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Advances and Opportunities in Food Technology Regarding Cancer Prevention and Progress

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Abstract

There is a great deal of debate surrounding the consumption of genetically modified organisms (GMOs), as the potential advantages for food producers and consumers come with possible medical and ecological risks. Many people have raised concerns about genetically modified foods (GM foods), particularly in terms of their short and long-term health effects. Numerous studies have been conducted worldwide to better understand the risks and benefits associated with GM foods. This review provides an overview of the current research on the potential link between food processing and cancer, preventive dietary approaches, fast-food consumption, microbiota, GMO features, the role of plant biotechnology concerning cancer, and various types of transgenic products. A comprehensive review of the current scientific literature was undertaken to examine the associations between cancer, GM foods, and developments in food technology. The safety of GM foods should be continuously evaluated through rigorous scientific research and transparent regulatory oversight to ensure long-term health.

Keywords: Cancer; Food technology; Genetically modified food; Genetically modified organisms; Plant biotechnology

1.INTRODUCTION

Cancer is a leading cause of mortality worldwide and is projected to rise by 70% over the next two decades (Siegel et al., 2023; B. Wang et al., 2022). Genetically Modified (GM) foods, developed through scientific innovation to improve yield and disease resistance (McGuire, 2016), are generally considered safe, yet concerns persist regarding their potential health risks, including carcinogenesis, teratogenesis, lethal effects, and fertility issues (Bawa & Anilakumar, 2013; Dona & Arvanitoyannis, 2009; Seralini, 2020; Shen et al., 2022). Plant biotechnology enables gene transfer between plants, resulting in transgenic food and cash crops. Cancer incidence varies significantly across regions, often due to differences in diet and lifestyle (Farkhondeh et al., 2021; Talebi et al., 2023). Nutritional components and dietary patterns such as the Western and Prudent diets can influence cancer risk (Bawa & Anilakumar, 2013; Shen et al., 2022). Additionally, microbial pigments show promise in biotechnology for applications in functional foods and biomedical products (Celedón & Díaz, 2021). Green biotechnology also contributes to sustainability by producing GM organisms and renewable biopolymers (Ribeiro et al., 2015). Modern biotechnology, especially through the development and use of genetically modified (GM) crops, represents a highly promising approach to significantly reducing the negative impacts of climate change. These advanced crops are engineered to possess traits such as drought tolerance, pest resistance, and improved nutrient efficiency, which contribute to more sustainable agricultural production systems (Seid & Andualem, 2021). Moreover, green biotechnology has advanced cancer treatment through plant-based innovations such as plant-derived nanoparticles, bioactive compounds from edible mushrooms, optimized therapeutic metabolites, and plant tissue cultivation in controlled environments. (Osman et al., 2024; Zahmanova et al., 2023). This review elaborates on the potential link between GM food consumption and cancer, and evaluates the current research landscape to identify future directions for cancer prevention and treatment.

2. FOOD PROCESSING AND CANCER DEVELOPMENT

2.1 Ultra-processed foods and cancer: microbiota-mediated mechanisms

Studies have indicated that the consumption of ultra-processed foods (UPFs) is associated with numerous negative health outcomes, including mortality (Schnabel et al., 2019), cancer (Cordova et al., 2023), type 2 diabetes (Duan et al., 2022), cardiovascular diseases (Duan et al., 2022; Roshanravan et al., 2023), irritable bowel syndrome (Schnabel et al., 2018), depression (Samuthpongtorn et al., 2023), and fertility disorders in adults (Lavellle et al., 2023). Additionally, researchers suggest that ingestion of UPFs may be linked to globesity and cardio-metabolic risks (Elizabeth et al., 2020). A reduction in bacterial diversity, a condition known as dysbiosis, or changes in gut microbiome composition, is a characteristic feature of various chronic inflammatory diseases, including obesity, inflammatory bowel disease, and cancer (Kalra et al., 2022).

Dietary modifications may affect the gut microbiota diversity and profile (Hullar et al., 2013), which in turn can either promote or inhibit Cancer progression (Greathouse et al., 2022; Hes & Jagoe, 2023). For instance, the metabolism of red meat and animal fats by gut bacteria leads to the production of hydrogen sulfide and secondary bile acids such as deoxycholic acid (DCA), which have been implicated in carcinogenesis. Conversely, plant-based polyphenols and fiber undergo microbial fermentation, yielding beneficial metabolites such as equol, urolithins, and short-chain fatty acids (SCFAs), including butyrate, which have been shown to exhibit cancer-preventive properties (Bultman, 2017). Furthermore, changes in enterotoxigenic microbial strain concentrations may alter fecal genotoxicity and cytotoxicity (Hou et al., 2022; Mai et al., 2009), potentially affecting cancer risk (Simpson et al., 2022; Tanaka et al., 2021). Cytotoxicity refers to the ability of certain substances to impair cellular function by disrupting metabolism, damaging structural components, or causing cell death. Genotoxicity describes the potential of agents to cause harm to genetic material, either by modifying DNA structure or by inducing sequence alterations (Nogacka et al., 2019) (Fig. 1). The role of microbiota in cancer development is exemplified by pathogens such as Helicobacter pylori. A recent case–control study by Ebrahimi et al. was the first to investigate the association between ultra-processed food (UPF) consumption and H. pylori infection, revealing a significant correlation between higher UPF intake and increased risk of infection. Notably, H. pylori strains carrying the cagA virulence factor are particularly pathogenic, as they can trigger chronic gastritis and significantly elevate the risk of gastric cancer (Bhatt et al., 2017; Ebrahimi et al., 2024)

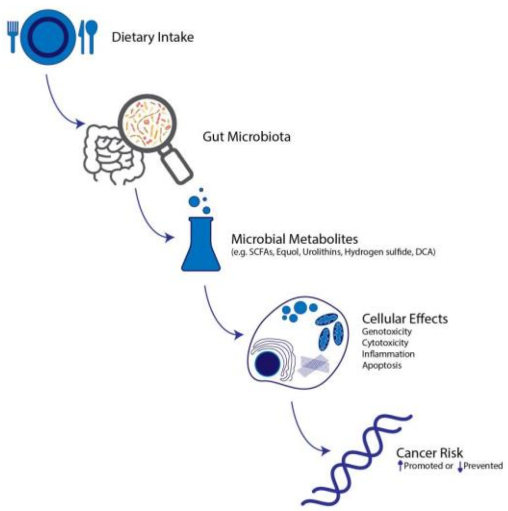

Figure 1. Simplified pathway showing the role of diet and gut microbiota in modulating cancer risk through microbial metabolites and cellular mechanisms

2.2 Fast food, additives, and cancer: understanding dietary risks

While ultra-processed foods (UPFs) have been broadly associated with cancer risk, fast food—a prominent subset of UPFs—poses distinct threats due to its specific composition and cooking methods. Fast foods are typically high in saturated and trans fats, salt, refined carbohydrates, and synthetic additives, and are often prepared at high temperatures that can generate carcinogenic compounds. This type of food has become increasingly popular in industrialized countries, leading to higher rates of non-communicable illnesses such as eczema, asthma, cancer, and obesity (Didarloo et al., 2022). Clinical evidence from multiple large-scale cohort and case-control studies supports these concerns. High intake of ultra-processed foods—especially fast-food items such as ready-to-eat meats, fried foods, and sugar-sweetened beverages—has been linked to increased risk of several cancers. A U.S. cohort study found a 29% higher risk of colorectal cancer in men consuming the most ultra-processed foods (L. Wang et al., 2022), while case-control studies in Iran and Jordan showed three- to fourfold higher odds of colorectal cancer associated with fried meats, falafel, and chips (Ebrahimi et al., 2024; Al-Dwairy et al., 2022). Another Jordanian study linked fast foods like chicken sandwiches and French fries to increased gastric and pancreatic cancer risk (Al-Khudari et al., 2023). The EPIC cohort reported elevated risks of head and neck and esophageal cancers with higher UPF intake (Papadimitriou et al., 2023), and recent evidence from the Southern Community Cohort Study linked fast food–style items—fried potatoes, processed protein foods, and mixed dishes—to a higher risk of liver cancer (Zhang et al., 2023). These findings reinforce the role of fast food consumption as a shared risk factor across multiple cancer types.

2.2.1 Saturated and Trans fats

Studies have found that a diet high in saturated fats has been linked to an increased risk of cancer, including breast cancer. This is thought to be due to the presence of palmitic acid, which is a major component of saturated fatty acids. However, beyond saturated fats, the type and balance of dietary polyunsaturated fatty acids (PUFAs) also play a crucial role in modulating cancer risk and inflammation, with omega-6 PUFAs potentially promoting inflammation, while omega-3 PUFAs are generally anti-inflammatory and protective (Sellem et al., 2019). It has been suggested that the increased prevalence of breast and prostate cancer among Asian immigrants to the US may be linked to their dietary omega-6 to omega-3 ratio, which is commonly higher than the optimal ratio of 4:1 and closer to 15:1 in average Western diets (Bojková et al., 2020; Lee et al., 2007; Nindrea et al., 2019). Eicosanoids derived from omega-6 PUFAs are often considered pro-inflammatory, whereas those from omega-3 PUFAs have anti-inflammatory effects. The dietary omega-6/omega-3 ratio influences the balance of eicosanoids, affecting immune regulation, inflammation, and cancer-related processes. Although arachidonic acid from omega-6 is theoretically linked to inflammation, human studies and systematic reviews have not provided conclusive evidence that omega-6 intake increases inflammatory markers (Balić et al., 2020).

Trans fatty acids (TFAs) are either monounsaturated fatty acids (MUFAs) or polyunsaturated fatty acids (PUFAs) with one or more double bonds arranged in a trans configuration. Industrially produced TFAs (iTFAs), generated through the partial hydrogenation of vegetable or fish oils, are generally the predominant source of TFAs in the human diet (Shoaib H, 2024). High intakes of TFAs have been associated with an increased risk of cardiovascular disease, and may also be linked to an increased risk of cancer; however, these associations have been mainly attributed to iTFAs. Moreover, elevated levels of saturated fat could potentially explain the higher risk of various human cancers associated with ruminant or natural TFAs (rTFAs) (Islam et al., 2019).

2.2.2 *Processed meat*

Eating large amounts of red meat and processed meat such as bacon, sausages, and salami increases the risk of developing several types of cancer, including breast, colorectal, colon, rectal, hepatocellular carcinoma, endometrial cancer, and lung cancers (Farvid et al., 2021). Cooking red meat at high temperatures, such as grilling, barbecuing, or frying, can produce potentially harmful compounds called carcinogens, including polycyclic aromatic hydrocarbons (PAHs) and heterocyclic aromatic amines (HAAs), as well as N-nitroso compounds (NOCs) (Llaha et al., 2022). Heme iron present in red and processed meat has been demonstrated to induce cytotoxicity, apoptosis, and hyperplasia of epithelial cells, lipid peroxidation, free radical generation, and DNA adduct formation in epithelial cells. Furthermore, it catalyzes the formation of NOCs that are associated with carcinogenesis (Bastide et al., 2015). Eating large amounts of red meat increases the risk of developing insulin resistance and increases IGF-I (insulin-like growth factor I) levels, moreover it has been linked to higher levels of inflammatory biomarkers and oxidative stress in the blood, the key ingredients in these meats, methionine and non-human sialic acid N-glycolylneuraminic acid (Neu5Gc), are thought to be the cause of this inflammation, which can lead to cell proliferation, tumor formation, and cancer development (Weroha & Haluska, 2012) Persistent Organic Pollutants (POPs) that accumulate in animal fat cells can disrupt endocrine pathways, leading to an increased risk of various chronic illnesses such as cancer (Guo et al., 2019). The key ingredients in these meats, methionine and non-human sialic acid N-glycolylneuraminic acid (Neu5Gc), are thought to be the cause of this inflammation (Chaturvedi et al., 2016). Studies have suggested that higher consumption of red or processed meats may be associated with shorter telomeres, which could result in chromosomal instability and an increased risk of developing cancer (Shen et al., 2020). High salt levels, commonly found in preserved and cured fast foods, may also play a role by altering cellular pathways. For instance, Salt-inducible kinase-3 (SIK-3) was discovered by Allu et al. to be a distinct molecular target that is particularly increased in breast cancer cells exposed to high-salt conditions, such as those present in salt-treated meats (Allu & Tiriveedhi, 2021). To reduce the risk of exposure to possible meat carcinogens, the consumption of processed meat and overcooking or high-temperature cooking must be limited (Maximova et al., 2020; Solans et al., 2021; Trudeau et al., 2020).

2.2.3 *Refined carbohydrates*

Excessive sugar consumption can lead to various health issues, such as DNA damage, the formation of advanced glycation end products, increased inflammation, and an increased risk of cancer. This is caused by postprandial glucose reactions, which stimulate the synthesis of pro-oxidant molecules and cytokines, as well as increase the level of insulin-like growth factor binding protein 1 (Du et al., 2022). High-intensity sweeteners, such as aspartame (E951), acesulfame-K (E950), and sucralose (E955), are much sweeter than sugar with minimal energy content. However, a recent large-scale population-based cohort study indicated that consuming these artificial sweeteners, particularly Aspartame and Acesulfame-K, could lead to an increased risk of cancer, particularly breast and obesity-related cancers (Debras et al., 2022).

2.2.4 Colorants

The FDA classifies colorants as substances that can be added to food, drugs, cosmetics, or the human body and will cause a color change (Kallscheuer, 2018). Table 1 provides a list of approved and commonly used microbially produced food colorants, and their associated properties and health effects. Microbial pigments such as lycopene, curcumin, violacein, and eumelanin offer multifunctional roles in functional food development beyond coloration. Their antioxidant, anti-inflammatory, and antiproliferative properties demonstrate strong potential in cancer prevention, particularly when produced via sustainable microbial fermentation. However, variability in bioactivity, dose-dependent effects, and lack of established RDA values highlight the need for regulatory clarity and further clinical validation before mainstream application in processed food systems.

Table 1. The main approved microbially produced food colorants in the market and their properties and health effects

Pigment	Color	Carbon source or precursor	Host microorganism		Recommended dietary allowance (RDA)	Positive effects	Negative effects	Ref.
Riboflavin (vitamin B2)	yellow	Glucose Glucose	Fungus Bacteria	*Ashbya gossypii* *Bacillus subtilis*	0.4-0.6 mg/ kg body weight (b.w.) per day	Aiding function of the photoreceptors in the retina Structurally protecting the surface of the eyes Reduced formation of nuclear cataracts in higher dietary intakes Reduced risk of colorectal cancer (intake of more than 3.97 mg)	No harmful toxic, genotoxic, cytotoxic, or allergenic effects Minor damage to the oral mucosa	(Sahm et al., 2014; Zschäbitz et al., 2013)
Lycopene	bright red	Glucose Glycerol, Glucose, Glucose	Fungus Bacteria Haloarchaea	*Blakeslea trispora* *Escherichia coli*, *Saccharomyces cerevisiae*, *Yarrowia lipolytica* *Haloferax mediterranei*	no RDA or upper unsafe limit	Reduced risk of prostate cancer Reduced risk of benign prostatic hyperplasia (BPH) Decreased risk of developing breast cancer Reduced incidence of lung cancer development Reduced risk of colorectal cancer mortality	Dietary lycopene intolerance or allergic reactions Increased risk of bleeding when taken with anticoagulant drugs Development of low blood pressure (in case of drug interaction) Lycopenemia (a discoloration of the human skin as a	(Hsieh et al., 2022; Ranveer, 2018; Sevgili & Erkmen, 2019; Zuo et al., 2018)

						Reduced risk of pancreatic cancer	result of high lycopene intakes)	
Curcumin	yellow	Ferulic acid; Tyrosine	Bacteria	*Pseudomonas putida, Escherichia coli*	0-3 mg/kg body weight (b.w.) per day	Antioxidant (at low doses) Antimicrobial Anti-malarial Anti-HIV Anti-angiogenic agent Antitumor Enhance chemotherapy and chemo-preventive impacts on cancer cells	Induce DNA damage caused by topoisomerase II and inhibit the tumor suppressor protein p53, and increase the production of reactive oxygen species in cells (at high doses) Promote nausea, diarrhea, and elevated blood ALP and LDH (at doses of 0.9 to 3.6 g/day for 1-4 months) Trigger allergic reactions	(Kim et al., 2017; Rodrigues et al., 2015; Soltan & Shehata, 2012)
Indigoidine	blue	Glucose; Glucose and L-glutamine Glucose, Lignocellulosic hydrolysate	Bacteria Yeast	*Escherichia coli* *Saccharomyces cerevisiae, Rhodosporidium toruloides*	no RDA record found	Antioxidant Antibiotic Signaling		(Day et al., 2017; Singh, 2017; Wehrs et al., 2019)
Violacein	purple	Glycerol and L-tryptophan, Glucose, Glucose	Bacteria	*Citrobacter freundii, Corynebacterium glutamicum, Escherichia coli*	no RDA record found	Antibacterial Antibiofilm Antiparasitic Antiviral Anticancer Antitumoral Immunomodulatory activity Nephroprotective activity Antidiarrheal and Ulcer-protective		(Cheng et al., 2022; Dogancı et al., 2022; Sun et al., 2016)
Betalains	yellow-red-violet	L-DOPA	Bacteria	*Gluconacetobacter diazotrophicus Escherichia coli*	no RDA or upper unsafe limit	Poorly absorbed in the gut Antibacterial Antifungal Anti-inflammatory	Diuretic	(Ceclu & Nistor, 2020)
Betaxanthins	yellow	Glucose	Yeast	*Saccharomyces cerevisiae*		Antioxidant Expectorant and carminative properties Hepatoprotective properties Cardiovascular health benefits Lipid peroxidation inhibitory properties Chemo-preventative effects		(Grewal et al., 2018)
Eumelanin	black-brown	L-tyrosine	Fungus	*Armillaria cepistipes* strain Empa 655	no RDA or upper unsafe limit	Antioxidant Anticancer Photoprotection		(Bayram, 2022; Pavan et al., 2020)

3. BIOTECHNOLOGICAL ADVANCES İN FOOD AND THEIR ROLE IN CANCER

Food processing provides numerous benefits, including protection from hazards, year-round accessibility to food, reduced spoilage, convenience, and potential nutrient enhancement (Erdman Jr et al., 2014). Processing protocols can significantly affect the absorptive potential of micronutrients and bioactive compounds such as vitamin C, folate, carotenoids, and anthocyanins (Balasooriya et al., 2020). Biotechnology presents opportunities to enhance food safety, crop resilience, and nutrition while also contributing to environmental sustainability by reducing pesticide dependence, minimizing agricultural waste, and improving resource efficiency. Other notable technological innovations include non-thermal food processing methods—such as high-pressure, pulsed electric field, and ultrasound-assisted techniques—which preserve bioactive compounds and nutritional quality during storage, potentially supporting cancer prevention. Additionally, 3D food printing enables personalized nutrition by designing foods with tailored ingredients and reduced levels of sugar, fat, and additives, offering promising avenues to lower diet-related cancer risks. In continuation, we will further explore these advancements and their implications.

3.1 Green biotechnology and cancer risk

In the past 50 years, scientists have been working on genetically modified crops (GM crops) to benefit the population's food resources. Among these trials, it was reported that the genes of Bacillus thuringiensis (Bt), a soil bacterium that produces toxins detrimental to insects but not to humans or other higher animals; can be utilized to generate crops with pest resistance, thus reducing the need for chemical pesticide usage (Ghadimi et al., 2021). Efforts are being made worldwide to minimize human exposure to pesticides due to their well-documented ability to disrupt endocrine function and induce genetic mutations. These harmful effects can result from direct environmental exposure or be passed down through parental transmission (Panis & Lemos, 2024). Furthermore, several literature reviews have highlighted the potential associations between pesticide exposure and the development of colorectal (Xie et al., 2024), gastrointestinal (Asadikaram et al., 2025), breast (Panis & Lemos, 2024), lung (Nitha & SS, 2025), and brain cancer (Ahmad et al., 2025).

The use of nitrogen fertilizers in agriculture harms the environment by causing eutrophication, increasing greenhouse gas emissions, and contributing to water pollution. These chemicals enter the food, water, and environment, posing both direct and indirect risks to human health (Chataut et al., 2023; Dhankhar & Kumar, 2023) Nitrites in the body can react with amines and amides, forming N-nitroso compounds (NOCs), which are known carcinogens. Nitrosamines, which are produced from nitrates, nitrites, and amino acids in the stomach, include N-nitroso dimethylamine (NDMA), a common dietary carcinogen. Studies have confirmed that NOCs such as NDMA and nitrosopyrrolidine (NPYR) can induce tumors in multiple organs, including the liver, pancreas, lungs, cervix, and stomach (Essien et al., 2022). However, this need for nitrogen fertilizers may be greatly diminished if the symbiotic rhizobia of the legume family, which are capable of absorbing nitrogen, are transferred to cereals and other non-legume crops (Deng et al., 2016).

It is known that the utilization of glyphosate-resistant crops enables the application of glyphosate, a broad-spectrum herbicide, as an alternative to plowing for the management of weeds (Van Deynze et al., 2022). A series of scientific papers suggests that glyphosate may contribute to cancer, but there is some disagreement: the European Food Safety Authority concluded in its reviews that glyphosate does not cause DNA damage. The European Union has extended the use of glyphosate until 2033 (Alves et al., 2025; Schluter et al., 2024) . This technique necessitates less tilling, which in turn increases water efficiency and consequently leads to a significant reduction in soil erosion, greenhouse gas emissions, nutrient loss, and eutrophication of lakes and coastal waterways (Mgendi et al., 2019).

In 2018, the WEMA (Water Efficient Maize Program for Africa) alliance developed royalty-free drought-tolerant maize, which could have a significant positive influence on the environment and freshwater resources in Sub-Saharan Africa (Afridi et al., 2022).

The main goal of the majority of agricultural biotechnologies is to increase yields while decreasing expenses (Knapp et al., 2017). Enhancing drought resistance, salt tolerance, and high and low-temperature tolerance in C_3 plants through the addition of C_4 type of photosynthesis properties, instituting male sterility or apomixis (asexual reproduction) to reduce energy expenditure, arresting natural reproduction and interbreeding with other species to preserve genetic diversity, and utilizing heterosis effects are strategies that can be employed to improve agricultural productivity (Gu et al., 2023; Saini & Kaushik, 2019). Another strategy for higher agricultural productivity can be obtained by applying genetic engineering to increase photosynthetic efficiency, accelerate biomass growth, and increase oil content and quality (Hu et al., 2023). Additionally, cyanobacteria (blue-green algae) and green algae can produce hydrogen using solar energy, with this potential able to be further enhanced through genetic modification (Eş et al., 2019).

3.2. Nutrition and food quality improvement

The biofortification method, which involves increasing the nutritional content of crops as opposed to adding nutrients during meal processing, has seen considerable progress through the utilization of transgenic plants as platforms for producing health-beneficial compounds in recent years (Napier et al., 2019). Modifying the fatty acid profiles of GM crops is a potential approach to increasing their nutritive value (Hefferon, 2015; Rauf et al., 2023). Canola is a viable substitute for fish due to its high omega-3 long-chain polyunsaturated fatty acid content (Pinhero et al., 2012). The J.R. Simplot Company developed the innate potato, a GMO that was approved by the United States FDA and the Department of Agriculture in 2014 (Powers et al., 2021). This potato utilizes RNA interference gene silencing to manage the expression of genes responsible for enzymatic darkening (Chincinska et al., 2023). Since Innate potatoes have lower concentrations of asparagine and reduced sugar levels, they fry or bake at high temperatures with 52-78% less acrylamide than regular potatoes (Gil-Humanes et al., 2014). Coeliac disease is an immunological disorder triggered by the ingestion of gluten. A research team developed wheat bread that may be suitable for those with celiac disease and other forms of gluten intolerance (Stander et al., 2022).

3.3 Edible vaccines

Edible vaccines are produced by genetically transforming plants with selected genes encoding bacterial or viral proteins, offering a safer alternative to conventional vaccines (Fatima et al.; Hanni et al.). The development of edible vaccines on plants has recently become increasingly popular. This is because, compared to regular vaccines, they do not require pre-administration preparation or purification, are more cost-effective, require less effort for delivery, have no storage issues, and are biocompatible. Recent research has demonstrated that edible vaccines can elicit both systemic and mucosal responses, and the production of oral vaccinations for all newborns around the world requires only 200 hectares of land (Valizadeh & Hayati, 2021). Edible vaccines have been used to prevent virus-induced cancer, like cervical cancer, Hepatitis B, infectious diseases like Cholera, diabetes, and Alzheimer's disease. For instance, researchers have developed plant-based vaccines for Hepatitis B, a major risk factor for liver cancer, by expressing Hepatitis B surface antigen (HBsAg) in plants such as potatoes and lettuce. These vaccines have been shown to activate the immune response. Similarly, transgenic plants such as tobacco and potatoes express the L1 protein of Human Papillomavirus (HPV). This plant-derived protein can self-assemble into virus-like particles (VLPs), which closely resemble the native virus and trigger an immune response. While still in the early stages of development, plant-based vaccines hold great potential as an alternative for areas with limited healthcare resources, especially when the selected plants or fruits are extensively grown among the target communities (Hanni et al.; Siamalube et al., 2024).

4. FOOD SAFETY AND REGULATORY CONSIDERATIONS FOR GM FOODS

4.1 Risk of GM Foods

Food allergy is a pathological immune reaction caused by the introduction of an antigen into a specific dietary component (D'agnolo, 2005). There is growing public unease about the utilization of genetic engineering in crops due to three potential adverse effects of the novel proteins present in GM foods: they may act as toxins or allergens; they may decrease the nutritional value of food; or they may cause changes in plant metabolic pathways, potentially resulting in the formation of new toxins or allergens (Shen et al., 2022). It has also been hypothesized that consuming GM foods can exacerbate viral infections because they contain viral genes (Kramkowska et al., 2013). It has been hypothesized that the increased prevalence of lymphoma in animals or humans consuming food from pesticide-resistant plants may be attributable to these plants (Metcalfe, 2003).

During genetic modification, antibiotic-resistance genes are employed to locate desirable characteristics. Should antibiotic-resistant genes be transferred to GM plants, animals, and bacteria in the human and animal microflora, it could potentially give rise to novel strains of bacteria and pathogens that are resistant to antibiotics (Richards et al., 2003), which reduces the effectiveness of antimicrobial therapy (Uzogara, 2000).

4.2 Risk assessment, regulatory policies, and commercialization of GM crops

The World Health Organization (WHO) defines risk assessment as the scientific analysis of adverse health effects resulting from human exposure to foodborne hazards. Accidental contamination of materials or raw materials with GM foods or derivatives is one of the common reasons for this. Preventive and corrective actions can be taken after the risk has been determined, and failure mode and effect analysis are useful tools for doing this. Newly, the EU Standing Committee on the Food Chain and Animal Health has implemented regulations for the safety assessment of transgenic food/food safety (Regulation, 2013), which follow the guidelines of the European Food Safety Authority. The new regulations require a 90-day rodent feeding test for each transformation event, and in some cases, a static test for plants containing cumulative transformation events with common crossing. Risk assessment of transgenic products and derived food and feed focuses on comparisons between transgenic plants and their traditional counterparts. This evaluation includes molecular characterization, comparative agronomic, phenotypic, and hybrid evaluation, toxicological evaluation of newly expressed products, and potential allergenicity of transgenic protein(s), as well as nutritional evaluation. The unintended consequences of genetic modification have also been evaluated to determine the potential toxicological consequences on humans/animals (Aguilera et al., 2013).

Several organizations, such as the WHO and the American Medical Association, have concluded that there is no evidence to suggest that genetically engineered food products pose a threat to human health or increase or decrease cancer risk. Several studies have found that transgenic foods have effects on animals such as altered hematology, reproductive ability, and increased toxicity (Singh et al., 2021). A literature search showed that GM plants do not increase the risk of cancer for people or animals consuming them. GM foods are widely consumed worldwide with no known side effects. Despite this, the safety of GM foods remains unknown due to a lack of long-term research. Besides that, 64 countries, including Australia, Japan, and all EU countries, require the labeling of GM foods. Consumption of fresh foods is preferable to processed ones to reduce cancer risk (Alrawi & Al-rawi, 2022).

All available GM Foods in the marketplaces have passed safety assessments, and it has been shown that, as a consequence of eating GM Foods, there are no effects on human health. It is reported that GM food poses three main risks: allergenicity, genetic hazards, and toxicity. These risks arise from the disruption of natural genes and the insertion of new genes and their products (proteins) in the organism (Rock et al., 2020). First, no allergic properties have been discovered relative to GM Foods now in the market. Regarding the second issue, the possibility of transfer is low; however, the use of gene transfer technology that does not contain antibiotic-resistance genes has been reinvigorated. Concerning the third issue, several nations have advanced preventative strategies such as the separation of GM and non-GM crops. Different genes are used in different ways in transgenic organisms. Hence, it is essential that each GM food product undergoes testing and safety evaluations individually, following global standards. The WHO and the FAO jointly work through the Codex Alimentarius Commission to establish standards, codes of practice, guidelines, and recommendations for food, including GMOs (Siegel et al., 2022).

GM varieties that have been approved for commercial use include food/feed crops (rice, maize, soybean, wheat, bean, flax, chicory, colza, tomato, eggplant, squash, sweet pepper, potato, apple, papaya, melon, and plum), cash crops (sugar beet, sugar cane, cotton, creeping bentgrass, and safflower), ornamental plants (petunia and carnation) and forestry trees (eucalyptus and poplar) (Montagu, 2019).

The discovery of Agrobacterium tumefaciens' Ti plasmid and its role in natural bacteria-plant transgenesis enabled the field of plant sciences to move towards biotechnology. Through the utilization of genetic modification technology and molecular-assisted breeding, biotechnological processes have been developed that have facilitated enhanced yields being achieved more sustainably (Montagu, 2019). To date, the majority of GM plants are transgenic. Recently, cisgenic GM plants that are genetically modified using a gene sourced from a sexually compatible plant have been developed (Kok et al., 2010). Approximately 10 years after the generation of transgenic plants in the laboratory, genetically modified food plants were brought into the commercial market. In 1994, the FLAVR SAVR tomato, modified to retard early fruit softening, was made available in U.S. grocery stores (Kramer & Redenbaugh, 1994). From 1996 onwards, insect-resistant Bt maize and Bt cotton, in addition to transgenic herbicide-tolerant soybeans and oilseed rape were planted on quickly expanding acreages (Kramer & Redenbaugh, 1994). Breeders are responsible for two main processes when creating cultivars: creating or collecting genetic variability and discriminating among the existing variability to identify and advance the wanted individuals that meet their breeding objectives (Salgotra & Chauhan, 2023). The success and efficiency of a breeding program largely depend on these two activities, so breeders are continually seeking new or improved technologies and methods that can help with these effects (Al-Khayri et al., 2015).

4.3 Environmental impact and public perception of GM foods

Sustainable agriculture has provided a set of principles and practices that aim to create a long-term ecologically sound approach to agricultural production including human food and fiber needs (Godfray & Garnett, 2014), preserving the environment and natural resources upon which agriculture depends (Pretty & Bharucha, 2014), making use of both renewable and nonrenewable resources as efficiently as possible (Gorjian et al., 2022), sustaining economic viability for farmers (Khan et al., 2021), and improving the standard of living for agricultural communities (Huang, 2017).

While green biotechnology has contributed to sustainable agriculture and improvement in nutrition and food quality, it has also brought several environmental problems. Some of the main issues can be noted as insecticide resistance, loss of biodiversity, and socioeconomic risks (Nasser et al., 2021; Venkatesh et al., 2020).

Transgenesis has the potential to produce herbicide-resistant pests or weeds, leading to increased use of herbicides, which can negatively affect human health through contamination of water and soil (D'agnolo, 2005; Li et al., 2004; Metcalfe, 2003).

The effects of green biotechnology on biodiversity are more complex. Agroecologists and ecologists are both apprehensive about the potential impacts that GM plants may have on the ecological equilibrium of the environment (Wolfenbarger & Phifer, 2000). They are especially concerned about the toxins that transgenic plants may generate, which could be released during the vegetative stage of their growth cycle. Additionally, they worry that these toxins may result in some pests becoming resistant to toxic compounds as they can accumulate in certain parts of the plants (D'agnolo, 2005; Metcalfe, 2003).

Rzymski & Królczyk (2016) conducted a survey of 1021 voters in Europe to gain insight into their attitudes towards the various uses of GMOs. The main concerns associated with GM foods included the potential for cancer development, allergic reactions, and adverse effects on native biota. Results indicated that more than half of the polled Polish researchers were against the production and distribution of GM foods, in contrast to the United States, where scientists generally deem these products to be safe (Chagwena et al., 2019; Rzymski & Królczyk, 2016). In recent years, the use of GM plants and organisms has become more common. On the other hand, Çatak & Atalay (2020) claimed that GMOs can produce unexpected changes in living things due to the introduction of transgenes. In a study on mice that were fed transgenic potatoes, cancer cells developed in rats, the development of the brain, liver, and testicles was prevented, part of the liver was dulled, and there were histological differences in the pancreas and intestine (Rzymski & Królczyk, 2016). Therefore, it is necessary to take legal, administrative, and technological measures to ensure a level of biological safety. The recent introduction of GM crops and products into the market has expanded the scope of food safety concerns, as evidence suggests a link between their consumption and an increased risk of various health issues, including allergies, premature aging, and cancer (Rab, 2019).

Since their introduction, GM crops have been the source of much controversy due to the ethical considerations surrounding them. These issues are both ideological, in terms of views on life itself, and practical, such as legal frameworks for intellectual property rights, risk assessment regulations for GM crops, and the distribution of benefits yielded by them, particularly regarding food security (Bennett et al., 2013). There seems to be a fundamental disagreement concerning GM crops from a philosophical standpoint (Karalis et al., 2020). One side holds that genetic engineering of crops is an inappropriate interference with life itself, while there is an opposing opinion that claims that our manipulation of the physical world through the production of novel chemicals and the living world through animal and plant breeding has been beneficial for humans in many ways, thus making GM technology nothing more than another step in this process (Abdul Aziz et al., 2022). This view also acknowledges that satisfactory mechanisms are in place to monitor scientific innovation and address possible risks (Bennett et al., 2013)

5. CONCLUSION

The relationship between food technology and cancer is multifaceted, encompassing dietary patterns, food processing methods, and biotechnological innovations. A growing body of evidence links UPFs to increased cancer risk through microbiota-mediated mechanisms, inflammation, and metabolic disruption (Cordova et al., 2023; Greathouse et al., 2022). In contrast, plant-based bioactive compounds—such as curcumin, lycopene, and urolithins—produced through microbial fermentation or functional food formulations, exhibit promising cancer-preventive properties (Bultman, 2017).

Green biotechnology has advanced both sustainable agriculture and cancer prevention. Innovations such as biofortified crops, edible vaccines, and transgenic plants have improved food quality, nutrient availability, and therapeutic delivery systems. Nevertheless, concerns remain regarding the long-term safety of GM foods, especially those involving herbicide resistance and allergenic potential (Shen et al., 2022). While existing data generally support the safety of approved GM foods, further long-term, independent studies are necessary to make public conviction and refine regulatory frameworks. Beyond genetic engineering, advancements in non-thermal food processing technologies offer promising approaches to preserve the integrity of cancer-preventive bioactive compounds during food production and storage. Future research should explore their long-term efficacy, particularly in maintaining functional lipids and minimizing compound degradation (Galanakis, 2024).

Future research should prioritize translational studies that bridge dietary interventions, microbial ecology, and cancer risk assessment. Greater attention must also be paid to standardizing the use of functional ingredients in processed foods, clarifying regulatory limits, and addressing gaps in consumer education. As food technology continues to evolve, an interdisciplinary, evidence-based approach will be key to maximizing its benefits while minimizing unintended health risks. While past experiences should be taken into consideration, it appears that the use of GM foods cannot be avoided, and their potential advantages should not be ignored due to unfounded fears. Therefore, caution is recommended while remaining vigilant for any early indications of negative consequences.

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