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BIOCHEMICAL PATHWAYS OF FOODBORNE PATHOGENS: UNDERSTANDING MECHANISMS OF VIRULENCE AND RESISTANCE TO IMPROVE FOOD SAFETY

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Abstract

Background: *Food-borne diseases are a threat to health and food safety worldwide. The knowledge of biochemical pathways of food-borne pathogens is informative of their virulence, resistance, and survival mechanisms, which is beneficial in the formulation of more effective food safety measures.*

Objectives: *The paper reviews biochemical processes that aid virulence and resistance in pathogens of food, and emphasizes technological development, intervention, and future research directions to promote improved food safety.*

Methods: *A literature review on the recent peer-reviewed articles concerning metabolic pathways, biofilm development, virulence regulation, antimicrobial resistance, genome-based approaches, biosensors, and emerging intervention technologies was carried out.*

Results: *it was found that through the analysis of biochemical pathways, there was a significant contribution to the survival of pathogens in an unfavorable environment, control of host immune responses, and resistance to antibiotics. Food systems have an enhanced persistence through the presence of biofilm formation, the transfer of plasmid genes, and environmental adaptation.*

Conclusion: *The profound knowledge of the biochemical processes is a useful chance to reinforce food safety systems. Biochemical research can be used in conjunction with technology to take better detection, prevention, and intervention steps against food-borne pathogens.*

I. INTRODUCTION

Overview of Foodborne Pathogens

Food-borne pathogens are microorganisms such as bacteria, viruses, and parasites that cause disease when taken in contaminated food. Such pathogens are of great concern in the world as they can bring about outbreaks, resulting in serious health complications and mortality all over the world. Martin et al. (2022) claim that food-borne diseases remain a constant problem among the population, and pathogens such as Salmonella, E. coli, Listeria, and Vibrio are the most commonly reported infections. The importance of knowing food-borne pathogens does not just lie in the implications they have on the health of the people, but the effects they have on the economy of the world are immense. Contaminated food may cause massive losses in terms of the cost of healthcare, productivity, and the recall of food. The heterogeneity of the microorganisms in food matrices complicates the process of food safety because the pathogenic organisms also tend to be genetically, physiologically, and cellularly heterogeneous (Martin et al., 2022).

Global Impact on Public Health and Economy

Globally, food-borne pathogens have a significant impact on the health of the populace. It is estimated by the World Health Organization (WHO) that 600 million and 420,000 individuals become sick and die, respectively, every year as a result of infected food. Food-borne diseases cause economic consequences that are both in direct costs (including medical costs) and indirect costs (including lost work days and decreased productivity). The situation is even more complicated in the case of the developing world since healthcare facilities and resources are not available. Moreover, the outbreak of high-profile pathogenic organisms, like Listeria monocytogenes and Vibrio types, may cause the breakdown of the world trade, and the food products recall that leaves the food industry with giant losses (Meireles et al., 2024; Dutta et al., 2021). The fact that the antimicrobial resistance (AMR) of food-borne pathogens is rising, which constrains the treatment options and, in most instances, is not helpful and poses an overall strain on the health systems, further complicates this situation (Dutta et al., 2021).

Need for Understanding Virulence Mechanisms

More information on the biochemical processes that facilitate the virulence of food-borne pathogens is required in designing effective food safety strategies. Virulence mechanisms refer to those mechanisms that enable pathogens to infect and evade immune responses, including secretion systems, toxin production, and biofilm formation. Metabolic reprogramming, stress response, and gene control are such biological processes that help such pathogens to survive in adverse environmental conditions, such as the acidic environment of the human gastrointestinal tract (Wu et al., 2024). It is hardly possible to control and prevent food-borne illness without an in-depth knowledge of these processes. It is possible to isolate the biochemical pathways enabling the pathogen to survive and maintain virulence, to allow the researcher to identify the possible targets of intervention, such as interference with metabolic pathways or biofilm formation.

Objectives of the Review

- Highlight the importance of studying biochemical pathways of foodborne pathogens.
- Explore the mechanisms of virulence and resistance that foodborne pathogens employ.
- Suggest strategies to improve food safety through the understanding of these biochemical mechanisms.

II. Biochemical Pathways in Foodborne Pathogens

Food-borne pathogens refer to those microorganisms that cause illness following the intake of the food that they are attached to. The examples of the pathogens are Salmonella, E. coli, Listeria, and Staphylococcus aureus, which are severe threats to society on the international level. These pathogens are complicated because of their pathogenesis, which allows the pathogen to penetrate into the host, avoid the immune system, and lead to disease. The major characteristic of their pathogenicity is that they can utilize biochemical processes that enable them to survive in adverse conditions and be pathogenic. The other menace that is arising and complicating food safety is the resistance of antibiotics, which are developed by these kinds of pathogens. According to Kim and Ahn (2022), the rise of antibiotic-resistant food-borne pathogens, in particular, those associated with the farm-to-table transmission, is having severe consequences on the management of food-borne diseases.

The pathogens are introduced into the host after contact with contaminated food. When ingested, these pathogens must avoid numerous different barriers, including the acidic stomach and gut immunity. These unfavourable conditions are linked to the ability of the pathogens to survive in metabolic and biochemical flexibility. Certain enzymes and metabolic processes play a role in the ability of pathogens to withstand acidic as well as oxidative stress in the gastrointestinal tract. To provide an example of this, E. coli and Listeria monocytogenes are capable of enduring acidic environments of the stomach, which is one of the required stages of their colonization and eventual infection (Gold et al., 2022). Moreover, microbial ability to produce biofilms, protective clusters of microorganisms, is a decisive characteristic that raises the survival of pathogens on food contact surfaces and the intestine of the host.

Virulence mechanisms can be quite complicated, which are facilitated by biochemical pathways that are engaged in the regulation of the pathogen behavior. One of the most important mechanisms of invasion, as well as survival of the food-borne pathogens in the host, is the secretion of the virulence factors. One of the ways is the Type III secretion system (T3SS) that is located in such pathogens as Salmonella and E. coli. It is a process where the proteins of the effector are readily packed into the host cells, and this leads to the destruction of the host cell functions, which permits the survival of the pathogen. T3SS is also involved with the regulation of the host cell signalling network that enables the pathogen to suppress the host cell cellular machinery to its advantage. In addition, the metabolic program pursued by the pathogens during the case of an infection is reorganized in the favor of the pathogens, which is beneficial to their survival and virulence. One such metabolic reorganization in one such pathogen, Listeria monocytogenes, is described by Wu et al. (2024) as adaptation to acid stress, which is a required adaptation to low gastrointestinal tract pH.

Another vital biochemical pathway that renders the foodborne pathogens virulent is biofilm formation. The biofilms also shelter the pathogens against the external environment stressors, such as antibiotics and the host immune system. They are incorporated within a matrix and rendered antimicrobial-resistant, and this is predetermined in the familiar food-borne pathogens, such as E. coli and Staphylococcus aureus. According to the authors, the fact that biofilms on the food contact surface encourage cross-contamination and the survival of pathogens in the food production setting is the most problematic issue (Ashrafudoulla et al., 2023) Host tissues may also be colonized by pathogens through biofilms, which not only enhance the resistance of the pathogens to environmental stress but also enhance the ability to colonize tissues, causing extended infections.

It is not only the biochemical pathway of biofilm formation that has a significant role in the virulence of pathogens, but also quorum sensing. Quorum sensing is a cell-to-cell communication, whereby the pathogens are able to regulate their behavior based on population density. Bacteria can also regulate the expression of virulence factors (toxins, enzymes) in this process to enhance their capacity to induce infection. Quorum sensing regulates the production of exotoxins, which have a major role in the pathogenicity of such pathogens as Vibrio cholerae and Staphylococcus aureus. These toxins lead to the impairment of the host cells, which damages the tissues and contributes to the symptoms being exhibited by foodborne infections (Borreby et al., 2023).

Enzymes are vital for a pathogen. The enzymes that play a significant role in the life and invasion of pathogens include proteins (e.g., proteins, etc.). The enzymes help the pathogens to digest the host tissues and evade the immune reactions. Indicatively, Listeria monocytogenes expresses phospholipases which facilitate passage of the pathogen through cellular membranes, and proliferation among the host tissues. On the same scale, Staphylococcus aureus releases proteases and lipases, which break down host tissues and help in the invasion of tissues (Borreby et al., 2023). These enzymes play a central role in the pathogenicity of the pathogen and its resistance to host immune response, and their inhibition with therapeutic interventions should be the focus of research on decreasing pathogen virulence.

Virulence is also a factor in the pathogenic organisms, either through the energy development pathways during their infection. Within the context of an infection, the pathogens need to acquire an adequate amount of energy to sustain their survival and replication within the host. An example of pathogens such as Salmonella and E. coli has been known to use either anaerobic or aerobic metabolic routes, based on the conditions in the host environment in which they are. These routes are very controlled and enable the pathogens to evolve in accordance with the varying conditions of the gastrointestinal tract. Zailani and Adnan (2022) state that the investigation of the metabolic pathways of foodborne pathogens can be useful within the framework of the mechanisms through which such pathogens are capable of maintaining their energy balance and how metabolic inhibitors can be viewed as potential therapeutic interventions to deal with the pathogenic infection.

The fact that the organisms can be resistant to the antimicrobial agents also predetermines the virulence of the pathogens. The problem of antimicrobial resistance (AMR) increase in the foodborne pathogen is one of the problems that is becoming even more complicated in regard to the treatment. The transfer of gene resistance in a horizontal direction has driven the effort of escape against the action of antibiotics of the pathogens Campylobacter and Salmonella (Ammar et al., 2021). They tend to exist in plasmids, and they can be transferred to the bacteria, guaranteeing the rapid spread of the resistance. As a result, the multidrug-resistant foodborne pathogens are a high risk to human health, and this fact leads to the topicality of the knowledge of their biochemical mechanisms.

The capability of foodborne pathogens to induce disease, which is determined by their capacity to utilize them, is also important in the identification of the biochemical pathways. The biochemical processes that can lead to the survival of the pathogen and its colonization and invasion are the biofilm formation and reprogramming of the metabolism, the quorum sensing, and the release of virulence factors. These strategies will be researched to come up with effective strategies on how to reduce food borne illnesses, and the growing issue of drug resistance. With the help of certain interventions, which are aimed at disrupting these biochemical pathways, e.g., the production of new antimicrobial compounds or the aid of probiotic interventions, the problem of foodborne pathogens and the enhancement of food safety at the global level can be attained.

III. Mechanisms of Virulence in Major Foodborne Pathogens

Foodborne pathogens are virulent due to complex pathophysiology mechanisms that promote their invasion, survival, and replication. Various food-related bacterial pathogens, including Salmonella spp., Escherichia coli, Listeria monocytogenes, Staphylococcus aureus, and Campylobacter jejuni, have different biochemical pathways to induce infection. These pathogens have some virulence factors comprising secretion systems, toxins, and enzymes that help them to avoid the host immune system and achieve infections. These mechanisms should be used to arrive at effective solutions that would be used in controlling food-borne disease and food safety.

Salmonella spp. may also be contracted as one of the most common foodborne bacteria and cause an enormous gastrointestinal infection array around the globe. The invasion genes are also one of the most significant virulence factors of Salmonella because they enable the Salmonella to gain entry into the host cells. In particular, the Type III secretion system (T3SS) is much more important in this respect as it allows the bacterium to directly inject virulence factors into the host cell and subsequently to subjugate the functions of the host cells to its benefit. Han et al. (2021) state that the T3SS of Salmonella is the hub of the potential of the microorganism to enter the epithelial cells and cause inflammation. Besides that Salmonella also uses metabolic adaptations to survive in a host. This is evidenced by the fact that it can switch between aerobic and anaerobic metabolism, which is highly adaptive to the capacity of the bacterium to survive in the limited oxygen conditions in the intestines. Besides this, Salmonella has also managed to control its metabolic processes to survive the acidic environment that prevails in the stomach and the intestinal system to guarantee its survival. Immune evasion is another virulence factor of Salmonella. Gelalcha et al. (2022) assert that the pathogen can suppress the host immunity, since this may be done by expression of some effector proteins, which may disrupt the immune cell pathways. This will help Salmonella to avoid diagnosis and destruction by the immune system of a host, and it has a higher chance of becoming infected.

Escherichia coli (E. coli) and, particularly, enterohemorrhagic strains are another important cause of foodborne illness. The strains produce Shiga toxins, which are central to their pathogenicity. The toxins suppress the production of proteins in the host cells, thereby causing cell death and contributing to the effects of E. coli infections, including hemorrhagic colitis. Gelalcha et al. (2022) suggest the Type III secretion system is instrumental in the transfer of Shiga toxins to the host cells as well as the injection of other effector proteins, capable of altering the host cell functions and providing bacterial survival. The gastrointestinal tract has a diverse variety of adhesive and colonization mechanisms in E. coli. It binds itself through pili and other adhesins to intestinal epithelial cells to create aggregates and therefore promotes colonization. The interaction of E. coli can lead to the emergence of attaching and effacing lesions on the host cells, which is the typical feature of pathogenicity in these bacteria, upon binding. Different signaling pathways and two-component systems strictly regulate this mechanism to identify environmental signals and to respond through the expression of virulence genes (Sun et al., 2024). It is through these mechanisms that E. coli can continue to survive within the host and avoid immune clearance.

Listeria monocytogenes is one of the food pathogens that is unique because of its ability to survive and replicate in host cells. Among the most notable virulence factors of Listeria is the fact that it might invade the host cell and evade the ingestion process by the vacuole, to the cytoplasm, where Listeria is able to replicate. A number of biochemical pathways are favourable to this intracellular survival process, some of which are the polymerization of actin that is utilized to translocate the bacteria to the cytoplasm of the infected host cell, and also allows the bacteria to infect other cells. It is also possible due to the presence of actin-motility, with Meireles et al. (2024) stating that Listeria can be translocated between the cells and avoids immunity. The enzymes, such as phospholipase, are also synthesized by the pathogen as the enzymes help the pathogen to disrupt the membranes of the host cells and enable the intracellular cells to enter the cells. Moreover, Low-nutrient conditions, including those in the host cell cytoplasm, can be endured by Listeria with the use of certain metabolic pathways. These pathways are highly controlled and contribute to the fact that the pathogen could obtain its own system of energy without being detected by the immune system.

Staphylococcus aureus is a widespread foodborne pathogen with the capacity to produce a set of enterotoxins. These are important toxins of S. aureus, and they lead to food poisoning epidemics and other infections. Enterotoxins secreted by S. aureus are heat-stable, i.e., they can survive even when the contaminated food itself is cooked, a phenomenon causing them to be of special concern in food safety. Banerji et al. (2021) clarify that the quorum-sensing biochemical pathway governs the production of enterotoxins by S. aureus to enable the bacteria to coordinate toxin production in response to the population density. This process is necessary in order to make the bacteria generate sufficient toxin to induce illness. Besides the production of enterotoxin, S. aureus has evolved mechanisms of environmental stress and immune responses by the hosts. It is also capable of surviving in salty environments, including food processing facilities, as well as evading the host immune system through the production of factors, including protein A, which binds to the host antibodies and prevents their attachment by immune cells.

Campylobacter jejuni is another important foodborne pathogen and is primarily related to poultry. One of the significant virulence-related factors of Campylobacter that are required to move and colonize the gastrointestinal tract is the flagella. The flagellation helps Campylobacter to get toward the intestinal cells and adhere to the epithelial surfaces, a significant stage in the establishment of an infection. Mousavinafchi et al. (2023) also state that Campylobacter produces numerous toxins, including cytolethal disting toxin (CDT), which can lead to a cell cycle arrest and result in damage to the host cell nuclear DNA. Motility of the bacterium and a combination of these toxins allow Campylobacter to persist further in the host and cause the disease.

The above-discussed pathogens are just some of the foodborne pathogens that have alternative virulence mechanisms other than the above-discussed mechanisms of foodborne pathogenicity. The cholera-causing pathogen is Vibrio cholerae, which is the causative organism of cholera toxin that affects the host cell signaling, resulting in typical cholera disease manifestations such as severe diarrhea. The cholera toxin genes are complex, and He et al. (2021) believe that they are sensitive to environmental factors. On the one hand, Clostridium perfringens is the pathogen that produces different types of toxins, such as alpha toxin and enterotoxins. These are toxins resulting in cell lysis, which are associated with food-borne disease. Each of these toxins is dependent on a number of factors to regulate its gene expression, and Camargo et al. (2024) are one of the variables that are based on the availability of nutrients and oxygen in the environment.

Foodborne pathogens have virulence mechanisms that are often diversified and complex. To survive and reproduce in the host, these pathogenic microorganisms have formed a set of maneuvers that are versatile to synthesize toxins and biofilm creation to control metabolism and escape immune responses. All these processes are highly applicable in developing new measures to prevent and control foodborne diseases, and also in addressing the growing problem of antimicrobial resistance of foodborne pathogens. Through further research on the biochemical process of such pathogens, one can discover useful facts about the behavior of such pathogens and more effective control of food safety.

IV. Resistance Mechanisms of Foodborne Pathogens

The resistance mechanisms of the foodborne pathogens are very advanced, and they have been modified to enable the survival of such microorganisms in the hostile environment, including the host and food preparation facilities. These mechanisms are significant in the process of enabling the survival and transmission of the said pathogens, and it is due to this phenomenon that the world has never witnessed the level of cases of antimicrobial resistance (AMR) as witnessed today. The foodborne pathogens also possess a set of resistance mechanisms which are not confined to antibiotic resistance, but also biofilm formation, among others, that influence the pathogenicity and survivability of the pathogen in the various ecological niches. The awareness of these processes plays a very significant role in the development of techniques on how to combat food-borne diseases and the supply of food safety.

One of the most concerning problems of the foodborne pathogens is the fact that they are also becoming resistant to antibiotics. Antibiotic resistance in human care systems has been actualized as an outcome of both the application of antibiotics in human health care systems and in agriculture. The resistance of the most common antibiotics, such as β-lactam and tetracyclines, is caused by acquisition or genetic mutation. As Kim and Ahn (2022) state, Salmonella, Campylobacter, and Escherichia coli are not the only pathogens that have become resistant to several antibiotics and have proven to be an incredibly important complication in terms of infection treatment. When the resistance mechanisms are pursued, it is normally achieved through the production of the enzymes, which are the β-lactamases, and which break down the antibiotics, rendering them useless. In addition to this, efflux pumps can also force antibiotics out of the bacterial cell, also contributing to its increased resistance. The primary way of transmitting antibiotic resistance is through horizontal gene transfer. The resistance genes can be transferred to other bacterial species not only with the help of plasmids but also with transposons or integrons, and this increases the resistance phenotypes of bacterial groups (Dutta et al., 2021). This portability of the genetic material of the pathogens is one of the biggest contributions to the survival of the antibiotic-resistant strains, especially in the food production environment, where antibiotics are highly utilized.

Resistance is another significant feature in the host immune system that determines the pathogen's survival in the host. These pathogens have been able to develop various schemes to avoid the immune system of the host and have succeeded in surviving and inflicting infections. The ability to escape immune recognition by the immune cells is among the most common immunological evasion mechanisms. According to the Salmonella case, the bacteria can also evade immune response by evasion of host antibodies through adaptation of their surface antigens (Ammar et al., 2021). Similarly, Campylobacter jejuni can also alter its lipooligosaccharide structures to avoid immune responses. Turbo with the antigen variation, there are also certain pathogens that lead to virulence factors, which directly interfere with the immune system of the host. These agents may be proteases, which destroy the immune molecules of the host, or Toxins that prevent the action of immune cells. It is environmental factors such as the metabolic state of the organism and the environment that regulate such virulence factors and indicate that the immune evasion systems of the pathogen can be triggered at any moment to help the pathogen infect the host (Hosseini et al., 2024).

Biofilm formation is one of the key resistance mechanisms enabling foodborne pathogens to be preserved in a very vast environment, such as food processing plants, medical devices, and the human host. Biofilms consist of structured clusters of bacteria in an outer layer of an extracellular matrix that adds to their extreme resistance to antibiotics and host defenses. On development, biofilms become difficult to eradicate, and they can lead to chronic infections. The formation of biofilms is mentioned as one of the most significant determinants of resistance of such pathogenic agents as E. coli, Salmonella, and Listeria to antimicrobial agents (Tao et al., 2022). Biofilms in food production settings are formed on food processing equipment, utensils, and storage containers, and cause cross-contamination and the growth of the pathogen. Biofilm matrix provides a physical barrier against the penetration of antibiotics, and also the bacteria in the biofilm are able to communicate and coordinate their defense mechanisms through the quorum-sensing process. This concerted action improves the resistance to the stresses of the environment and antimicrobial interventions by the pathogen.

The survival of foodborne pathogens in the food production environment is also dependent on environmental resistance mechanisms. Foodborne pathogens should be capable of enduring diverse physical and chemical conditions, such as alterations in temperature, PH, and osmotic pressure. As an example, most pathogens can exist in low temperatures, such as refrigerated foods, where they remain in an inactive form but can be activated as the conditions are just right. Moreover, other pathogens are very insensitive to pH changes. An example of these is Campylobacter, which has developed a system to survive acidic conditions in the stomach and intestines and subsequently infects them (Mousavinafchi et al., 2023). Other pathogens, such as Salmonella and Listeria, are able to survive under extreme environmental factors such as low-nutrient conditions in the majority of food matrices. The biochemical pathways that facilitate such survival measures have exposed the pathogens to the environmental stressors, which ensure their survival in food production and food processing environments (Black et al., 2021).

The resistance of foodborne pathogens to antibiotics, host immune system, and environmental factors has been a challenge to food safety. Since the incidence of foodborne diseases is increasing in the world, there is a need to establish correct mechanisms to fight these virulent pathogens. Details on the molecular mechanism of resistance can be used in designing new points of treatment that can be novel antimicrobial agents or new types of treatment. In addition, the spread of resistant pathogens can be reduced through the augmentation of hygiene, the regulation of the use of antibiotics in the food industry, and the imposition of more stringent food safety standards. The possible solutions to the identified problem are the exploration of a potential solution that involves the use of bacteriophages as natural antimicrobials and other new ways to address the problem (Khan et al., 2023; Farid et al., 2023).

In conclusion, foodborne resistance to pathogens is multi-factorial and heterogeneous and involves genetic adaptation, immunity, biofilm formation, and harsh environmental survival. The pathogens are more virulent through these processes, and the control and prevention of food-borne diseases becomes more difficult. In order to address these issues, the theoreticalization of the biochemical process which will support the resistance and formation of collective actions to enhance food safety is required. Using the results of the research and taking certain steps, one can reduce the impact that antibiotic-resistant foodborne pathogens can have on the health of people and improve the food security in the world to a considerable extent.

The implications of biochemical knowledge about the biochemical pathogenesis of foodborne pathogens in food safety statutes, pathogen identification, and interventions that can be used to prevent and control food-borne illnesses are enormous. It can identify the biochemical control to regulate the pathogen virulence and resistance that can enhance and guide the effectiveness of the current food safety standards. The data can be incorporated into the improvement of the regulations and efficient food safety policies that will eventually minimize the risks of contamination and ensure food safety.

The food safety laws are also quite efficient, as the knowledge of biochemical mechanisms of pathogens can result in more targeted and efficient safety requirements. As an example of the introduction to the food matrices, pathogens can be of different genetic, physiological, and cellular diversity levels, making the traditional approach to food safety, including detection and identification of pathogens, less effective (Martin et al., 2022). It is possible to understand the biochemical pathways of pathogen survival to improve the food safety standards and mitigate the challenges presented by the pathogen behavior, like resistance to some environmental conditions. These advances in understanding also may result in creation of more effective pathogen detection methods, including foodomics, a newly emerging practice that combines approaches to analyze techniques, including genomics, proteomics, and metabolomics, to determine the presence of pathogens in food systems and their interactions (Balkir et al., 2021). Food producers can timely intervene in the best way to eliminate the outbreak to improve food safety with improved detection of the pathogens.

Good targets for the food safety interventions are also provided by the biochemical pathways. There are two potential strategies that can be employed to utilize the biochemical pathways knowledge in the fight against foodborne pathogens, and they are biocontrol agents and antimicrobial peptides (AMPs). By exploiting some biochemical activities, the beneficial bacteria and bacteriophages can be utilized as biocontrol agents to compete or eliminate foodborne pathogens in food environments. Such agents can manipulate certain metabolic routes of the pathogens without having to harm the pathogens, taking into account the food structure or human health. One of them is AMPs, which are natural, antimicrobial peptides and may change the cell membrane of bacteria or inhibit the action of major enzymes, consequently preventing the survival of pathogens (Maurya et al., 2021). The AMPs can be used as specific antimicrobial agents to reduce the risk of foodborne illness with regard to specific virulence factors. This is a more viable and natural substitute that is scientifically applicable in accordance with biochemical information and the known conventional chemical preservatives.

In addition, there is the direct attack on virulence factors due to biochemical intervention, which is highly promising. Virulence factors include the toxins secreted by E. coli and Listeria monocytogenes, which play a central role in the formation of the disease by the pathogen. Interventions can be developed to prevent the production or counter the effects of the toxins by understanding the biochemical pathways that control the production of these toxins. As an example, Type III secretion system inhibition in Salmonella prevents the injection of virulence factors into host cells and limits the capacity of the pathogen to initiate infection. In the same manner, one of the primary resistance mechanisms of foodborne pathogens, biofilm formation, can be targeted by disrupting the processes of quorum sensing, one of the biochemical pathways of bacterial communication (Tao et al., 2022). By disrupting such pathways, we are possibly in a position to come up with food safety measures that will be more effective in ensuring that pathogens do not occur in the food processing facilities, as well as in the human body.

The biochemical pathways can also be used in currently existing methods of food safety, such as Hazard Analysis and Critical Control Points (HACCP), pasteurization, and irradiation. HACCP is a mature food safety management system that reports potential hazards and controls them during the food production process. Although HACCP has succeeded in diminishing foodborne illnesses, a comprehension of the biochemical processes of the pathogens could help to improve the technique by enabling more accurate identification of the critical control points and dispersing the interventions to the maximum. As an example, an understanding of the ways in which pathogenic microorganisms such as Listeria change their metabolic pathways in response to environmental stressors may be used to develop more effective temperature regulation measures during food processing and storage (Meireles et al., 2024). The process of pasteurization and irradiation may be better done under the conditions of biochemical pathways of a pathogen's survival under the pressure of heat or radiation, which can yield more effective treatment to guarantee the food is safe and nutritionally unaltered.

The other high-level food safety development that can positively be positively influenced by the biochemical knowledge is antimicrobial treatment. Through the knowledge of the mechanism of resistance of foodborne pathogens to antimicrobial agents, scientists will be in a position to enhance the current methods of controlling food safety, including the use of preservatives, in a bid to address the specific mechanism of resistance used by pathogens. This has been demonstrated by the occurrence of instances where the efflux pumps are over-expressed concomitant with the resistance of this or that antimicrobial agent to a pathogen. It can be counteracted by restricting the efflux pumps to revitalize the action of the antimicrobial agent (Kim and Ahn, 2022). In the same way, they can study the process of biofilm formation by pathogens such as Campylobacter in order to come up with a novel approach to break down the production of biofilms in order to increase the effectiveness of antimicrobial agents (Ammar et al., 2021). One can also enhance the food safety measures by knowing the biochemical mechanism that makes certain food substances resistant to pathogens, which will help in keeping the pathogens under control, even in the most demanding conditions.

Besides, the effects of climate change on natural food pathogens, especially concerning the acclimatization of the pathogen to the environmental conditions, also demonstrate the role of biochemical research in the sphere of food safety (Singh et al., 2023). All the behavior and virulence of pathogens may be impacted through the alterations of the food production system, increased temperatures, and changes in precipitation patterns. The importance of the adaptation of pathogens to the changing environmental circumstances by the transformation of their metabolic pathway cannot be underestimated in the prediction and prevention of the impact of ECs on food safety. The knowledge of biochemical processes of food pathogens has been extensively applied to food safety regulations, detection principles, and food control. The existing food safety strategies can be improved and be more specific to address the issues of metabolic adaptations, the expression of virulence factors, and biofilm formation, which will result in the creation of more sustainable solutions to the problem of foodborne pathogens. Since food safety is now being transformed in relation to the emerging new challenges, the application of biochemical research to food safety processes will be extremely beneficial in protecting the health of the community and ensuring food safety. Improving antimicrobial resistance, conducting more research, and applying biochemical knowledge to food may also contribute to the danger of food-borne diseases in the food industry.

VI. Advances in the Biochemical Understanding of Foodborne Pathogens

The innovations in the biochemical research of the foodborne pathogens have had a great influence on the development of better methods of their detection, identification of new virulence factors, and the development of efficient methods of control of the food-borne diseases. The innovations that involve the existing technologies and the augmentation of learning on the behavior of the said pathogens are crucial in augmenting food safety interventions and advances in the detection and prevention of risks of these pathogens.

The new studies and discoveries have resulted in the development of substantial information on the virulence of food pathogens. The biochemical pathways that are specific to the survival and virulence of pathogens have received special attention. Investigation of genomes of pathogens that cause foodborne diseases has reported novel information about molecular pathways that mediate the interaction of pathogens with their hosts. Mather et al. (2024) maintain that the development of genomic sequencing has also shown that the organisms of the pathogenic group of Salmonella and Escherichia coli can evade the immune system and can also endure adverse conditions, along with infecting the host. These virulence factors are usually tightly controlled by the intricate biochemical networks, two-component systems, and quorum sensing, in which the pathogens can sense and react to the host environmental changes.

Besides the new virulence that has been unveiled, metabolomics and proteomics have come up with more information regarding the metabolic processes that the pathogen undergoes during the invasion process. Metabolomics has assisted scientists in determining the metabolic profile of the pathogen and finding out the major metabolic processes that the pathogen needs to survive and be virulent. By use of these kinds of technologies, it is possible to detect some of the generated metabolites and proteins by the pathogens to acquire useful information about how they behave in the host and their interactions with the host cells (Wang et al., 2023). Proteomic studies have also provided insight into proteins of pathogenesis, which harbor proteins of adhesion, invasion, and immune escape. Its discoveries are critical towards the establishment of some treatment and intervention strategies that can interfere with these biochemical activities and restrain the impact on the population of Foodborne diseases.

The biochemical pathways are not only implicated in the knowledge of the known foodborne pathogens, but also in the new virulence factors and new pathogens. Along with the changing environment of the foodborne pathogens, the new threats are presented along with the ones that may have abnormal biochemical properties that will allow them to survive under various conditions or treatment. New pathogens, including multidrug-resistant Campylobacter and Vibrio cholerae, are reported to be usually accompanied by emerging resistance mechanisms and virulence factors that render them highly challenging to manage (Mather et al., 2024). These new virulence factors are often associated with adaptive biochemical pathways through which the pathogens can develop in line with the changes in the environment (change in temperature/ pH or in the presence of antimicrobial agents). One should have a sense of the biochemical premise behind these adaptations to predict and prevent the effects of emerging pathogens on food safety.

The capability of the foodborne pathogens to adapt to the environmental dynamics is one of the largest problems in the fight against foodborne pathogens. The pathogens must keep adapting their biochemical activities to suit the changing environments, such as the acidic environment of the stomach and the nutrient-restricted environment of the food matrices. The contemporary study was dedicated to the efforts of determining the metabolic control of pathogens, such as Salmonella and Listeria, when subjected to environmental pressure. Using Listeria as an example, it can employ its metabolic pathways to survive in low-nutrient environments, but Salmonella is capable of adjusting its energy pathways to the availability of oxygen in the host (Taiwo et al., 2024). The mechanism of development of such adaptive mechanisms is normally controlled by the regulatory networks that perceive environmental signals and trigger the expression of the genes. It is the awareness of these networks that can guide the researchers to come up with mechanisms of interfering with the pathogen adaptation and reducing the chance of infection.

The use of technological innovations has also been very crucial in the identification of food-borne pathogens, in that these advances have resulted in faster and more reliable means of identification of pathogens and their virulence. Traditional methods of detecting pathogens, such as culturing and biochemical analysis, may be time-consuming and may not be able to detect all pathogens, especially those found in complex food substances. Nonetheless, the situation has changed. Nowadays, the sphere of molecular tools has undergone certain advances and altered the manner in which the process of pathogen detection takes place entirely. According to Kabiraz et al. (2023), molecular techniques such as polymerase chain reaction (PCR), next-generation sequencing (NGS), and others have significantly enhanced the sensitivity of the detection of the pathogen and specificity. The genes associated with virulence factors are identifiable with the assistance of the mentioned tools, and it means that pathogenic strains of food and medical samples could be revealed within a limited period of time. With that, the electrochemical biosensors were also incorporated in order to identify the pathogens. It is a promising technology, and it will offer a choice that can be carried out in real-time at a reasonable price to track foodborne pathogens (Wang et al., 2023).

CRISPR-Cas systems, genomics sequencing, and mass spectrometry have also come in handy, as far as the pathogen study is concerned. To exemplify this, it could be applied to make amendments to the genome of the pathogen with the help of CRISPR technology in the most precise way, which allows researchers to determine the role of certain genes in resistance and virulence. The genomic sequencing is able to provide in-depth data regarding the genetic structure of the pathogens, and certain new virulence factors and resistance mechanisms may be determined. Rather, mass spectrometry is becoming increasingly popular to identify the expression of proteins and identify a biomarker of pathogenicity (Liu et al., 2022). These technologies have provided a monumental advancement in this area that provides an extensive range of biochemical pathways that govern the behavior of pathogens, and also give rise to pathways under which certain interventions may be formulated and advanced to provide food safety.

In conclusion, the bio-chemical evolutions of foodborne pathogens have been capable of providing the necessary information on the process by which these pathogens virulence, adaptation, and resistance mechanisms take place. Besides offering a better picture of an agent-caused disease, the resulting discoveries have been substituted with more efficient detection and treatment techniques. Through the assistance of technologies such as CRISPR, genomic sequencing, metabolomics, and proteomics, the scientists will continue to uncover the complexity of biochemical pathways that assist pathogenic organisms to survive and cause disease in humans. Such technological innovations will play a central role in improving food safety and the health of individuals since foodborne pathogens continue to evolve.

VII. Future Directions and Strategies to Improve Food Safety

Food safety in the future is viewed through the formulation and application of a general strategy that would incorporate the multi-disciplinary knowledge to deal with the multi-faceted issues presented by foodborne pathogens. Foodborne diseases are one of the most significant matters of interest on an international level, and a multi-disciplinary approach that involves food safety experts and microbiologists, biochemists, and governmental health employees is essential in gaining a clear understanding of the complexity of the pathogen virulence and in working out an effective management strategy. As Tan et al. (2025) note, it is possible to have a more holistic view of elements of biochemical, environmental, and regulatory impact on the behavior of the pathogen and spread of foodborne diseases. This learning integration in other fields, such as microbiology, biochemistry, food science, and epidemiology, can assist the researcher and policymakers to address the various agents of foodborne disease to develop more effective and targeted cures to maintain the population s health.

The two disciplines particularly need to work together in investigating the biochemical mechanisms that may be underlying pathogen virulence. Microbiologists are able to identify the pathogens and investigate their genetic structure, whereas biochemists can focus on the virulence and resistance biochemical processes. Food safety experts can then use this knowledge to formulate prevention measures that would then target some of the virulence factors or metabolic pathways. As an example, food safety can be directed to prevent the formation of biofilms on the food processing equipment by considering the contribution of biofilm formation by foodborne pathogens. Similarly, the knowledge of the specific metabolic processes will also be utilized to develop solutions, such as the antimicrobial agents that inhibit the development and survival of the pathogens. With such specialists working together, they will be in a position to ensure that the food safety practices are based on the latest scientific discoveries and that they can be utilized to manage the dynamic nature of food-borne pathogens.

It has measures and control measures that must be implemented to mitigate the risks of foodborne pathogens. Vaccination is one of the most promising measures that can be undertaken in order to control foodborne diseases. It is also possible to ensure immunity against specific pathogens with the help of vaccines and minimize the number of infections. As an example, Salmonella and E. coli vaccines have demonstrated good potential in preventing infections, especially in high-risk groups like food industry workers or in healthcare facilities. The paper by Chowdhury et al. (2023) points to the potential of bacteriophages as an alternative to antibiotics to control foodborne pathogens as a natural choice. Biological control agents could be bacteriophages, which are viruses infecting bacteria and causing their death, utilized in food production and processing to control bacteria causing diseases without affecting the useful bacterial species or foodstuffs. These biocontrol agents provide a solution to the problem of antibiotic resistance among foodborne pathogens in a friendly and sustainable manner.

Other measures besides vaccines and bacteriophages, including good sanitation measures, food handling techniques, and food preservatives, remain significant in the alleviation of the threat of foodborne diseases. Chowdhury et al. (2023) point out that the combined solution, comprising the use of both prevention methods, such as vaccination and bacteriophage treatment, and the classical ones, such as hygiene and temperature control, may be highly effective in reducing the number of foodborne disease cases.

The governmental policies are also to be updated according to the recent research discoveries concerning the virulence and resistance of the pathogen. The nature of the foodborne pathogens is also changing, and policymakers should also make sure that the regulations and food safety standards are founded on the existing scientific evidence. According to Tan et al. (2025), food safety regulations must be informed based on the emerging knowledge about the available research on resistance of pathogens to resistance, new virulence factors, and new types of pathogens in food. The implementation of modern detection technologies, including CRISPR and genomic sequencing, could be supported with the help of the policies, in an endeavor to make sure that the detection and control of foodborne pathogenic agents are better controlled. In addition, the formulation of policies to enhance sustainable agricultural practices and proper management of antibiotics in foodstuffs manufacturing is necessary to address the continuously rising problem of antimicrobial resistance.

Some of the gaps in the research that are to be closed to enhance our knowledge on foodborne pathogens and practice better food safety are as follows. Another potential direction of research in the future is the study of new biochemical processes by which foodborne pathogens adapt to survive under varying conditions. As an example, the discovery of the role of metabolic reprogramming in maintaining the survival of pathogens in stressful environments, including temperature or acidity variations, might result in the creation of new control measures. Another point made by Menon and Jain (2021) is that blockchain technology can enhance transparency and traceability in the agri-food supply chain. Using blockchain with food safety systems, the researchers and policymakers would be able to monitor and trace the foodborne pathogen movements throughout the supply chain, which would further improve the response to outbreaks. Furthermore, the research related to the influence of the environmental conditions, such as alteration of climate and contamination, on the virulence and resistance of foodborne bacteria is crucial. The presence of climate change can modify the threat to food safety, namely, in the areas where a relevant issue concerning food-borne diseases can already be noticed (Singh et al., 2023). These environmental factors will be required to be put in perspective when formulating food safety measures that are flexible to the changing requirements.

The food safety in the dynamic environment of the evolving food-borne pathogens would necessitate a multi-disciplinary sense which would include, but not be restricted to, the knowledge of microbiological, biochemical, food safety, as well as policy. Foodborne disease transmission can be controlled with the help of sanitary adaptations and implementation of preventative measures in the form of vaccines and bacteriophages, as well as other improved sanitation measures. This must be done through future studies of biochemical mechanisms of the pathogen resistance and virulence, and influence of environmental factors on the pathogen behavior. These loopholes may be taken advantage of to develop more effective approaches to food safety and protection of human health by filling in these loopholes and by introducing new technologies and approaches.

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