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Next-Generation Halal Biomanufacturing: Microbial Fermentation, Cellular Agriculture, and The Circular Bioeconomy

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Abstract

The global halal food market is expanding rapidly; however, many foodstuffs today especially in high-value regions are processed with additives or processing agents, such as gelatin and L-cysteine, derived from theologically prohibited or ambiguous sources. To overcome these compliance vulnerabilities, microbial fermentation and advanced biotechnology have emerged as strategic, high-yield alternatives. This review systematically evaluates the foundational frameworks required for halal-certified bioproduction. It outlines critical control points in microbial processing: strain isolation, cultivation media, fermentation conditions, downstream recovery, and digital traceability through blockchain technology and the Internet of Things (IoT). In addition, this review examines the Islamic jurisprudential perspective on next-generation genetic engineering, highlighting how high-precision tools like CRISPR-Cas9 and AI-driven bioinformatics can synthesize compliance-verified enzymes without utilizing exogenous animal DNA. Finally, this review explores microbial alternatives and cellular agriculture approaches for controversial protein-based ingredients, red bio-colorants, and complex aromatic compounds. By aligning modern biomanufacturing technology with Shariah compliance to advance a Halal Circular Bioeconomy, the food industry can establish an ethically sound, eco-aware supply chain for the burgeoning Muslim consumer market.

Keywords: Halal Biomanufacturing; Microbial Fermentation; Food Biotechnology; Shariah Compliance; Cellular Agriculture

1. Introduction

Religious beliefs can play a considerable role in determining dietary habits (Fay & German, 2008; Kwon & Tamang, 2015; Mukhtar & Mohsin Butt, 2012). Muslims are under the Qur'an and Hadiths that prescribe foods that are permissible (halal) and prohibited (haram), including prohibitions on pork, carrion, blood, alcohol, and specific harmful substances (Armanios & Ergene, 2018). Food processing must adhere to these dietary laws and abide by 'halal' principles, according to Fischer (2008) and Kwon and Tamang (2015). The halal food industry is booming, bolstered by an almost 25% Muslim world population (Pew, 2017) and a projected market value of $2.6 trillion by 2020 (Grand, 2018). Fueled by a consumer "right-to-know" of products to be ethically produced free of non-halal components, demand for certified products is growing. In modern manufacturing methods, many companies in production use prohibited substances since in bulk porcine and non-halal slaughtered cattle are routinely used as raw materials to obtain gelatin and chymosin (Al-Mazeedi, Regenstein, & Riaz, 2013). Microbial fermentation offers a strategic solution to these compliance challenges by fostering closer collaboration of biotech firms and certifications (Fischer, 2015).

Such re-derivation of halal bioproducts from gene technologies like recombinant DNA technology (rDNA) and Genetically Modified Organisms (GMOs) can be considered to increase the yields of halal bioproducts as long as they adhere to Islamic belief. Theoretically, it is also feasible to consider alternative fermentation methods, in which microbes are transformed or cultured into food and beverage products. While gene sourcing controversy continues, many recombinant products have now received halal certification as they are an essential ingredient for improving the lives of humans. Others argue that so are the health benefits of biotech implementation that it becomes a religious obligation (Peacock, 2010). Biotechnology has a rapid and cost effective substitute for harmful additives (e.g., L-cysteine, gelatin, chymosin) (Al-Mazeedi et al., 2013). However, halal integrity must be monitored and optimized from growth media to surfactants and downstream recovery agents to satisfy compliance with production costs and quality (Dodge, 2009; Piggott, 2002).

The successful navigation of such complicated biomanufacturing crossroads will necessitate strong, standardized oversight. This is a key point where the regulations enacted by organizations like the Department of Islamic Development Malaysia (JAKIM) are a global standard for the compliance with halal certification (Majid et al., 2015). These stringent, highly evidence-based protocols to verify microbial lineage, processing aids and downstream chemical inputs (JAKIM) create a pragmatic and structurally driven model for the

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biotechnology sector. By taking this kind of advanced certification ecosystem as an underlying lens, we assess the touchpoints of critical control of microbial engineering, examine the theological ramifications of next-gen genetic modification, and endorse microbial substitutes as the ultimate pathway towards a more ethically transparent and sustainable halal food supply chain.

2. Literature Review

2.1 Principles of Halal Bioprocessing

Biomanufacturing is done in a sequential fashion with preparing upstream and recovering downstream, which must be done in accordance with strict Islamic dietary laws from beginning to end in order to produce a halal-certified product. Monitoring are necessary to ensure a theological and sanitary compliant process and cover five critical stages: Isolation of microbial strains, composition of cultivation media, fermentation parameters, downstream purification, and packaging. Moreover, because the objective of Islam's jurisprudence is to protect human health, all substances with scientific effects on such health are forbidden (Qaradawi, 1994). The employment of non-toxic, safe materials is an implicit baseline for the production steps and stages.

2.2 Microbial Lineage and Strain Isolation

While industrial microorganisms are commonly isolated in diverse environments such as soil and dairy, halal bioprocessing completely restricts these primary sources. To become halal, it is necessary to obtain strains from hygienic, allowable niches; a strain of microbial is non-halal when isolated from the forbidden sources of blood, feces or carrion. Research done by Kurniadi & Frediansyah (2017) supports that porcine-related probiotics or estrogen-secreting bacteria are prohibited in halal cultivation. Despite those distinct theological boundaries, the commercial biotechnology sector is quite accustomed to using non-halal strains. Commercial enzymes (such as proteases, lipases) are typically derived from microbes that can be sourced from animal carcasses or feces (Loperena et al., 2012).

Likewise, food science studies examined employing lactic acid bacteria (LAB) from human feces for vegetable fermentation, and Zamora, Carretero, and Pares (2006) investigated LAB cultures collected from porcine blood. Such practices question certification authorities, as there is no empirical evidence to suggest whether microbes from impure sources may be "purified," religiously "purified" from impurities by successive generations of cultivation in strictly halal media, as certified bodies believe.

Genetically Modified (GM) strains add further theological ambiguity. The Islamic permissibility of these technologies is conditional on their precise source of origin, the traits of the final bioproduct and the biological output of the transgene, and the consequent long-term effects and physiological consequences if the transgene has a long-term effect on human physiology. In order to avoid ambiguity, it is strongly recommended that mixed cultures with unverified GMOs not be studied and that people must have explicit knowledge of the gene origins (Abdullah, Ma'Radzi, Saleh, Kamal, & Yaacob, 2011). At the end of the day, using only microorganisms with a verified and unbroken lineage that is halal-compliant is the safest way to meet compliance, and retain the trust of consumers.

2.4 Inoculum Preparation Using Nutritional Media

Apart from the microbe itself, the medium of food preparation for inoculum is very essential to halal compliance. Microbial research commonly employs nutrient-rich, non-halal animal derivatives to maximize cell growth. Although brain heart infusion (BHI) broth and agar have become increasingly popular, they often contain porcine gelatin and animal tissues. This dependence has been demonstrated by the BHI media culture of *Corynebacterium glutamicum* to produce L-ornithine (Kim, Lee, & Lee, 2015), and BHI broth use for amylase production, through solid-state fermentation by *Bacillus licheniformis* (Kaur et al., 2017). Another significant ethical obstacle is the use of blood derivatives, which are strictly prohibited from starter cultures under Islamic law (Kurniadi & Frediansyah, 2017). However blood-supplemented agar is widely used in farming practices. Blood-based matrices have had their use in the production of inulinase expression for *Acinetobacter baumannii* (Muslim, Ali, Salman, Al Kadmy, & Muslim, 2015) and in the culture of *Streptococcus zooepidemicus* for the biosynthesis of hyaluronic acid (Pourzardosht & Rasaee, 2017). Further, digested fish blood proteins on starter cultures for fermented food products have been reported (Fanous, 2010).

Inoculation phase, in which active biomass is moved to the main bioreactor, adds additional risks of contamination. Cellular dispersion requires lipid-based emulsifiers (e.g., polysorbates). Interestingly, as noted by Karahalil et al. (2017) and Karahalil, Germec, Karaoglan, Yatmaz, Coban, Inan, et al. (2019), Tween 80 (polysorbate 80) is routinely added to optimize microbial suspension in inoculum solutions. Since these emulsifiers may be made from animal fats non-halal fats, their pure origins should be rigorously verified. After incubation, preservation of viable cultures at cryogenic temperatures (−80 °C) needs halal-compliant cryoprotective agents. Though glycerol, lactose, skimmed milk powder, and whey are the common base (Alonso, 2016), active carbon is increasingly employed in the preparation process. Not only for the beverage purpose, but the active carbon serves as a carrier, which promotes genetic stability and dampens fluctuations of heat in order to keep cells viable during freezing (Alonso, 2016; Malik, 1990). But, since active carbon can be synthesized from calcined animal bones, not botanical sources, the provenance must be explicitly halal certified to ensure compliance throughout the lifecycle of biomanufacturing.

2.5 Stability and Composition of Fermentation Media

Fermentation media provide the biochemical conditions for cellular growth, metabolism synthesis, and biochemistry. Accessible carbon and nitrogen, which can only be needed for such media (a lot of it is from animal tissue), and this necessitates an intense theological consideration. It is difficult to achieve halal compliance with animal-derived carbon sources. For instance, *Yarrowia lipolytica* W29 has been employed to bio-convert lard to microbial oils, citric acid, lipases (Lopes, Gomes, Silva, & Belo, 2018). The manufacture of red pigments from *Monascus ruber* CCT 3802 also employs glycerol, a substrate that has long been found in non-halal animal fats (Meinicke et al., 2012). They also deserve the same strict treatment as nitrogenous supplements. These laboratory consumables (meals obtained from blood, banned species, or animals which were not killed according to Islamic practice; also, peptones and hydrolyzed proteins from the laboratory products are non-compliant. Also, hydrolysis of tryptones with porcine trypsin makes the substrate completely haram suitable for production for the biomanufacturing purposes. The meat from the Ahl al-Kitab (People of the Book) has been traditionally accepted in Islamic law. But modern Sunni and Shi'a authorities today pay greater attention to the individual butcher of the slaughterhouse practices (Armanios & Ergene, 2018). The kosher rites as practiced by Jews resemble that of Islamic states, but a crucial theological contrast is that the blessing of being kosher is provided to the herd of animals and not individually (Regenstein, Chaudry, & Regenstein, 2003). To meet the dual certification standard, various practical business modifications are made in the industry with practical adjustments, namely, now there are industry adaptations that permit Jewish slaughterers the customary Islamic invocation to be performed by the Jewish slaughterers during the process.

In the modern day, bioengineering has shifted from wasting so-called high cost waste and nutrient enriched industrial byproducts to low cost waste and high nutrient value industry byproducts in order to optimize economy and economic efficiency as opposed to cost-effective clean ones. Meat, bone, feathers and blood meal from slaughterhouse effluents and other residues are frequently applied in matrices for example to highly high yield producing products (Nikolay et al., 2013; Turhan, Bialka, Demirci, & Karhan, 2010; Villa et al., 2013; Yatmaz et al., 2016). Similarly, whey is regularly used as a nutritious n repository for microbial growth (Germeç, et al., 2019; Karahalil, Germec, & Turhan, 2019). When these above factors are highly concentrated, anthropogenic origin of these highly concentrated and animal source is more necessary as these conditions can be determined with certainty. Contemporary researchers highlight, in order to avoid such safety precautions and at the same time address global environmental issues, a shift towards Halal Circular Bioeconomy. This approach goes into higher abstraction in waste management by repurposing organic waste streams: the fruit pomace, the agricultural lignocellulose, and the effluents derived exclusively from the certified halal food processing (Sulaiman, Othman, Baharuddin, Mokhtar, & Tabatabaei, 2014) as primary fermentation substrates. This closed-loop bioeconomy also fits perfectly into the Islamic jurisprudential concept, tayyib, which stands for wholesome, pure, sustainable.

Through the use of eco-friendly, halal-certified waste streams to drive microbial cell factories, this industry is not only avoiding ambiguities on religion regarding the sources of the nutrient extracted from animals, but it is also laying the foundation for a sustainable zero-waste model of subsequent biomanufacturing practices.

2.6 Fermentation Machinery and Control

The bioreactor's functioning is as important as the biological components it produces. Stringent sanitation, washing and autoclaving to a length of time specific to the equipment's previous use is required to eliminate any post-fermentation impurities, such as leftover biomass and spent media, and to retain halal certification (Al-Mazeedi et al., 2013). In industrial-scale

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facilities producing both halal and kosher products, special ritualization ("kosherization") is required. It is a process that includes extensive detergent washing followed by 24 h of dormancy and final sterilization with steam and hot water according to the order of a religious inspector (Al-Mazeedi et al., 2013; Fischer, 2015). As such, both active fermentation and the operation of chemical products, in particular the addition of functional additives and processing agents, require a degree of theological consideration. As an example, gelatin is occasionally applied to protect sensitive cells from mechanical shear forces (Rahim, Hasan, Harith, & Abbas, 2017). Additionally exogenous enzymes are commonly employed to decompose complex agro-industrial substrates into easily fermentable monomers prior to inoculation (Turhan et al., 2010).

Another issue is excessive foaming which inhibits the recovery of products and could lead to contamination. This means that industrial antifoaming agents used for this need to be specifically halal-certified the agents can be made from synthetic polymers, animal fats, or blood serum. Contemporary bioprocessing often employs cell retention methods, wherein microbes and enzymes can be incorporated into polymeric matrices, preserving their viability, stability with environmental resistance, in order to maximize production economics. However, these stabilizing matrices present great halal compliance risks. Animal derived polymers such as gelatin, inorganic adsorbents such as calcined bone char, and protein-based hydrogels from casein or whey need stringent provenance inspection to eliminate non-halal processing enzymes (Alonso, 2016; Datta, Christena, & Rajaram, 2013; Qureshi & Maddox, 1995).

One of the alternatives to prolonging the lifecycle of biocatalysts focuses on microbial biofilms grown in the bioreactor by customizing internal structure like the plastic composite support (PCS) system material. This technique has been successfully employed in the commercial biosynthesis of lactic acid, lysozyme, and pullulan (Cheng, Demirci, & Catchmark, 2011). Although PCS matrices are formulated for very precise fermentations, using biochemically complex components such as bovine albumin or red blood cells is a critical breach of halal integrity of the bioproduction process (Ercan & Demirci, 2015; Germec, Yatmaz, Karahalil, & Turhan, 2017).

2.7 Downstream Processing and Target Recovery

After the fermentation is complete, downstream processing is performed systematically to remove metabolic impurities to obtain a stable target bioproduct. These essential recovery processes need other chemicals for example, filter aids, flocculants, buffer salts, acids, and bases, with all of them requiring strict halal certification (Dodge, 2009). Chemical flocculants are ubiquitous in non-food industry but are not widely used in purification of halal bioproducts; harmful substances have an adverse effect on human health and Islamic dietary rules strongly forbid the use of dangerous substances (Wibisono et al., 2018).

Porous adsorbents have been widely employed to filter away residues from spent culture media (Qureshi & Maddox, 1995). It also uses activated carbon which can be either used as a free-flowing slurry or be placed in a packed column as an adsorbent which works either alone or in combination with diatomaceous earth, such as Celite (Gonçalves, 2011). In industrial manufacturing processes, the packed adsorption of activated carbon columns facilitates recovery of large amounts of oligosaccharides to recover salts, pigments, as well as other molecular pollutants from crude broth (Mûkhtar & Ijaz, 2014; Sarhaddar, Scheibl, Berghofer, & Cramer, 1997). Significantly, although most commercial carbon is obtained from the botanical environment, a substantial fraction of it is obtained from animal sources, such as skeletal bones. Realizing the deep theological implications of this sourcing, most of the suppliers have taken the first and foremost steps towards obtaining strict local halal certification from halal certification bodies and compliance with the requirements of Muslim consumers around the world (Wibisono et al., 2018).

2.8 Packaging, Labeling, and Traceability

During the last phase of biomanufacturing, it is necessary to formulate and package a product strictly based on halal standardization including addition of standardization agents, chemical preservatives and packaging. Figuring out the origin of packaging material is essential; animal-derived compounds such as stearates and a variety of special coatings are typically used in industrial packaging (Ermis, 2017). Moreover, processing stabilizers need proper theological examination. For instance, using bovine serum albumin (BSA) to freeze-dry powdered products poses a significant compliance risk if the source animal has not been ritually slaughtered (Srirangsan, Kawai, Hamada-Sato, Watanabe, & Suzuki, 2011).

The physicochemical migration of prohibited substances into the commodity also gets into the crosshairs of non-compliant packaging. Riaz and Chaudry (2018) have noted that trace components from direct-contact label materials, including cellulosic paper and synthetic plastics, might enter the food matrix, a process that a certification body must evaluate systematically. There is also an issue of unauthorized "halal" labeling without proper certification that is a huge barrier to Muslim consumers apart from that with regard to the integrity of packaging.

Since standard labeling law doesn't require companies to announce incidental processing aids or equipment history, we don't have absolute theological certainty without outside verification. This means the most secure protocol is one that is limited by the recognition of halal companies, making it impossible for any commercial manufacturer to source from non-certified sources as it must be done through verified entities. Yet it is highly porous as well as regulated. Askomi, Yusop, and Kamarulzaman (2018) observed high prevalence of unauthorized use of official halal logos in uncertified products in many countries. To counter fraudulent labeling, and to restore the transparency of supply chains there are now more digital traceability tools, such as QR codes and advanced barcodes, being adopted. These technologies enable consumers to seamlessly validate the regulatory status of a product at the point of purchase just by connecting with the centralized databases of official halal authorities using mobile applications.

Whereas QR codes and mobile applications have improved consumer transparency, the future integrity of the halal supply chain will depend on the integration of Blockchain technology and the Internet of Things (IoT). Because conventional labeling regulations fail to provide protection against incidental contamination or fraudulent certification, permissioned blockchain networks can deliver an immutable, decentralized ledger that permanently documents all processes in the biomanufacturing lifecycle. This digital architecture with associated IoT sensors that provide real-time environmental and logistical monitoring makes compliance automatic through smart contracts. If the product differs from halal critical control points during transit or processing, the system will automatically alert to the anomaly, making unauthorized or fraudulent halal claims virtually impossible, and achieving total theological certainty for the end user (Kurniawan et al., 2023).

3. Islamic Perspectives on Transgenic Technology and Fermentation

GM is a process of transferring genomic information between organisms, generating genetically modified organisms (GMOs) to use genetically modified foods in bioengineering (Majid, Abidin, Majid, & Chik, 2015). These technologies offer significant environmental and bio-socio-economic advantages as in minimization of pesticide application, sustainable planting, food supplies (Akhmetova, 2016; Muhammad, 2010). Genetically modified microbes are responsible for optimizing product yields while minimizing unwanted by-products in industrial fermentation to the highest potential of a product achieved through fermentation.

However, the GM foods face international resistance as an expression of a multitude of ethical and religious concerns (Atalan-Helicke, 2015; Brown, 2011), the transgenic tool has been widely criticised as the subject of ongoing theological debate in Muslim societies. But the vast majority of mainstream halal certification institutions will not ban GMOs outright. The regulation of transgenic crops is still an open question, but mechanisms for microbial growth are relatively straightforward. The evaluation of the GMO-enhanced fermentation procedure depends on four key parameters: the biological origin of the transgene, the kind of taxonomic transition (e.g., animal to microbe), its adverse effects on human health, the environment, and the fulfillment of a fundamental social responsibility. One of the core principles of halal transgenics is that transmitting a gene from illegal donors (such as porcine) to a bona fide host will result in the product being unambiguously haram (Che Man & Sazili, 2010). To further complicate this approach, scientists propose that jurists must also examine completely synthetic, de novo in vitro genes which do not contain any prohibited animal materials (Regenstein, Chaudry, & Regenstein, 2013; Riaz & Chaudry, 2003).

Plant-derived transgenes are generally the safest option, and have no halal limitations if they are nontoxic. Conversely, the donor species is also carefully scrutinized for animal-derived genes. If a gene is from a quintessentially halal animal, the relevant donor's vital status (alive or dead at extraction), however, does not preclude the gene from the permit and has not prevented the gene from permissibility (Institution, 1997; Khattak et al., 2011). Moreover, Islamic laws mandate long-term toxicological tests for recombinant metabolites for patient safety. No pathophysiological effects of commercial microbiological food processing in GM have been proven to benefit human patients up to the current stage, in spite of concerns of public health concerns in theory about GM (Blair & Regenstein, 2015; Csutak & Sarbu, 2018).

In addition to the proven classical recombinant DNA methods, the emergence of such precision genome-editing tools as CRISPR-Cas9 is an important new frontier in halal biomanufacturing. Notably, compared to pre-existing transgenic strategies that typically need to add foreign genetic material (possibly coming from ambiguous or non-halal donors), CRISPR enables efficient de-coding or upregulation of a microbe’s native genes with no addition of exogenous DNA (Gan & Ling, 2022). Theologically, the "cisgenic" procedure reduces the risk of compliance since it reprogramming of the organismal already approved, halal germline information, makes metabolite production very high. The collaboration of artificial intelligence (AI) and state-of-the-art bioinformatics has also made it possible for researchers to conduct in silico screening of large genomic databases now (Pourseif et al., 2025). This permits the rapid recognition and de novo synthesis of highly efficient, synthetic enzyme sequences without the requirement to extract genetic material from disputed animal reservoirs. The "necessity" of the genetic modification is the justification for the halal status of the work, in the end. Islamic ethical systems embrace biotechnological breakthroughs that contribute towards human health.

As a result, only approved transgenic and genome-editing technologies, capable of the desirable use in either a societal or industrial sphere, for example the production of biotechnology, are regarded to satisfy a range of genetic sourcing stipulations. In contrast, genetic engineering for purely cosmetic applications (e.g., fluorescent decorative fish manufacturing for aesthetic purposes) has remained controversial and typically excluded for utilitarian justification (Gong et al., 2003; Tonelli et al., 2017). Under strict guidance, GM approaches attuned and calibrated to halal requirements have the transformative power of an environmentally-resilient, deeply competitive, ethically aligned bio-invention venture for developing halal compliant approaches that would change the pathway to ingredients sourcing and a world-class, ethical bio-invention enterprise through which GM's competitive and environmentally superior bio-invention enterprise can revolutionize the world's food industry ingredients supply chain.

4. Microbial Substitutes for Theologically Ambiguous Ingredients in Foodstuffs

Nutrient supplements such as gelatin and L-cysteine come from theologically forbidden sources, which complicates the halal certification of processed foods. Zoological and botanical reservoirs provide perennial sourcing, ethical, and yield challenges. As a result, microorganisms have proved to be an essential and highly efficient tool thanks to recombinant DNA technology. The development of microbial cell factories offers unique biomanufacturing benefits such as rapid growth and high volumetric productivity representing a cost-effective alternative with animal-derived processing tools that have come into contention. To efficiently compensate for global market shortcomings, microbial substitution is mainly directed toward the three main ingredient classes: functional proteins, red bio-colorants, and volatile aromas (Hartel, Joachim, & Hofberger, 2018; Riaz & Chaudry, 2018).

4.1 Protein-Based Ingredients

The dietary market is dominated by cheap animal-derived protein substrates. Bovine whey (180–190 million tons/yr production) is an example, and the enzymes used for coagulation must be obtained from sources considered acceptable to preserve its halal condition (Ranganathan et al., 2018). Moreover, the industry exploits a substantial amount of raw blood and slaughterhouse effluents for their superb gelation and emulsification capabilities (Álvarez, Bances, Rendueles, & Díaz, 2009; Ofori & Hsieh, 2012). As blood derivatives are utterly forbidden in Islam in that their basic macromolecular structures can resist thermal treatment over time their clandestine use to substitute for premium halal proteins is a serious regulatory and theological challenge. In this way, with about 30% of the world commercial blood coming into the culinary sphere, its clandestine consumption remains one of the reasons for distrust from the Muslim population (Ofori & Hsieh, 2012). This widespread adulteration has prompted the development of advanced detection methods to safeguard religious integrity.

Apart from the ordinary microbial fermentation, the emerging field of cell-culture agriculture and cultivated meat is the most important contemporary disturbance in halal protein sourcing. Recently, leading Islamic regulators such as Malaysia's JAKIM and Singapore's MUIS issued landmark fatwas addressing this innovation (JAKIM, 2020; MUIS, 2024). With these decisions it was decided that cultivated meat may be considered halal, by which the basic stem cells are extracted from a halal-compliant animal slaughtered according to Islamic rites, as well as the cultivation media being void of any prohibited substances, which include fetal bovine serum. Through precision cellular agriculture as an alternative to conventional animal farming, the industry has the potential to lead to significantly lower clandestine utilization of blood-derived proteins and an environmentally beneficial highly scalable and theologically appropriate protein reservoir for Muslim consumers.

4.2 Red Colorants and Pigmenting Agents

Synthetic dyes face ever further restrictions worldwide because of carcinogenic and mutagenic risks (Dikshit & Tallapragada, 2018; Hartel et al., 2018), yet the $1.7 billion natural colorant market also has its own halal challenges (Cortez, Luna-Vital, Margulis, & Gonzalez de Mejia, 2017; Rodriguez-Amaya, 2019). Animal blood is considered a natural red enhancer and poses considerable biological risks, such as hepatitis E transmission; it is classified as haram (Boxman et al., 2017; Ofori & Hsieh, 2012). And, in the same vein, the cochineal (carmine), derived from the *Dactylopius coccus* Costa insect, remains at an impasse in theological agreement concerning the incorporation of insects into agriculture, both because of the high price but also due to severe allergic risks (Hartel et al., 2018; Müller-Maatsch & Gras, 2016; Sigurdson, Tang, & Giusti, 2017; Voltolini, Pellegrini, Contatore, Bignardi, & Minale, 2014). In response, microbial cell factories especially single-celled algae and fungi such as *Penicillium oxalicum* provide scalable, low-cost and halal-compliant "Natural Red" pigments that completely ignore seasonal and religious limitations (Dufossé, 2018; Nigam & Luke, 2016).

4.3 Aromatic Chemicals and Flavor Synthesis

Traditionally, flavors, like vanilla, are produced in commercial synthesis using organic solvents (e.g., ethanol), with residual ethanol being 35% from extraction based on standard FDA guidance (Administration, 2000b; Barnekow et al., 2007; Berger, 2007). For strict Islamic prohibitions against intoxicants, certifying agencies require strict post-extraction desiccation. For example, IFANCA, JAKIM, and MUI have determined the maximum quantity of allowed residual ethanol in flavorings is only 0.5% to 1.0% in flavorings (Bali, 2017; Riaz & Chaudry, 2018). In order to completely bypass these theological and regulatory hurdles, green chemistry is practiced using eco-friendly and non-solvent methods such as ionic-liquid assisted separation and microbial flavor synthesis (Gmoser, Ferreira, Lennartsson, & Taherzadeh, 2017). It is a biotechnological shift to deliver a robust ethanol-free pathway for production of halal aroma and products worldwide.

5. Conclusion

Biotechnology and microbial cell factories are already basic to the framework for the contemporary global food market. These advanced biomanufacturing approaches would present an unprecedented competitive advantage to the halal sector: a consistent, tightly managed series of processes for a variety of key functional ingredients (chymosin, gelatin, and natural red colorants) which would, before now, cause consumer disbelief. But that transformative potential could be exploited only within the framework of strict Islamic jurisprudential principles for the processing aids, exogenous additives, and operating methodologies, under the guidance of the strong regulatory frameworks introduced by JAKIM as well. With the continued evolution of the industry, precision tools such as CRISPR-Cas9 and AI-enabled bioinformatics will help to further protect biomanufacturing from theological uncertainty by facilitating the de novo production of compliance-verified enzymes. Moreover, by situating these biotechnological processes within a Halal Circular Bioeconomy, the industry can leverage certified organic waste streams to accelerate sustainable and highly efficacious production. In the future, speed-up of such interdisciplinary work that combines cutting-edge microbial genetics with rigorous shariah compliance will be required to evolve these emerging bio-innovations from its laboratory settings to the global industrial sector.

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Conflict of Interest

The author declares no conflict of interest.

Declaration on the Use of Generative AI

Authors declare Grammarly is generative AI used in the manuscript only for language enhancement.

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