounds. This contributes directly to public health protection and long-term consumer confidence in plant-based foods.

On the innovation front, metabolomics fosters the development of next-generation plant-based products tailored to diverse dietary needs. By linking metabolic markers to flavor, texture, and nutritional outcomes, manufacturers can optimize formulations that closely replicate animal meat while aligning with sustainability goals. Additionally, metabolomics supports sustainable sourcing by verifying geographical origin and production methods, enabling transparency in eco-labeling and carbon footprint reporting. As consumer demand shifts toward environmentally responsible choices, metabolomics provides the scientific foundation for substantiating sustainability claims. Ultimately, the integration of metabolomics into food innovation pipelines will not only safeguard authenticity but also accelerate the transition to resilient, health-promoting, and sustainable food systems that address both consumer expectations and global environmental challenges.

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