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Review

Chemical Safety Assessment of 3D Printed Food Materials and Development of Innovative Formulations

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Abstract: As an emerging and transformative technology in the culinary and food manufacturing sectors, the development of 3D printed food heavily depends on the continuous optimization of material systems and the rigorous assurance of chemical safety. This paper comprehensively analyzes the diverse types and functional characteristics of 3D printed food materials, encompassing basic nutritional ingredients (such as cereals, high-quality proteins, and various fruits and vegetables), essential food additives (including thickeners, stabilizers, and gelling agents), and specialized printing auxiliary materials (such as supporting structures and binding agents). Building upon this foundational classification, the review systematically discusses the full-chain risk associated with chemical safety assessment. This involves a detailed examination of natural toxins and pesticide residues in basic agricultural ingredients, the strict regulatory compliance of synthetic additives, the potential residue migration from auxiliary materials, complex chemical changes occurring during thermal or mechanical processing, and advanced finished product testing methodologies. Furthermore, it elaborates on strategic approaches for innovative formulation development. These strategies focus on meticulous ingredient screening, precise additive adjustment, auxiliary material improvement, and enhanced processing adaptability, ultimately aiming to perfectly balance printing performance, structural fidelity, and consumer safety. The comprehensive study demonstrates that implementing full-chain risk assessment protocols and targeted formulation optimization are absolutely critical to ensuring the commercial viability and sustainable development of 3D printed food technology in the modern food industry.

Keywords: 3d printed food; chemical safety; food formulation; food materials; risk assessment; food processing

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1. Introduction

1.1. Development Status of 3D Printed Food

3D printed food technology represents a novel and rapidly advancing area within food processing, characterized by its ability to transform raw ingredients into predetermined shapes through precise layer-by-layer material deposition. This innovative approach has found applications across various domains [1]. In domestic settings, it facilitates the swift creation of customized pastries and flour-based products tailored to individual preferences. Within the catering industry, it enables the production of visually appealing dishes that elevate the dining experience [2, 3]. Furthermore, in specialized dietary contexts, it offers the capability to design liquid or semi-liquid foods that are easier to consume, catering to the needs of individuals with swallowing difficulties, as well as infants and young children. A key advantage of 3D printed food lies in its exceptional control over shape and structure, allowing for the precise fabrication of intricate designs while minimizing ingredient waste. As technological costs decrease and equipment becomes more compact, the accessibility of this technology is expanding beyond research laboratories, marking a significant innovation in the food industry.

1.2. Importance of Chemical Safety Assessment

Chemical safety serves as a foundational requirement for the broader adoption of 3D printed food [4, 5]. Unlike traditional food systems, the material composition of 3D printed food is significantly more intricate, encompassing a variety of components such as primary ingredients, additives, and auxiliary substances. The production process introduces unique steps, including material blending, extrusion, and shaping, which can potentially introduce novel chemical risks. For instance, interactions between different materials or alterations in processing temperatures may lead to the formation of harmful compounds. Additionally, residual or migrating auxiliary substances could compromise food safety. Overlooking these risks not only poses a threat to consumer health but also undermines public confidence in the technology, thereby impeding its advancement. Consequently, conducting a comprehensive chemical safety assessment is essential to ensure the sustainable development of this innovative technology and to uphold the fundamental principles of food safety.

1.3. Significance of Innovative Formulation Development

Innovative formulation development plays a pivotal role in advancing 3D printed food technology. Traditional food ingredients often exhibit physical properties such as viscosity and flowability that hinder their direct application in printing processes, leading to issues like structural instability and molding fractures. By innovating formulations, these physical characteristics can be optimized to align with the operational requirements of printing equipment, thereby enhancing the stability and precision of the molding process. Furthermore, formulation development must address multiple critical objectives. It is essential to ensure the safety of the materials while preserving the nutritional integrity of the ingredients, minimizing nutrient degradation during processing or material adjustments. Additionally, taste and flavor must be carefully considered to meet consumer expectations for sensory quality [6, 7]. Beyond these factors, innovative formulations can also mitigate reliance on materials associated with higher chemical risks, reducing potential safety concerns at the source. This comprehensive approach transforms 3D printed food from a conceptual innovation into a practical, safe, and high-quality application, bridging the gap between technological feasibility and consumer-ready products.

2. Characteristics and Common Types of 3D Printed Food Materials

2.1. Basic Ingredients

The fundamental requirement for basic ingredients in 3D food printing is their ability to exhibit physical properties conducive to the printing process, such as moderate viscosity, optimal fluidity, and stable plasticity. These characteristics directly influence the quality and precision of the molded output. Commonly used basic ingredients can be categorized into several groups. Cereals, including wheat flour, rice flour, and corn flour, are among the most prevalent due to their high starch content. When heated with water, starch gelatinizes, forming a semi-solid colloid that provides essential structural support for printing. Additionally, cereals are cost-effective and widely available [8]. Proteins, such as whey protein, soy protein, and egg white, are valued for their gelation properties and extensibility. The viscosity of protein-based materials can be adjusted to ensure smooth extrusion through the nozzle and to maintain structural integrity post-molding. Fruits and vegetables are typically utilized in puree or powder form, including carrot puree, strawberry powder, and spinach powder. Fresh produce contains significant moisture and fiber, which can lead to excessive fluidity if used directly. To address this, fruits and vegetables are often dehydrated, pureed, or combined with other ingredients to achieve a balanced moisture and fiber ratio suitable for printing. Lipids, such as butter and vegetable oil, enhance material lubrication, reduce nozzle wear, and contribute to texture adjustment. However, excessive lipid content can compromise the structural stability of the printed material, necessitating careful formulation to maintain balance.

2.2. Food Additives

Food additives in 3D printing are primarily utilized to enhance the performance of printing materials and address deficiencies in the physical properties of basic ingredients. These additives serve distinct purposes and are categorized based on their functions. Thickeners, such as xanthan gum, guar gum, and konjac powder, play a crucial role by increasing the viscosity of materials through molecular interactions, which helps prevent unintended material flow or deformation during the printing process. This is particularly beneficial for highly fluid ingredients like fruit and vegetable purees. Gelling agents, including gelatin, sodium alginate, and carrageenan, contribute to the rapid solidification of materials by forming three-dimensional network structures, ensuring the stability of printed layers and reducing the risk of interlayer separation. Emulsifiers, such as mono- and diglycerides and lecithin, enhance the uniformity and stability of oil-water mixtures, preventing separation and promoting consistent texture. Humectants, including glycerol and sorbitol, regulate the moisture content of materials, thereby minimizing issues such as nozzle blockages or structural imperfections caused by uneven moisture distribution during the printing process [9]. All additives must adhere to food-grade standards, with precise dosage control being essential to maintain both safety and the desired sensory qualities of the final product.

2.3. Printing Auxiliary Materials

Printing auxiliary materials play a vital role in the creation of complex structures, even though they do not directly form part of the main food product. These materials are essential for ensuring both safety and functionality during the printing process. Supporting materials, for instance, are used to provide temporary structural support for suspended or hollow designs. They must be easily separable from the primary material and safe for consumption. Common examples include starch-based supports, such as modified starch, and sugar-based supports, such as sucrose derivatives. These can be removed post-printing through methods like dissolving in warm water or applying gentle heat, ensuring no residues remain [10, 11]. Binding materials are another critical category, enhancing interlayer adhesion in multi-layered structures. These materials, often natural colloids like pectin, gum arabic, and xanthan gum blends, form films between layers to maintain structural integrity and prevent separation. They are designed to minimize migration, ensuring no harmful substances are released into the primary ingredients. Additionally, filling materials are employed to adjust the density or porosity of ingredients. Examples include microencapsulated dietary fiber and maltodextrin, which improve material uniformity and reduce nozzle blockages during printing. These materials are carefully formulated to maintain the flavor and safety of the final product while minimizing the introduction of unnecessary chemicals, thereby reducing potential safety risks.

3. Chemical Safety Assessment of 3D Printed Food Materials

3.1. Chemical Risk Assessment of Basic Ingredients

The chemical risks associated with basic ingredients primarily stem from their inherent properties as well as the conditions under which they are stored and handled. Natural toxins present a significant hazard; for instance, improper storage of cereals can facilitate the growth of harmful molds, such as those producing toxic compounds. Similarly, certain fruits and vegetables, like sprouted potatoes or unripe tomatoes, naturally contain alkaloids that may lead to poisoning if consumed in excessive quantities. Residual substances also pose a concern, as fruits and vegetables may retain pesticide residues, while meat and dairy products could contain remnants of veterinary drugs. When these substances exceed established safety thresholds, they have the potential to cause long-term health issues. Additionally, oxidative deterioration of ingredients prior to processing warrants attention. For example, the oxidation of lipid-based components can result in the formation of aldehydes and ketones, which not only degrade nutritional value but may also introduce toxic effects. Unsaturated fatty acids in cereals and nuts are particularly susceptible to oxidation, accelerating spoilage and amplifying chemical risks.

3.2. Chemical Risk Assessment of Food Additives

The chemical risks associated with food additives primarily revolve around their proper usage and potential interactions. A common concern is the excessive application of certain additives, such as thickeners and gelling agents, which can lead to gastrointestinal discomfort when consumed in large quantities. Prolonged overconsumption of specific additives, such as artificial colorants, may also impose additional health burdens over time. Another critical issue is the risk of illegal adulteration, where industrial-grade additives, such as non-food-grade gelatin, are improperly used in place of food-grade alternatives. This practice can introduce harmful substances, including heavy metals and toxic solvents, into the food supply. Furthermore, the combination of different additives may result in unintended chemical reactions [12]. For instance, interactions between preservatives and antioxidants could produce unknown harmful compounds or compromise the stability of the additives, thereby increasing potential safety risks. These factors underscore the importance of stringent oversight and adherence to safety standards in the use of food additives.

3.3. Chemical Risk Assessment of Printing Auxiliary Materials

The chemical risks associated with printing auxiliary materials primarily arise from residue and migration. Residual components, if not thoroughly removed, can pose significant health hazards. For instance, certain synthetic supports may contain non-degradable chemicals that could be harmful when ingested over extended periods. Migration of binding materials is another critical concern, as small molecular components can transfer into the primary ingredients, potentially altering the chemical composition of the food. This risk is heightened at elevated printing temperatures, where migration rates tend to increase [8]. Additionally, the degradation of auxiliary materials during storage or processing can lead to the formation of harmful byproducts, such as aldehydes and acids. These substances may contaminate the primary ingredients, compromising both safety and quality. Comprehensive risk assessments are essential to mitigate these potential hazards effectively.

3.4. Chemical Risk Assessment in the Processing Procedure

Chemical risks during processing are closely associated with the unique techniques employed in 3D printing. One significant factor is high-temperature printing, which can lead to the thermal decomposition of proteins and fats in ingredients, resulting in the formation of harmful substances such as heterocyclic amines and polycyclic aromatic hydrocarbons. Similarly, carbohydrates subjected to elevated temperatures may undergo chemical reactions that produce acrylamide, a compound known to pose toxicity risks. Additionally, exposure to light and oxidation during the printing process can induce chemical changes in food components. For instance, ingredients containing vitamins may degrade when exposed to light, while lipid-based ingredients can oxidize and become rancid upon contact with air, generating unpleasant odors and potentially toxic compounds. Furthermore, the materials used in printing equipment can contribute to contamination, as substances such as metal ions from metal nozzles or plasticizers from plastic components may migrate into food. Acidic ingredients are particularly prone to accelerating this migration process.

3.5. Chemical Safety Testing Methods for Final Products

Testing methods for final products must address critical risk points through practical and efficient approaches. Fundamental procedures include routine component analysis, which identifies heavy metals such as lead and cadmium, as well as contaminants like pesticide residues and mycotoxins, ensuring adherence to established safety standards. Rapid screening technologies, including test strips and portable spectrometers, are highly versatile and enable swift detection of common toxins such as aflatoxins and unauthorized additives like industrial gelatin, making them suitable for preliminary evaluations conducted on-site. Additionally, collaborative risk assessments play a vital role in examining the interactions between microorganisms and chemical substances. This is crucial because certain chemicals can compromise human immunity, potentially heightening susceptibility to microbial infections. Such comprehensive evaluations are essential for ensuring product safety in complex and dynamic environments.

4. Development of Innovative Formulations for 3D Printed Food

4.1. Formulation Optimization Based on Basic Ingredient Risks

To mitigate risks associated with natural toxins, residues, and oxidative deterioration in basic ingredients, it is essential to optimize formulations by addressing these challenges at their source. The selection of ingredients should prioritize varieties with inherently low levels of natural toxins, such as potatoes with reduced alkaloid content and cereals free from mold contamination. Ingredients known to have high toxin levels, such as sprouted potatoes and immature beans, should be avoided entirely. For fruits, vegetables, and cereals that may contain pesticide residues, pretreatment processes can be refined to enhance safety, including soaking in clean water or peeling to minimize residue levels. Meat ingredients should be sourced from verified suppliers to ensure the absence of veterinary drug residues. Additionally, formulation ratios must be carefully adjusted to mitigate oxidation risks. This includes limiting the proportion of high-oil components, such as nuts and animal fats, and incorporating natural antioxidants like tea polyphenols, vitamin C, or rosemary extract to slow lipid oxidation. For fruit and vegetable purees with high moisture content, blending them with highly absorbent cereal powders, such as oat powder, can help balance moisture levels. This adjustment reduces microbial growth and chemical deterioration caused by excessive moisture, thereby enhancing ingredient safety while maintaining the viscosity required for 3D printing applications. These measures collectively ensure the formulation is both safe and suitable for innovative food printing processes.

4.2. Formulation Adjustment Based on Food Additive Risks

To mitigate risks associated with excessive use, unauthorized addition, and reactive interactions of food additives, formulation adjustments should adhere to the principles of "streamlined, natural, and safe." A key strategy involves minimizing additive usage by leveraging the inherent properties of primary ingredients to replace certain additives. For instance, the gelation properties of egg whites can be utilized to partially substitute synthetic gelling agents, while the natural viscosity of banana puree can help reduce the reliance on thickeners, thereby maintaining the authentic flavor of the original ingredients. Emphasis should also be placed on prioritizing natural alternatives, such as employing konjac powder, guar gum, and other naturally derived thickeners instead of synthetic ones, and using natural colorants like beetroot juice and turmeric to limit the introduction of chemical substances at the source. Furthermore, compatibility among additives must be ensured through preliminary testing to avoid undesirable reactions. For example, tests should confirm that no harmful substances are generated when xanthan gum is combined with sodium alginate, and that gelatin and vitamin C remain stable when used together [13–15]. Additionally, strict adherence to food additive usage standards is essential, ensuring that the quantity of each additive remains within safe limits to prevent risks associated with chemical reactions during formulation design.

4.3. Formulation Improvement Based on Auxiliary Material Risks

To mitigate risks associated with residues, migration, and degradation products of auxiliary materials, formulation improvements should aim to balance the safety and functionality of these materials. Emphasis should be placed on using edible supporting materials, such as those derived from modified starch and maltodextrin, which dissolve readily in water or saliva. These materials can be easily removed through simple rinsing or chewing after printing, thereby minimizing the potential for residual toxicity. Additionally, the development of low-migration binding materials is essential. Natural water-soluble colloids, such as pectin and gum arabic, are particularly suitable as binders due to their stable molecular structures, which resist the migration of harmful substances to main ingredients under conditions of high temperature or extended storage. These materials are especially effective when paired with acidic or lipid-rich ingredients. Furthermore, simplifying the types of auxiliary materials by optimizing the ratios of main ingredients can reduce dependency on auxiliary components [16]. For instance, adjusting the ratio of cereal flour to protein can enhance interlayer adhesion, thereby decreasing the need for binders. Similarly, designing integrated structures to replace complex suspended ones can lower the demand for supporting materials, effectively reducing risk points associated with auxiliary materials at the formulation level.

4.4. Formulation Development Adapted to Processing Conditions

To mitigate risks associated with high-temperature hazards, accelerated oxidation, and potential reactions with processing equipment, formulation development must prioritize enhancing material resilience to these conditions. A critical strategy involves designing heat-resistant formulations by incorporating components such as cross-linked starch and modified cellulose. These materials exhibit stability under elevated temperatures, thereby minimizing the decomposition of ingredients and reducing the formation of harmful substances like heterocyclic amines and acrylamide, which can result from the interaction of proteins and fats. Additionally, adjusting the pH of ingredients is essential to prevent overly acidic or alkaline environments that could intensify chemical changes during high-temperature processing. Optimizing antioxidant formulations requires a dual focus on both processing and storage conditions. This can be achieved by controlling water activity, for instance, through the addition of maltodextrin to lower moisture levels, and by incorporating natural antioxidants such as rosemary phenols to delay lipid oxidation. Employing vacuum mixing processes further reduces ingredient exposure to air, enhancing stability. Compatibility with processing equipment is another critical consideration. For acidic ingredients like tomato or lemon flavors, buffering agents such as calcium carbonate can be added to neutralize acidity, thereby preventing corrosion of metal nozzles and reducing the risk of metal ion migration [14, 17]. For formulations with high lipid content, incorporating natural emulsifiers like lecithin can minimize oil residue on nozzles, reducing contamination risks and ensuring smoother processing operations.

4.5. Safety Verification of Innovative Formulations

Innovative formulations undergo rigorous multi-stage verification processes to ensure their safety while maintaining optimal printing performance and chemical stability. A critical aspect of this verification involves simulated testing of the printing process under laboratory conditions, replicating actual parameters such as temperature, pressure, and processing time. This approach allows for the identification of potential chemical changes, including the formation of harmful substances at elevated temperatures or the degradation of additives during processing, ensuring the chemical stability of the formulation throughout the printing phase. Additionally, finished product testing is conducted to evaluate key safety indicators. Rapid detection methods are employed to measure levels of heavy metals, pesticide residues, illegal additives, and other hazardous substances, ensuring compliance with established food safety standards. Parameters such as pH and water activity are also assessed to determine the product's vulnerability to harmful substance growth during storage. Furthermore, the balance between nutritional value and safety is carefully verified. This includes testing the retention rates of essential nutrients, such as proteins and vitamins, to ensure that the formulation maintains its nutritional integrity while optimizing safety. In cases where further assurance is required, short-term consumption safety evaluations may be performed to observe the formulation's impact on fundamental human physiological indicators [13]. These comprehensive measures aim to achieve formulations that are not only safe and printable but also nutritionally beneficial.

5. Conclusion and Outlook

As an emerging technology, the advancement of 3D-printed food fundamentally depends on achieving a robust balance between safety, functionality, and practical applicability. Based on the present analysis, chemical safety assessment should extend across the entire production and consumption chain rather than focusing on isolated stages alone. This assessment needs to include natural toxins and contaminant residues in raw ingredients, the compliant and controlled use of food additives, the potential migration of residues from auxiliary and contact materials, chemical transformations induced during printing and post-processing, and the final risk identification of the printed product before consumption. Neglecting any one of these interconnected links may introduce cumulative or hidden safety concerns that compromise product reliability and consumer acceptance. In this context, innovative formulation design represents one of the most effective strategies for risk control. Through more rigorous ingredient screening, more precise adjustment of additive types and dosages, improvement of auxiliary materials and equipment-contact components, and better adaptation of formulations to processing conditions, it is possible to enhance printability, structural stability, and product consistency while simultaneously reducing chemical risks at the source. Such an integrated approach supports not only safer production but also the coordinated improvement of sensory quality, nutritional value, and manufacturing feasibility.

Looking ahead, the development of 3D-printed food can be advanced from at least three closely related directions. First, safety assessment technologies should be simplified and translated into more accessible, rapid, and practical on-site detection tools, thereby lowering technical barriers for routine monitoring in research, pilot production, and industrial settings. Second, industry standards and regulatory frameworks should be further refined to define clearer safety thresholds for raw material selection, additive dosage, auxiliary material use, and key processing parameters, while also promoting standardized operating procedures and quality-control systems throughout production. Third, greater emphasis should be placed on the application of natural materials, including the development of formulations based on directly printable natural ingredients, so as to reduce excessive dependence on additives and auxiliary substances. At the same time, formulation design should be integrated with nutritional requirements, enabling the development of functional and personalized products with improved health value. In addition, future progress will likely depend on stronger interdisciplinary collaboration among food science, materials science, engineering, and quality assurance. As technologies become more mature and standards more comprehensive, 3D-printed food is expected to move beyond experimental and niche applications and become more broadly incorporated into daily dietary practice under the premise of assured safety, ultimately supporting personalized, convenient, and potentially more sustainable food supply systems.

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