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Innovations and recent advances in meat products technology: A comprehensive review

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Abstract

The meat industry is undergoing a paradigm shift driven by the dual needs of global food security and sustainable production. This review explores recent technological breakthroughs that address traditional challenges in meat processing, including shelf-life extension, quality enhancement, and supply chain transparency. We examine non-thermal technologies such as Irradiation and Pulsed Electric Field (PEF), which offer superior microbial safety and improved meat tenderness without compromising nutritional value. Furthermore, the article delves into the transformative potential of 3D Printing (3DP) for customized nutrition and Artificial Intelligence (AI) for precision processing. To address growing concerns regarding food fraud and safety, the integration of Blockchain technology for end-to-end traceability is analyzed. While these innovations offer significant environmental and economic benefits, challenges regarding high commercialization costs and consumer acceptance remain. This review synthesizes current research to provide a roadmap for the future of meat science, highlighting the transition toward a more efficient, ethical, and consumer-centric industry.

Keywords: Meat technology, irradiation, pulsed electric field, 3d printing, blockchain, artificial intelligence

Introduction

Meat serves as a cornerstone of human nutrition, functioning as a primary dietary component that provides high-quality, highly bioavailable protein (approximately 70%) and a suite of essential nutrients. It is recognized as a dense source of B-complex vitamins, with a particular emphasis on Vitamin B₁₂, and provides heme iron in a form that significantly enhances the absorption of iron from other dietary sources. While the biological value of meat protein is slightly lower than that of egg albumin, its unique amino acid profile effectively complements plant-based nutrition, establishing meat as a vital element for achieving balanced meals and meeting global protein requirements.

The nutritional architecture of meat is diverse, with macronutrient and micronutrient profiles varying significantly across different animal species. As noted by Afzal *et al.* (2024) ^[1], meat is predominantly composed of protein, maintaining an average concentration of approximately 23% across most varieties. In contrast, the lipid profile exhibits considerable fluctuation; lean cuts of red meats, such as beef and lamb, typically maintain fat percentages below 7%, whereas chicken contains approximately 4.7 g of fat.

On a global and domestic scale, the poultry industry has emerged as the most rapidly expanding segment of the livestock sector. In India, the scale of this growth is evidenced by a total poultry population estimated at 851.81 million according to the 20th Livestock Census. By 2024, India achieved a global rank of 4th in broiler chicken production, generating an annual output of approximately 4.5 million tons of broiler meat. Kumar *et al.* (2022) ^[22] specifies that this sector is geographically concentrated, with states such as Andhra Pradesh, Tamil Nadu, Karnataka, and Telangana collectively dominating the national poultry landscape. This industrial expansion coincides with the forces of globalization, which have fundamentally altered consumer lifestyles and dietary patterns. Sorenson *et al.* (2011) ^[31] and Siro *et al.* (2008) ^[30] highlight that an expanding public knowledge regarding the nexus between diet and

health has catalyzed transformations within the processed food industry. To meet these evolving demands while addressing economic constraints, there is a critical shift toward innovative processing solutions. According to Thangavelu *et al.* (2019) [32], the integration of advanced meat-processing technologies to replace traditional, energy-intensive methods offers a viable pathway to significantly reduce energy consumption and overall production costs.

Non-Thermal Processing Technologies

Foundations of Modern Meat Technology

Recent advancements in food manufacturing have pivoted toward processing technologies that enhance flavour profiles while preserving staple recipes. The adoption of these innovations is complex, influenced by development costs, relative advantages, and the degree of regulatory compliance. Both non-thermal and thermal technologies are now utilized to physically disrupt muscle structures and enhance protein denaturation, directly impacting the texture and juiciness of meat products. Warner *et al.* (2017) [35] suggest that the future of the industry lies in combining these inventive technologies to offer diverse and acceptable surfaces for meat consumers.

Food Irradiation: Principles and Applications

Irradiation involves exposing meat to medium-to-low-level energy radiation, such as gamma rays, X-rays, or high-energy electrons. This ionizing radiation releases energy sufficient to displace electrons from atoms or molecules, effectively eliminating harmful bacteria and extending shelf life. The mechanism of action is two-fold:

- **Direct Action:** Irradiation breaks the bonds between base pairs in microbial genetic material (DNA or RNA), neutralizing the cell's reproductive ability.
- **Indirect Action:** The process creates free radicals and reactive oxygen species from water molecules, further damaging microbial structures.

While irradiation is a cost-effective and efficient method with minimal temperature increase (2.8°C per 10 kGy), Jia *et al.* (2009) [17] caution that it can induce biochemical changes in lipids and proteins. However, these can be mitigated by combining irradiation with freezing or heating to preserve nutritional and sensory qualities.

Pulsed Electric Field (PEF) Technology

As an electrical-based preservation method, PEF utilizes microsecond high-voltage pulses (10 - 60 kV) to create pores in cell membranes - a process known as electroporation. This leads to cell disintegration and microbial inactivation without the detrimental effects of high heat. Gomez *et al.* (2019) [12] identify PEF as a promising strategy for destroying living cells while maintaining the core features of meat products. Recent studies highlight several processing advantages of PEF:

- **Quality Enhancement:** PEF disrupts muscle fibers and connective tissue, weakening collagen structures to improve meat tenderness and colour.

- **Digestibility:** Bhat *et al.* (2019) [3] observed that PEF treatment significantly increases soluble protein levels and improves *in vitro* protein digestion kinetics by partially unfolding meat proteins.
- **Efficiency:** PEF accelerates fermentation, reduces drying time, and enables the production of low-salt products by speeding up curing and brine uptake.

Despite these benefits, Kantono *et al.*, (2019) [20] noted that PEF may increase fat oxidation in frozen-thawed muscles, requiring careful management of storage conditions to maintain sensory quality.

Emerging digital and additive manufacturing frontiers in meat science

3D Printing of Meat: Addressing Sustainability and Customization

Three-dimensional printing (3DP), also recognized as Additive Manufacturing (AM) or rapid prototyping, represents a transformative shift in meat production. This technology facilitates the creation of complex solid objects from digital blueprints, offering a promising solution to the sustainability challenges and high environmental footprints associated with conventional livestock farming. By producing cell-cultured meat, 3DP can replicate the nutritional profile and organoleptic properties of traditional meat while simultaneously reducing land occupation and waste emissions.

The methodology primarily utilizes raw materials in powder or paste forms, enabling the rapid production of custom-shaped items without the need for intensive pre-processing or traditional butchery. Beyond environmental benefits, 3DP provides a platform for personalized nutrition, catering to the specific dietary requirements of vulnerable or specialized populations, such as children, the elderly, pregnant women, and military personnel.

Technical Framework and Bio-ink Development

The integration of tissue engineering, biochemistry, and advanced manufacturing forms the scientific foundation of 3D-printed meat. The production sequence follows four critical stages:

- **Cell Sourcing:** Primary cells, including myocytes (muscle cells) and adipocytes (fat cells), are obtained from animals via biopsies.
- **Cell Culture Proliferation:** These cells are cultivated in strictly controlled environments enriched with specific growth factors and nutrients to encourage rapid multiplication.
- **Bio-ink Development:** Cultivated cells are combined with biomaterial scaffolds - often biopolymer gels - to create "bio-ink". The structural integrity required for cells to arrange into intricate three-dimensional tissues is provided by this scaffold.
- **3D Printing Process:** Utilizing extrusion or inkjet-based technologies, these bio-inks are deposited layer-by-layer to build meat-like structures.

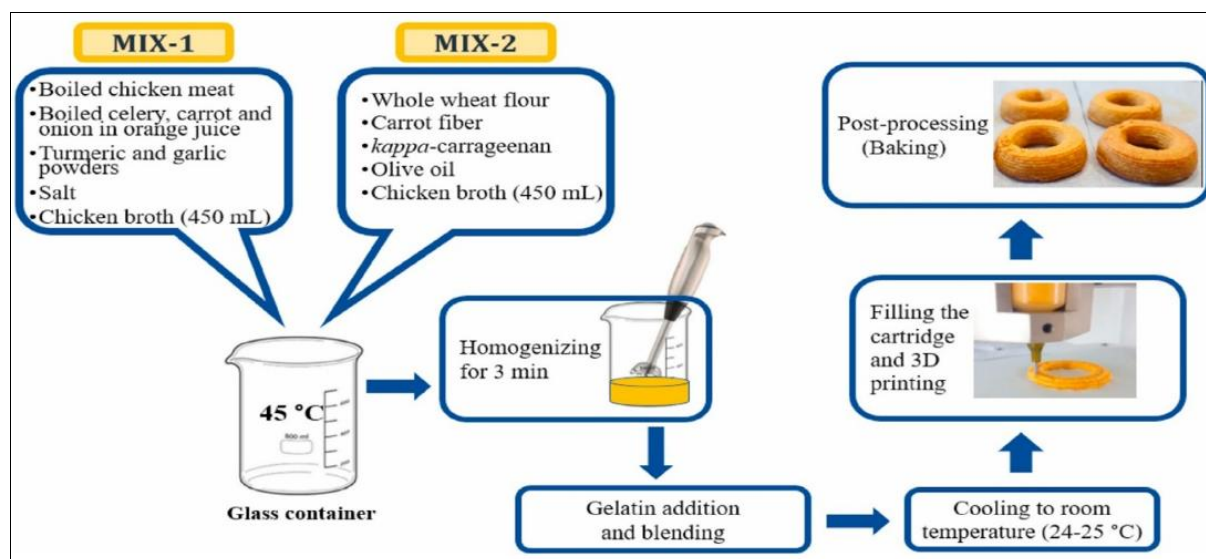


Fig 1: Comprehensive processing steps from raw material matrix formulation to finalized 3D printed chicken meat-based functional products

Blockchain: Restoring Transparency and Consumer Trust

Historical contamination crises, such as the heavy metal contamination in Irish pork in 2008 and the European horsemeat scandal in 2013 have resulted in significant product recalls and a profound erosion of consumer confidence. Blockchain technology addresses these vulnerabilities by acting as a decentralized, immutable online ledger managed by a broad network of participants.

By providing real-time access to critical data regarding

product origin, processing methodologies, and safety certifications, blockchain enhances accountability at every stage of the supply chain. This technology supports sustainable consumption by enabling consumers to scan QR codes and verify the health and provenance records of meat products, thereby encouraging informed purchasing habits. Consumers can use QR codes to verify the origin and health records of products, supporting sustainable consumption habits (Zhang *et al.*, 2022)^[37].

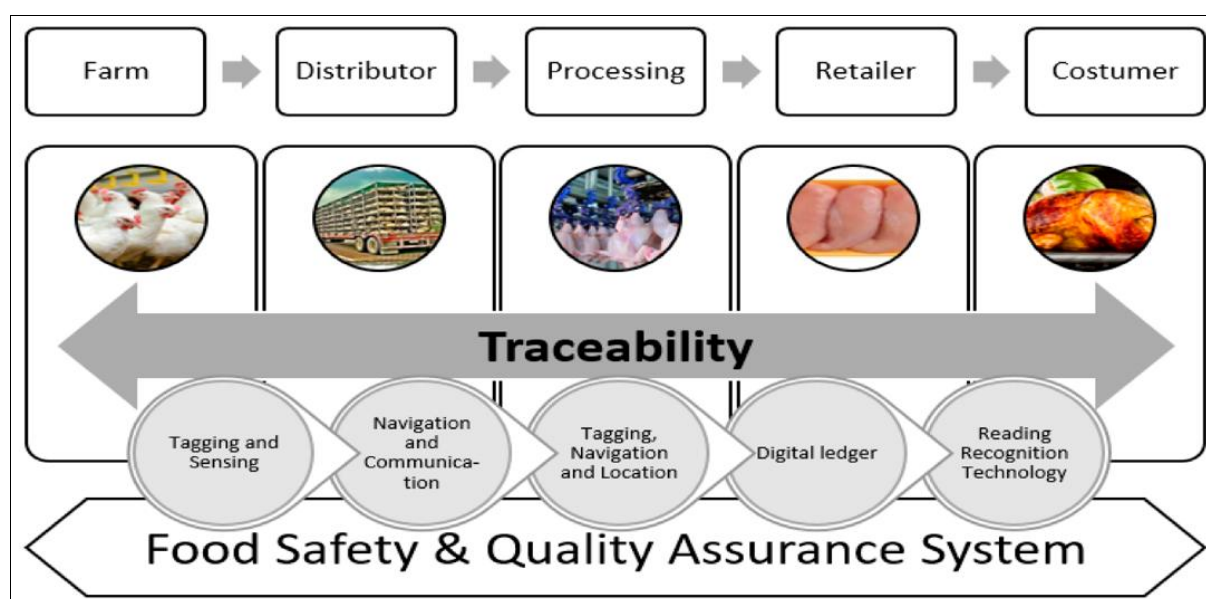


Fig 2: The Blockchain Traceability Loop from Origin to Consumer

Artificial Intelligence (AI) in Precision Processing

The adoption of Artificial Intelligence is essential for maintaining competitiveness and operational efficiency in a modern meat processing landscape. AI offers transformative solutions to the industry's most pressing challenges, including labour shortages, quality control, and the need for precision cutting.

Enhancing Operational Efficiency

AI systems provide several advantages through high-accuracy data analysis and automation:

- **Precision and Yield:** AI algorithms analyze anatomical data to execute precise cuts, which optimizes yield and

significantly reduces raw material waste.

- **Quality Assurance:** Vision-based AI systems detect physical defects in real-time, ensuring that only products meeting the highest standards reach the marketplace.
- **Automated Sorting:** Advanced models can detect specific anatomical markers, such as the pelvic bone, to accurately segregate carcasses based on gender, further improving product consistency.
- **Resource Optimization:** By automating repetitive and labour-intensive tasks, AI reduces institutional dependency on human labour and contributes to more sustainable processing practices.

The convergence of 3D printing, blockchain, and artificial intelligence signifies a new era for meat products technology. While 3DP addresses the ethical and environmental challenges of production, blockchain provides the necessary transparency to restore consumer trust, and AI optimizes the industrial throughput. Collectively, these technologies pave the way for a more resilient, ethical, and consumer-centric meat industry.

Future Prospects

The meat industry is standing at the precipice of a technological revolution where sustainability, efficiency, and deep customization will redefine the global food landscape. According to Ramirez *et al.*, (2021)^[28], we anticipate a move toward "smart" processing plants where AI-driven automated systems optimize processing, significantly improving production efficiency and product consistency. As AI-powered vision systems become more sophisticated, they will offer transformative solutions to optimize every aspect of meat processing, ensuring that only the highest quality products reach the market.

Parallel to robotic automation, the widespread adoption of digital ledgers will create a "trust economy" within the meat supply chain. According to Ghadge *et al.* (2023)^[11], blockchain technology offers a promising method to enhance transparency and accountability at every stage of the supply chain. This allows consumers to verify the origin and health records of products via QR codes, encouraging informed and sustainable consumption habits (Zhang *et al.*, 2022)^[37].

Furthermore, the rise of alternative proteins will be heavily influenced by advancements in additive manufacturing. According to Mantihal *et al.* (2020)^[23], technologies such as 3D printing allow for the creation of meat products with precise textures and shapes, enabling significant waste reduction and addressing environmental and animal welfare concerns. Innovations in plant-based and lab-grown meats are expected to provide alternative protein sources that cater to shifting consumer preferences and ethical considerations.

However, the realization of these prospects depends on overcoming significant technical and social hurdles. According to Jeong *et al.* (2024)^[15], methods like Pulsed Electric Field (PEF) must continue to enhance food safety by reducing pathogens while maintaining nutritional quality. Ultimately, while these advancements show great promise, challenges related to cost, scalability, and consumer acceptance must be addressed before achieving widespread implementation across the industry (Warner *et al.*, 2017)^[35].

Conclusion

Meat remains a cornerstone of human nutrition, providing highly bioavailable protein, vitamin B₁₂, and heme iron. However, as the industry faces growing demands for efficiency and ethics, production methods must evolve. Recent advances in Irradiation and Pulsed Electric Field (PEF) have established robust safety frameworks by reducing harmful bacteria and extending shelf life without compromising nutritional density.

The integration of digital and additive manufacturing - specifically 3D Printing (3DP), Artificial Intelligence (AI), and Blockchain offers unprecedented customization and transparency. 3D printing addresses environmental and animal welfare concerns by enabling the production of cell-cultured meat with precise textures, significantly reducing land use and waste. Meanwhile, blockchain guarantees end-to-end traceability through irreversible data, rebuilding

customer trust following earlier contamination events, while AI maximises carcass segregation and processing efficiency. Despite this potential, widespread implementation is hindered by high commercialization costs, complex regulatory compliance, and the need for greater consumer acceptance. According to Warner *et al.* (2017)^[35], the future of the industry lies in the synergy of these inventive technologies. By embracing these advances and addressing existing barriers through research and education, the livestock products technology sector can meet global protein demands while upholding the highest standards of safety, ethics, and long-term sustainability.

Conflict of Interest

Not available.

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