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REVIEW

The food industry supply chain in the light of COVID-19: the constraint and development of measures to ensure food safety and quality control

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Abstract

The international borders opening led to goods and people migration with a significant change of consumer behavior, this favored new food-borne diseases uprising and outbreaks worldwide. Recently, the resurgence of COVID-19 has highlighted the limitations of the world-health surveillance measures and caused unprecedented effects on the food supply chain and the food industry. Amid this recent crisis, aroused population and scientific concerns and the demand for food safety and quality control improvement trough-out the food supply chain. To solve this constraint, it is primordial to understand food supply chain contamination stem and develop new, more sensitive, specific effective, and efficient point-of-care detection methods to segregate food items at an early pathogen contamination stage. 3D printing technology positioned itself as the solution because it enables the synergistic action of new molecular detection methods combined with the new 3D printing techniques for the production of high end-point biosensors capable of direct testing of food along the production line and the food supply chain. Because 3D printed biosensors are user and eco-friendly, convenient, fast, and take away the laboratory analysis constraints, 3D printed molecular biosensor devices are the new trend to enhance the food safety screening performances and guarantee food quality. We aimed to present how impactful COVID-19 was in the food industry and food supply chain across the globe and the adaptive measures that have been put in place to ensure consumer were provided with safe food with the usage of biosensors and 3D printed technology.

1. Introduction

COVID-19, recognized as a global pandemic by the world health organization in January 2020 (Sohrabi *et al.*, 2020), primarily originated from the food market in Wuhan, China (Hui *et al.*, 2020). The virus responsible for the COVID-19 disease is a Coronavirus, which was first identified in the mid-1960S. According to the US Center for Diseases Control (US CDC), coronaviruses exist in various forms and cause mild to severe symptoms while the transmission route is primarily among species of the same type, zoonotic transmission could also be observed. Caused by the SARS-COV virus, the COVID-19 disease is a zoonotic type of virus leading to a severe acute respiratory syndrome that could lead to the death of the diseased patient (Pressman *et al.*, 2020). The world health organization estimated that the COVID-19 pandemic caused worldwide over 242.3 million confirmed cases and 4.9 million confirmed deaths (Ritchie *et al.*, 2020) and led to a significant life and society disruption worldwide and unnamed challenges to public health and economy.

The COVID-19 pandemic has a devastating impact on the population's social life, health, and wealth. To curve the spread of the diseases and reduce the death toll related to the pandemic, travel restrictions and the country lockdown have been established. These measures, while reducing the spread of the diseases, have had severe and unprecedented impacts on the people's livelihood, health and food systems. This disruption put thousands of millions of people at risk of falling into extreme poverty, enterprises facing an existential threat

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that could lead to a 3.32 billion global workforces at risk of losing their livelihood and an estimate of 822 million people undernourished by the end of the year (World Health Organization, 2020). Although data have shown that food nor food packaging are pathways for the spread of COVID-19 (Goldman, 2020), The US CDC reported 4913 confirmed cases and 20 corona deaths toll from 115 meat processing units in 19 states (Waltenburg *et al.*, 2020; Dyal *et al.*, 2020) which aroused population paranoia on food-related COVID-19 transmission. The combination of the above factors led to severe and visible stress on the food supply chain and food industry these contribute to attracting the attention of worldwide researchers and business experts (Rothan and Byrareddy, 2020; Amankwah-Amoah *et al.*, 2021). The travel restriction limits the product and labor mobility between countries and caused a scarcity of raw material to sustain the demand of the food industry production line.

One of the basic population needs is the ability to feed and nourish themselves. This needs have to be fulfilled even during the catastrophe and pandemic-like situations. The food industries rely at 83% on goods provided by agriculture, as such, is in perpetual dynamic. With COVID-19 and restrictions measures put in place, they faced problems like production losses, shortage of raw materials, scarcity of human resources as many cities were on lockdown, cancelation of orders due to unavailability of transportation means and strengthening of control procedures, spoilage of product in the production line with a high risk of foodborne related diseases because of the increase of the storage time and delay of deliveries to consumer (Donthu and Gustafsson, 2020; Sanchez-Ramirez *et al.*, 2020) in that regards researchers were required to innovate and find a new source of the raw material to supply their production chain, ameliorate the distribution and improve safety measures and food quality control. This opening to new product sources, in combination with the necessity of implementing the WHO measures to stop the spread of the disease, have forced the food industry to innovate in their food safety and HACCP measures to guaranty the safety of the food distributed to the population (Pressman *et al.*, 2020; World Health Organization, 2020).

One of those measures is the use of 3D printed technology to develop a point of care biosensor to guaranty food safety. Food safety is a primordial part of food science dealing with aspects of food such as food adulterations, food microbiology and biology, food physical and chemical properties quantification and qualification. Among those various food safety concerns, the crucial and essential ones are those presented by food -borne pathogenic bacteria and viruses. Food-borne infections affect an estimated 600 million people each year, including 163 million children, resulting in almost 420 000 fatalities (Havelaar *et al.*, 2015). Whereas the Corona virus alone causes more than 242.3 million confirmed cases and 4.9 million confirmed deaths globally (Ritchie *et al.*, 2020). Biosensors are miniaturized sensors used for in-situ detection of pathogens and contaminants. Their production involves a synergized action of a transducer responsible for signal amplification and conversion, and a bio-receptor involve in the detection of the biological, biochemical, and chemical signal derived from the tested target. Once produced, the biosensor signal could be equally identifiable either qualitatively or quantitatively. Primarily, biosensor production relied mostly on silicon-based materials (Nag *et al.*, 2016) and has been applied in fields such as biomedical, environmental, industrial, and robotics with numerous drawbacks as they were temperature-dependent, expensive to produce, low biocompatibility, weak signal with averagely high noise. The Biosensor commonly used production includes photolithography (Kwak *et al.*, 2014; Lee *et al.*, 2015), screen printing (Khan *et al.*, 2014; Azim *et al.*, 2019), laser cutting (Patko *et al.*, 2014; Schleier *et al.*, 2017), contact printing (Khan *et al.*, 2015; Truby *et al.*, 2018), and 3D printing (Baumgartner *et al.*, 2020; Agostino *et al.*, 2020). The latter was developed to solve the shortcomings observed in the rest of the reported biosensor production methods.

The 3D printing technology's simple fabrication principle enables the development of prototypes with high accuracy, replication, and resolution. The wide range of materials used for the production, implementation of complicated and complex design, allow the integration of a wide variety of color and materials with chemical and mechanical properties in one prototype thus simplifying the fabrication of sensors with multifunctional and mechanical attributes. 3D printing is cost-effective, robust, and durable with the capability to withstand tough usage conditions. The fabrication of a 3D printed biosensor prototype is a one-step activity, with little or no human intervention. This technic increases the possibility of prototypes customization while maintaining its high reusability without compromising their efficiency and sensitivity. Polymers like polydimethylsiloxane (PDMS), polyethylene terephthalate (PET), and polyimide (PI) (Dudala *et al.*, 2019; Lim *et al.*, 2019; Wang *et al.*, 2020), PolyLactic Acid (PLA) (Simoes and Dong, 2018; Lim *et al.*, 2019), PMMA (Carrell *et al*, 2019; Nguyen *et al.*, 2019). Associated with microfluidics and nanomaterials like quantum dots (Banerjee and Jaiswal, 2018; Vidic *et al.*, 2019), carbon nanotube (CNTs) (Yang *et al.*, 2017), graphene (Li *et al.*, 2019; Shahrokhian and Ranjbar, 2019), and gold nanoparticles

(Ghanei-Motlagh and Hosseinifar, 2020) and green-labeled nanomaterial are some common conductive materials that have been used to develop the electrode part of the sensing prototypes. The conjugation of these above-listed polymeric substrates and electrodes plays their role in deciding the resultant electrical, mechanical, and thermal characteristics of the prototypes. These biosensors are highly sensitive and specific, making the pathogen detection process swift thereby reducing the production costs involved. 3D printed biosensors are analytical devices able to quickly and directly detect pathogens and toxins from food substances. The detection process is therefore made possible by the inbuilt 3D printed physical or chemical transducers and biological detection materials. The output signal is then displayed, stored, and analyzed to generate useful diagnostic information. Experts are regularly coming up with various types of 3D printed biosensors to improve the speed and efficiency of the food pathogen detection process. The advancement in 3D printed biosensors presents researchers with ample study scopes on the potentiality for direct food pathogen detection.

Given the importance of COVID-19 diseases and their impact not only on the health status and death toll increase of the society, but also, the consequential disruption it causes on the food industry and food supply chain. The purpose of this essay is to illustrate the limits and major concerns COVID-19 imposes on the food sectors globally, in terms of food supply chain disruption, food insecurity, and food safety. A presentation and comparison of the HACCP innovation plans that were put in place to curb the spread of COVID-19 and its threat to the food sector worldwide is also included. Furthermore, the potential 3D printing trend as a multipurpose solution in a global food industry through the production of food safety biosensors is also the focus on this study.

2. COVID-19 and the food industry

2.1 Disruption of the food supply chain

The food supply chain encompasses all the activities involved in the transformation of production site raw material (farm and husbandry) into ready-to-eat food products that could be directly used by the consumers. It takes into account the sources of the raw material; the means used to supply the processing units, the processing and transformation steps as well as the handling, distribution, and sale to the consumers (Bendekovic *et al.*, 2015). The food supply chain can therefore be considered into stages such as raw material production (agricultural and husbandry supply of vegetable, cereal, meat, and others) post-harvest handling, and transportation (storage in or out the production site and transportation into the processing warehouse) processing and distribution (from the food industry to the wholesale or retailer) and consumption as presented in Figure 1.

Throughout the food supply chain, food product delivered to the consumers can be contaminated with pathogens as presented on Figure 2. Depending on countries regulatory measures are put in place at different level of the food supply chain to ensure that quality and safe food are provided to the populations. Generally, two organs regulate the food supply chain safety depending on where the product is destined (Staniforth, 2020). Each food industry establishes its production safety control point based on the regulation dictated for the national market by the state government. They establish regulations, policies, and standards that have to be respected while at an international level, the associations such as WHO, international trade rule, and FAO, regulate the exchange and standards to be followed (Food and Agriculture Organization, 2020). Although it was never reported a single case of COVID-19 transmission through food, travel restrictions and border closure restricted the transportation of goods. Base on the reports, the flights' transportation of goods reduced to

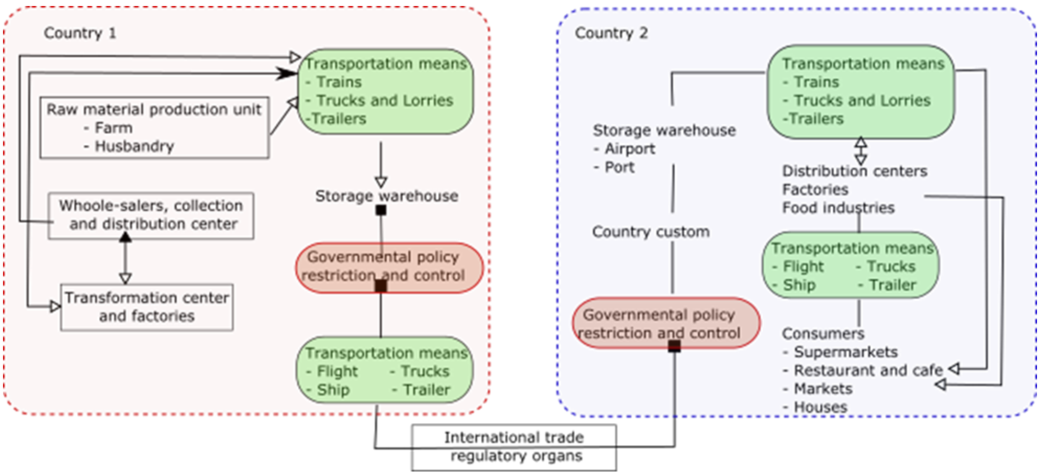

Figure 1. Diagram of a national and international supply chain in the food-related industry

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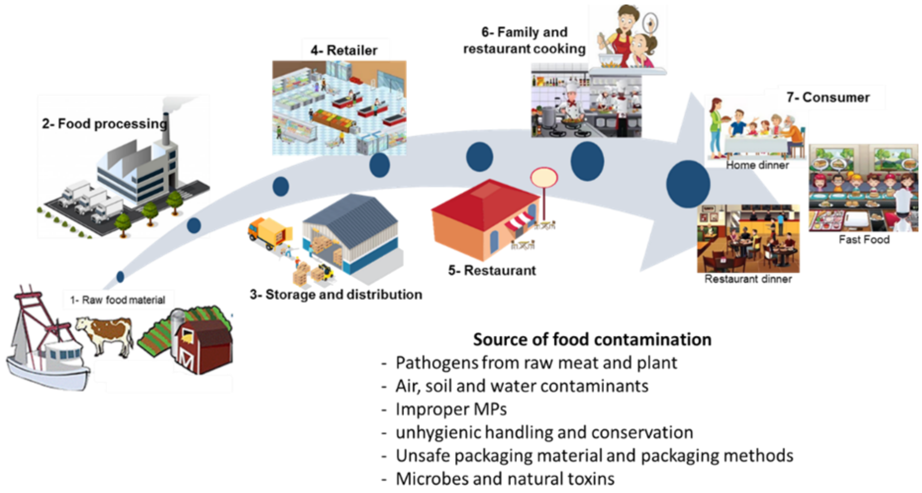

Figure 2. Food supply chain and source of contamination, tackle by end of point 3D printed biosensor

80% worldwide in the first year of COVID, while distribution with trucks reduced 60% (Bakalis *et al.*, 2020). Most of the production units have shown incapacity to supply the transformation unit with raw material because of the lockdown and the incapacity for seasonal workers to reach the farm, and some workers were ill and incapacitated (Nature Plants, 2020). This workforce scarcity combined with the fear for the disease results in a significant disruption in husbandry, horticulture, planting, harvesting, and all the labor-intensive which play to increase the severity of the need already observed in the sector before the COVID-19 (Richards and Rickard, 2020; Stephens *et al.*, 2020).

These conditions facilitate the disruption of the supply chain and cause a shortage of some goods, particularly for those companies relying on an international supplier of raw material (Balwinder-Singh *et al.*, 2020). In such conditions, and with the increasing demand for a food product, some governments put in place a food protectionism act, which restricted more the exchange of goods between countries (Espitia *et al.*, 2020). It was observed worldwide a disruption of food industries particularly the animal production sector. This was observed in countries like China, the US, the UK, Germany, India, Iran and other developing countries (Attia *et al.*, 2022). From the delay in supplying, a butterfly effect whereby farmers were forced to destroy part of their production. Wang *et al.* (2020) reported that the dairy producer destroyed 14 million milk daily in the US while 5 million liters were destroyed in the US. The inability during COVID-19 to maintain constant the food industry supply chain put in jeopardy their ability to control the availability, affordability, quality, freshness, and safety of the product supplied to consumers (Stephens *et al.*, 2020). With the restriction put in place during the COVID-19, consumers eating habit change was observed. Because of the lockdown, and the fear of contamination, restaurant, and other fast food, as well as a supermarket, were abandoned by consumers, who preferred and were obliged to cook at home (Hassen *et al.*, 2021; Ogundijo *et al.*, 2021). In this context, a constant and heavy stress were put on food industry worldwide. For example in the meat industry firm, their inability to sustain their supply of raw material increases (Kayikci *et al.*, 2022), leaving some processing unit capacity to decrease to 25% for the pig processing, 462 meat packaging, and 257 food processing plant, while COVID-19 affected 93 farm facilities in the US. Therefore, it was also observed an obvious shift in the volume and kind of meat product available to consumers (Bina *et al.*, 2022). It was estimated that at least 54036 workers have been tested positive to COVID-19 when 232 of them died because of COVID-19. This impact was also visible in the Iran meat market whereby COVID-19 induced a supply and demand market conflict resulting in a severe decreased of meat market performances particularly in the beef market environment (Zamani *et al.*, 2022). In the British beef and sheep industries, livestock husbandry were least affected by COVID-19, to reduce these negative impact, the government develop a resilient approach where food processing unit workers were given the status of key workers which allowed them to freely move during lockdown while additional safety and cleanliness measure were put in place in livestock farm and processing unit (Payne-Gifford *et al.*, 2022). In Brazil 2400 meat plant workers from 24 slaughterhouses were tested position with COVID-19 while in the UK meat processing unit were closed after 246 workers have been tested positive to COVID-19 and 1553 positive cases were reported in meats processing plant (Dyal *et al.*, 2020; Ijaz *et al.*, 2021). In the fish processing sector, Ghana reported 534 staff member's positive with COVID-19, and more than 100 COVID-19 cases were reported in slaughterhouses in France (Overstreet, 2020). In developing countries, because of their dependency to exportation for husbandry supplies like feed, vaccines, and drugs, due to COVID-19 traveling restriction and countries border lockdown, the impact on food industry

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particularly the poultry and other crops industries were significant. It was observed a reduction of pig feed consumption of 34.7 million tones in China and Africa while the egg and chicken meat production sector assisted at a culling, smashing and dumping of their production (Attia *et al*., 2022; Rahimi *et al*., 2022; Yao *et al*., 2022)

2.2 Food insecurity and COVID-19

The ability of the country and community to maintain a constant food supply to the population during a crisis is a prerequisite for human wellbeing. This aim can only be maintained with the combined effort of food industries and the government. After the first COVID-19 case was detected and once it was officially declared as a worldwide pandemic, a series of international centralized measures have been put in place to stop the spread of the diseases. Among those measures, the closure of borders, lockdown of communities and cities, and closure of factories to reduce population gathering were widely applied (Sohrabi *et al*., 2020). This action led to the complete disruption of the food industry supply chain. It could be predicted, based on the previous historical pandemic, that a significantly low return of assets could be imputed to this new pandemic. With the border closure, a reduction of raw material supply has been observed. It was expected that measures to stop the spread of COVID-19 will disrupt manufacturing companies. The food industry unlike other manufacturing companies, deal with the delivery of goods and services (foods) required for human survival it was important to maintain open companies while improving the safety control standard in place to provide safe food to consumers, contributing therefore to the improvement of their ability to fight the disease (Bendekovic *et al.*, 2015).

With all those restrictions in place, food industries faced the loss of the billions of income worldwide while others were forced to shut down that led to the increase of food insecurity worldwide resulting from the negatives changes in food availability, accessibility, usability and stability (Louie *et al.*, 2022). In contrast to such procedures, the population's survival instinct caused frantic purchasing and storage of food in order to deal with a foreseeable disruption in food supply. The market price theory states that the price of a product on the market is dictated by elements such as scarcity of the product, the capacity of the firm to keep constant the supply chain of that products, and consumer demand of the specific good (Banton, 2020). Around the world, consumers highly preferred flour with staple products and were in stock shortage in the food distribution points. Consumers were more interested in home cooking and baking than in restaurants and fast food. This led to the increase in the price of goods, as indicated in Figure 3, the price of primary products inflated during the pandemic (Balleer *et al.*, 2020; Rio-Chanona *et al.*, 2020). However, because of the unavailability of raw material to supply the production line and the increase of the demand for a certain type of goods, the market faced a shortage in supply which increase the scarcity of the product and played an adverse role on the price inflation. The medium and lower-income population class were left not able to satisfy their primary food intake. This incapability was caused by certain nations' market protectionist rules, along with the government's failure to subvention and preserve farm output since they were primarily focused on health and social aid programs to stabilize and stop the spread of the epidemic (Brown, 2021; International Labour Organization, 2021). This tends to abandon the food industry to their faith, with the direct harmful impact on new and emerging private sector medium companies (Global Alliance for Improved Nutrition, 2020). According to the UN, before the COVID-19 onset, the world was facing an insecurity increase from 23.3% to 26.4% from 2014 to 2018, which represents more than 10% of the population, on averagely 821 million people. The COVID-19 harmed the ability of an additional 260 million people to fend for

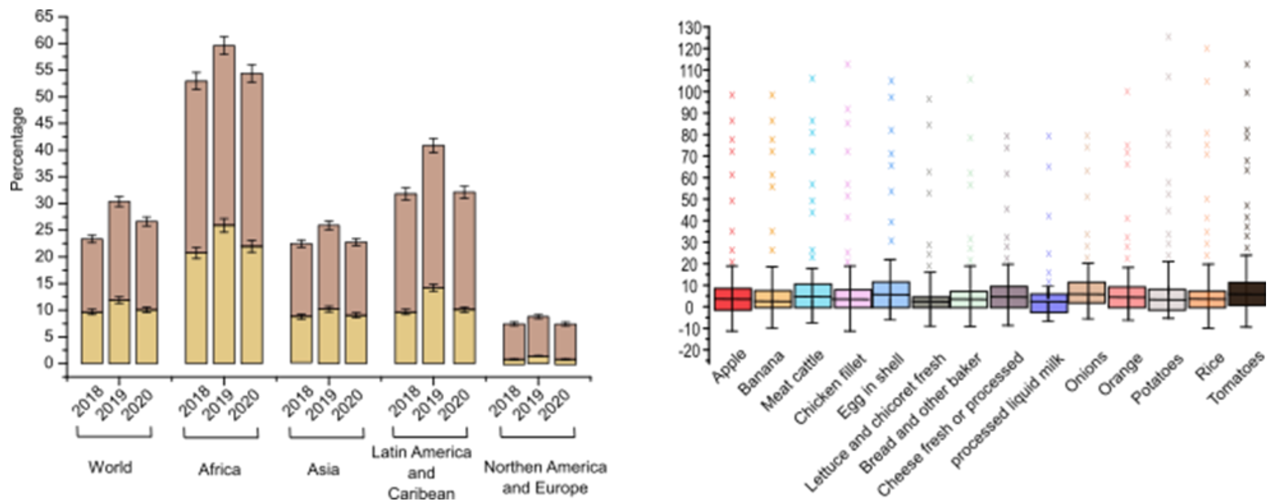

Figure 3. FAO data compilation of 14 goods daily food price change across the world between February 2020-October 2021

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themselves (Avery, 2021), as illustrates in Figure 3. In Australia, it was observed that the food insecurity prevalence was 21% among consumer and were significantly severe for those aged bellow 30 and living with disabilities while they reported that COVID-19 led to an increase in the food price which negatively impacted the quantity and types of food they could afford purchasing during the pandemic (Godrich *et al*., 2022). Identic observation were made in UK during the pandemic where most of their population bellow 30 years had a higher odds of not having access to nutritious and healthy food and being hungry and not eating. It was observed that 30% of the single parent and the population below 30 years old experienced a severe state of hunger due to their inability to access nutritious and healthy food during COVID-19 (Brown *et al*., 2022). In the US it was reported that low income worker was the one most susceptible to lose their job during the pandemic which result in the loss of their income and their inability to fend for themselves. In general the inability for population to work and produce income during pandemic due of social distancing, city lockdown play a significant role on one ability to sustain his food quality and quantity balanced, to reduce this food insecurity impact, the US government elaborate multiple social Aid plan such as the Families First Coronavirus Act which enable an increase of the Supplemental Nutrition Assistance to vulnerable population (Fang *et al*., 2022). It was observed that COVID-19 impact on food security in developing countries was mainly due to the changes in the food value chain and the inability for the government to put in place social aid program to help vulnerable population to address production loss generated during COVID-19 and the restriction measure that were put in place (Wegerif, 2022; Zhang *et al*., 2022). The food insecurity during COVID-19 pandemic was particularly severe in low income households and female head families (Dasgupta and Robinson, 2022).

2.3 Food safety and HACCP plan

As a consequence of the COVID-19, travel restrictions on goods and humans have forced the food industries to face scarcity of supply in raw material and the need to change their usual supplier to maintain constant the supply of goods to the population. Alongside from travel restrictions and border closures, new gathering and social distancing methods implemented to reduce disease transmission have prompted the food industry to reconsider and develop a new plan for workers to ensure continuity in the delivery of goods. COVID-19 highlighted in some country the absence or non-implementation of safety measure recommended by WHO in food industries. It was observed worldwide that one out of five food industries implemented the safety systems following the Global Food Safety Initiative sets of standards while only 2% of food industry introduced HACCP measures only as a result of COVID-19 burden (Wang, 2022). The HACCP strategy for food manufacturing companies should ensures that contamination risks connected with these modifications are addressed. It is therefore primordial to include the plan identification of additional critical control points and conduct a risk assessment of the production line to ensure that potential risk associated with the change of the production routine linked to the introduction of new raw material for processed goods production has been sorted out and sealed. Additional checking points for the workers need to be installed to enable continuous and timely screening of the workers to detect and isolate potential causes of disease and avoid spreading and the start of a new outbreak (Dyal *et al*., 2020). To maintain and reinforce social distancing measures, a new setting of the work environment is required and a clear set of production shifts should be established to be able to maintain the production line level. It is, however, important to notice that hand sanitizing and frequent hand washing protocols have been required for workers in a food industry environment, not conducive for it. To maintain those sanitation measures, an engineered workplace should be considered. Automatic water-tape, door, and hand sanitizer distribution was one way used in food processing facilities to limit the contamination. It was also observed that awareness of hygiene measure and the improvement of personal hygiene among workers reduced the risk of viral transmission in the food production plant (Jung *et al*., 2022). The fan must be placed in an area susceptible to reduce cross-contamination of workers. Non-coercive measures should be present to workers to encourage them to stay at home when ill or when having disease-related symptoms (Waltenburg *et al*., 2020; World Health Organization, 2020). In addition to the general improvement of food industry hazard control point measures, it is important to elaborate detection biosensors that could operate independently of the technical skills level necessary to detect pathogen along the food production line. In the recent years, several methods have been used to screen food items although they were limited to a well-furnished laboratory. Innovation made with 3D printed technology have open doors to multiple application in the field of food science for food safety purpose.

3. Application of and future trend of 3D Printed technology in the food industry safety

3.1 The 3D printed technology in food science

Several reasons contribute to the skepticism of the population towards food processing units as COVID-19 hotbeds for outbreaks. The inability to maintain social distancing, and the likeliness of saliva droplets contaminated with the COVID-19 virus to be spread on products while talking. Combined with the fact that workers have low income and rely solely on their working hrs to fend for themselves and family, the non-coercive measures are more unlikely to be followed. The food processing unit environment is favorable for microbe proliferation because the high humidity degree is an additional factor to facilitate the spread of the COVID-19. It was reported that the COVID-19 virus could survive in a cold and dark environment, which further increases the contamination and transmission rate inside the food industries (Pressman *et al*., 2020). Evaluation of the survival rate of the COVID-19 virus under several temperatures (4, 22, 37, 56, and 70°C) and different surfaces (paper, tissue paper, wood, and clothes) show that the COVID-19 virus is highly stable at 4°C but is only stable on smooth surfaces while being susceptible to standard disinfectants. It was also reported that when present in aerosol, they can remain stable and survive for 3 hrs. They could also survive for 4, 24, 48, and 72 hrs respectively on copper, cardboard, stainless steel, and plastic. It is therefore predicted that above 70° C, and with minimum sanitary measures such as cooking of the food, separation of cooked and uncooked product, hand washing with food graded sanitizer should be enough to ensure the safety of the food supply to the consumer (Bakalis *et al*., 2020; Pressman *et al*., 2020).

In food science and food-related industry, biological process evaluation faces 4 major challenges. The first one is the sterility or the ability of sensors to avoid the unwanted biochemical process. Secondly is the stability due to signal deterioration with successive use, variation of temperature, and time. Followed by its predictability as there is an alteration of the biosensor with time. Finally, the general cost of the process is important as they need an elevated concentration of substrate to product with a high concentration of waste produce.

In the food industry HACCP plan, a critical point whereby testing the food that enter the production unit and passing through the production line is required. pertaining the restriction and lockdown measures in play during the COVID-19 pandemic, important is for researchers in the food science field to develop Point of a care detection method that will enable on-site rapid detection of a food product. 3D printing technology could position itself as an adequate solution to those issues. Since the 3D printing concept development in the 1970s, it has been applied in various production companies and fields such as aeronautics, mechanics, physics, medicine, and robotics. The past years after COVID-19 onset, the worldwide concern related to food safety, induced a significant effect on individual's life and wellbeing. Food safety and quality control that has to be enhanced through food-borne contaminants screening at an early stage. While food-borne pathogen contamination derived from poor food product handling could lead to outbreaks or serious health issues if not detected on time, as it was the case of COVID-19 viruses. Although bacteria are the major cause of food safety issues with COVID-19 outbreaks, food-borne viruses outbreaks gain attention. Several researchers reported worldwide food virus outbreak cause many diseases, with the major one being the COVID-19 one (Donthu and Gustafsoon, 2020; Amankwah-Amoah *et al.*, 2021). Given these above-mentioned circumstances, a food safety imperative towards the development of advanced food screening methods that could easily and repeatedly be applied in food factories and other food screening is necessary. Therefore, food researchers are working actively in biosensors production helped with 3D printing technology to simplify and ease the detection of pathogens and enable their implementation in the detection of new pathogens while providing their results in real-time.

The 3D printing process, as represented by Xu *et al.* (2017), starts with the conceptual drawing of the prototype biosensors in a digital model. This can be achieved with the help of a computer aid design software (CAD), a 3D scanner (CT), and by photogrammetry which is a process whereby a series of pictures or images of an object is obtained in slice photo-scanning at different positions and reconstitute virtually. This model is then converted in 2D and 3D design, which will then be converted to an STL file readable by all the 3D printers. Those STL files contain all the data about the biosensor prototype to be printed in the form of a triangular coordinate that will be used while printing the 3D prototype layer by layer depending on the 3D printing techniques to be applied. Before 3D printed biosensors could be practically applicable for effective food safety protocol, important challenges remain to be addressed. Therefore, constant effort must be devoted to the achievement of multiplexing testing, sensors sensitivity enhancement, and quantification improvement. As such, some technics for signal enhancement as silver nanoparticles and dual-labeling aptamers have been integrated with paper-based and microchip sensors to improve their qualitative signal. At the same time, when coupled with a smartphone, a more quantitative and multiplexing detection could be performed for foodborne and chemicals detection without pretreatment procedures. Biosensors represent devices that are capable of converting contaminants bio-activities to a signal that is identifiable and converted by a bio-receptor, then depending on the biosensor type, is amplified by a transducer and represent in a quantifiable and distinguished output signal with waveform features susceptible to be enhanced for high throughout food safety screening purpose (Habimana *et al.*, 2018; Sajed *et al.*, 2019; Simoska and Stevenson, 2019).

3.2 Trends of 3D printing technology for food safety

Several milestones have paved the way for 3D printing development and application in food science. One of the major ones is its recent insertion, as an advanced POC endpoint devices production technique that promoted the development of a biosensor for food screening against the pathogen, pathogen toxin, and flood hazards. Researcher were able to combine those abilities for the production of biosensors for the rapid and effective screening of food and food product in food industries (Zhang *et al*., 2022).

As presented on Figure 4, the synergetic positive effects of the artificial learning system, smartphone, and gold nanoparticles properties have been successfully integrated to develop a 3D printed optical sensor (Cao *et al*., 2022). For the colorimetric screening of Hg^{2+} with a detection limit of 1 nM–0.2 ppb (Sajed *et al.*, 2019). Nitrate is one of the major waterborne chemicals hazards to humans that have severe health effects even after short -term exposure; a colorimetric 3D printed sensor has been successfully produced. The detection of Nitrate was then made possible up to the limit of 1.2 mg/L (Baumgartner *et al.*, 2020). Besides organic and inorganic substances, 3D printed optical biosensors have been widely used for food screening against pathogen and pathogen toxins. Animated with the concern of reducing human intervention and multiple steps preparation involved while proceeding to food sample analysis, and particularly pathogen detection, Nguyen *et al.* (2019) produced portable centrifugal microfluidic and were able to integrate compartment with reaction buffer that enable all the detection step to be performed with a single device. These device systems were used for the detection of *Escherichia coli* O157:H7, *Vibrio parahaemolyticus* and *Salmonella enterica* serovar Typhimurium food poisoning bacteria. Using the 3D printing stereolithography technique, a complex micro bio-reactor for food biochemical analysis has been miniaturized and produced. This 3D printed Micro bio-reactor completely overcome the challenges listed previously. It integrated a microfluidic device and enabled the coupling with a screen-printed electrode for the electrochemical monitoring of glucose usage during the reaction with a sensitivity of 20 g/L for the online monitoring within 8 hrs evaluation (Panjan *et al.*, 2018). Li *et al.* (2016) used the stereo-lithography 3D printing technique to produce a good designed portable toxin detector. To detect the deadly Aflatoxin B1 in rice, their 3D printed USB-compatible electrochemical biosensor made use of the screen printed inter-digitate electrode coated with antibodies for direct detection of the toxin. Their device using cyclic voltammetry, depicts a high selectivity and sensitivity toward Aflatoxin B1, and was able, under optimized condition, to detect Aflatoxin B1 with a limit of 5ng/ml within less than 1h of the detection process. A biosensor for the detection of Cryptosporidium using 3D printed micro total analysis (3D µTAS) systems has been developed. This 3D µTAS DNA biosensor depicted towards Cryptosporidium 1.8 ng/mL limit of detection while a good positive linear range between 2.5 ng/mL to 0.1 µg/mL was observed with a sensitivity of 12.844 µA/(µg/mL) allowing 6 and 23 times enhancement of respectively the detection limit and the sensitivity compared to the commercially available screen-printed electrode. To perform an On-site recovery of food-borne bacteria DNA, Jeong *et al.* (2019) developed a smartphone-based centrifugal system

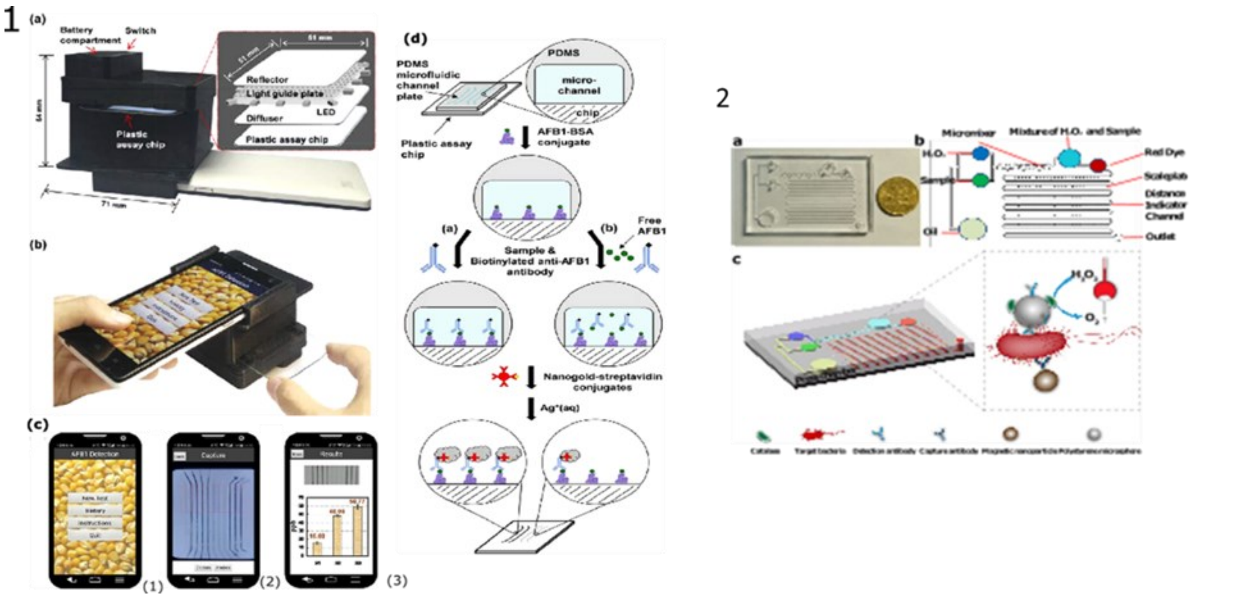

Figure 4. 3D printed smartphone-based biosensor for direct detection of 1) AflatoxinB1 and 2) bacteria in food sample

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performing extraction and purification of DNA. A low cost 3D printed electrochemical biosensor has been produced for rapid and sensitive detection of *E. coli*, it was able to detect as low as 53 CFU and quantify as low as 270 CFU of bacteria within 15 minutes using 500 µL of sample while maintaining the minimal cost per sample at USD 2.50 (Malhotra *et al*., 2022). Given by its performances, it could easily and effectively implement for the point of care pathogen testing in various fields. Using the same 3D printed technic, a label free paper based biosensor was developing for colorimetric protein targets detection in small volume sample. The biosensor show an improved detection limit with 60 µl sample compare to the one on 500 µl samples, additionally using this detection method the detection time was shortened from 90 mins to 20 mins (Guo *et al.*, 2022)

Even though considerable work has been done in the application of 3D printing for the production of the biosensor in food science, some factors protract from his complete integration. One of the primary limitations is the overall design of the sensor. However, 3D printing allows a variety and ease of the biosensor design, researchers need to work on the production of biosensors capable of integrating most if not all the sample pretreatment steps, to avoid or reduce human manipulation and error that could arise. A fully integrated design will ease the detection process and render the biosensor friendly and convenient for day-to-day use by the population and food industry. The second factor that needs to be considered is the printing material quality, variability, and availability. One of the world's biggest issues in the recent year has been the rising demand for eco-friendly and ecologically responsible items, so the biosensor is be able to fit in the on-site detection model. As a result, novel polymer powders, high-performance thermoplastic materials with heat and chemical resistance, and composite materials that combine lightweight, robustness, and other physical qualities are being developed. Another orientation is to develop a new immunoassay approach for biomarker detection. Although researchers, so far developed food sensing platforms for foodborne bacteria, toxins, and hazardous substances, foodborne virus detection still needs to be considered as they are responsible for numerous death. Viruses, with their incapability to replicate in host-free environments, devices for bacteria bio-sensing must extensively be changed because of the small sizes of viruses, to be able to detect virus particles. Additionally, because the intrinsic composition of viruses differs from those of other food-borne pathogens, in term of the presence or not of the cell wall, it is necessary to adapt and develop a special biosensor for food viruses' detection. Furthermore, depending on each country, standardized detection protocol required the use of a large volume sample which make it essential for 3D printed biosensor to be designed to be flexible enough to be adaptable in all settings while meeting up on-field applicability and user-friendliness (Zhang *et al*., 2022). Besides viruses being present in trace amounts in food and given the complexity of the food matrix, separation, purification, and concentration are essential in virus detection, therefore, they need to be integrated into the devices to be produced to reduce the sample pre-treatment step and human manipulation that frequently lead to a biased result and false positive. Another factor to look into is the improvement of the biosensor sensitivity, this problem can be dealt with by integration of nanomaterial (graphene, nanotubes, gold, and carbon), which can improve the sensitivity and lead to the creation of new functionalities when carbon and graphite nanoparticles have been mixed in appropriate quantity with the plastic polymers, they tend to transform the printed structure in an electrically conductive material which can therefore be used for electrochemical sensor or electrode production, it has also been proven that the scaffolding of Optic fiber in a D printed structure, can create an adequate milieu for its use as an optical detector which was not possible since the soft structure of optic fiber makes it susceptible to deformation when integrating into biosensor device and hence reduce its optical properties. Another aspect to look into it is the miniaturization abilities conferred by the 3D printing technics which could enable the integration of electronic devices which was not possible previously. Nowadays, it will be a great prospect to design and produce a wireless biosensor that could operate away from his signal recording station allowing there for the detection to be made at some distance and in a moving work configuration, it will in collaboration with geo-localization lead to the era of pathogen sensing technology. The integration of new technology, the internet of things, and machine learning in biosensor development need to be considered as 3D printing techniques help to miniaturize and integrate complex patterns and ease the sensor design and production process.

4. Conclusion

The food industry as a supplier of quality food for human nutritious needs is vital for the population's wellbeing at an equal level as the health sector. As such, they should be protected and researchers should constantly seek innovative solutions to avoid unpredictable catastrophes. One of the key points for the survival of the food industry is the maintenance of the food supply chain continuance. This should be guaranteed during the harsh time and particularly during the pandemic, as COVID-19 to prevent food crises and

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the legion of social and economic damages that could be aroused. The COVID-19 pandemic help to undercover the weaknesses of the current food supply chain and serve as an awakening signal to strengthen the loose end observe the food industry systems. Although no report has proven the direct food transmission of COVID-19, it is, however, important to notice that foodborne viruses that exist cause outbreaks when the food safety chain is not controlled. Research enabling the development of new point of care testing technologies for the food an effective and efficient screening along the supply chain is, therefore, a must. The food industry supply chain should be flexible enough to integrate testing points which right now are stuck in the laboratory, however, to solve these shortcomings, 3D printed technology and the 3D printed biosensor with their flexibility, ease of production and great adaptability and repeatability is to look upon as a sure means to quickly develop end of the point detection device, that could be cheap and eco-friendly.

Conflict of interest

The authors declare no conflict of interest.

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