Journal of Advances in Food Science & Technology

Volume 11, Issue 3, Page 17-26, 2024; Article no.JAFSAT.12145
ISSN: 2454-4213

Robotics Autonomous Systems (RAS) in Food Laboratories are the Future of Food Processing Industries: A Review

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

Article Information

DOI: https://doi.org/10.56557/jafsat/2024/v11i38725

Open Peer Review History:
This journal follows the Advanced Open Peer Review policy. Identity of the Reviewers, Editor(s) and additional Reviewers, peer review comments, different versions of the manuscript, comments of the editors, etc are available here: https://prh.ikprress.org/review-history/12145

Review Article

Received: 04/04/2024
Accepted: 06/06/2024
Published: 08/06/2024

ABSTRACT

Recent advancements in robotics have witnessed significant progress in both industrial and mobile robotics, paving the way for a new era of automation. However, a paradigm shift is underway in robotics research, focusing on enhancing the interaction between humans and robots, termed as service robotics. This emerging field aims to cater to a wide array of human social needs by bridging the gap between man and machine. Traditionally, laboratory automation has been constrained by the rigid control mechanisms of computer-driven robots. Despite their utility,

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Cite as: *A J, M., V, M., J, S., & R, M. (2024). Robotics Autonomous Systems (RAS) in Food Laboratories are the Future of Food Processing Industries: A Review. Journal of Advances in Food Science & Technology, 11(3), 17–26. https://doi.org/10.56557/jafsat/2024/v11i38725*

particularly in liquid handling tasks, many laboratory procedures remain only partially automated. Nonetheless, by breaking down laboratory processes into discrete unit operations and integrating them, overarching analysis schemes can be accomplished. The future of laboratory automation necessitates interdisciplinary skills, requiring scientists to blend biological knowledge with engineering expertise to fully exploit its potential. Simultaneously, a new wave of robotic innovations is permeating various sectors, from robot lawn mowers to autonomous vehicles, alongside smarter robots in manufacturing environments. This progression underscores the increasing reliance on automation, with future research endeavours expected to pivot towards leveraging laboratory automation to tackle novel scientific challenges. This abstract underscore the necessity for future scientists to acquire a comprehensive skill set that integrates both biological knowledge and engineering expertise. It highlights the trend towards greater automation in laboratory environments, representing the merging of scientific and engineering fields to tackle new research challenges.

Keywords: Robotics; automation; pipetting; sample handling; productivity.

1. INTRODUCTION

“Food crises lead to uneven access to nutritious food in the right amounts and quality, which is recognized as a worldwide risk in society” [1]. “Food demand will rise by 59% to 98% by 2050 due to increases in the world population and personal incomes in developing nations” [2]. “This necessitates concentrating on enhancing efficiency by implementing cutting-edge technologies such as robotics autonomous systems (RAS) in food laboratories” [3]. The concept of robotic automation systems, is not a new one; it has been utilized across various industries. For instance, in construction, RAS is employed to erect high-rise structures [4], while in the tourism sector, it aids in tasks like goods delivery and check-in. Additionally, RAS plays a crucial role in transportation, particularly with the use of self-driving trucks [5].

Promising Role of RAS in Enhancing Food Safety and Addressing Supply Chain Challenges [6].

1.1 History of Robotics

The origin of the term “robot” is placed in more recent times: namely, it comes from the Czech word “robota”, meaning “heavy work” or “forced labor”. The term "robotics" was introduced by the Czech writer Karel Capek (1890-1938) in 1920 in his novel. “Industrial applications of robotics have gained paramount importance in the last century. The beginning of “Industrial Robotics”, as we currently define it, can be dated back to the 1950s, although some kinds of automatization in the industrial environment have started to appear since the Industrial Revolution. The evolution of industrial robots can be subdivided into four categories, as in, with the first three covering the time span from the 1950s to the end of the 1990s. Fourth-generation robots (which range from 2000 to the present), are characterized by high-level “intelligent” features such as the capability of performing advanced computations, logical reasoning, deep learning, complex strategies and collaborative behavior” [7].

Basic components of a robotic system:

- ✓ **Power supply:** The power supply provides electrical energy to the robotic system, powering all its components. It could be a battery, mains electricity, or another power source depending on the application.
- ✓ **Actuators:** Actuators are devices that convert energy into mechanical motion. They are responsible for the movement of the robot, such as rotating a joint, extending an arm, or moving a gripper. Common types of actuators include electric motors, pneumatic cylinders, and hydraulic systems.
- ✓ **Electric motors (DC/AC):** Electric motors are a type of actuator that converts electrical energy into rotational mechanical energy. Direct Current (DC) motors are often used in robotics for their simplicity and controllability, while Alternating Current (AC) motors might be used for specific applications requiring higher power or speed.
- ✓ **Sensors:** Sensors are devices that detect and respond to changes in the robot's environment or internal state. They provide feedback to the controller, allowing the robot to perceive and interact with its surroundings. Examples of sensors used in robotics include proximity sensors, cameras, lidar, accelerometers, and gyroscopes.
- ✓ **Controller:** The controller is the brain of the robotic system. It processes information from

sensors, determines the appropriate actions based on programming or algorithms, and sends commands to the actuators to execute those actions. The controller's functionality can vary from simple microcontrollers for basic tasks to sophisticated computers running complex algorithms for advanced robotics applications.

1.2 Reasons for Automating Processes

It is necessary to decrease direct labor, improve quality, increase production, make it harder for workers to complete tasks manually, make it harder to consistently meet specifications, make processes more flexible, make work safer for employees, and remove a source of contamination.

2. ROLE OF ROBOTICS IN THE FOOD SAFETY

“Generally, food safety refers to the avoidance of illnesses resulting from the consumption of contaminated food. The issue of food safety has been increasingly discussed through product recalls; for example, the presence of Salmonella in chickens. Another well-known example of a food safety crisis was the discovery of horsemeat in some beef products, as well as the increased detection of porcine DNA in some processed “Halal” products in the United Kingdom” [8]. “The growing attention towards food safety might be due to increasingly stricter legislation and economic motivation” [9]. “Food safety failure or recall can be a devastating factor that often tarnishes a company’s reputation” [10]. “A wide range of standards and systems has been developed to help companies manage food safety issues. For example, the Hazard Analysis Critical Control Point (HACCP) system aims to analyze and control biological, chemical, and physical hazards across the entire food supply chain” [11]. “The core idea of HACCP is to offer a structured method to identify risks along the food supply chain and where possible either reduce those risks or eliminate them. The underlying feature of HACCP systems is the traceability of products along the food supply chain. The government has enforced legislation to encourage traceability during all stages of production, manufacturing, and distribution. However, the complex and interconnected nature of food supply chains limits their traceability in the food industry. In this context, food companies have used RAS to address traceability within their supply chains”. [12], high-lighted a recent success story in which Walmart used RFID technology to improve food safety on the dinner tables of Chinese consumers. In this application, information such as farm origin, storage temperatures, processing data, expiration dates, and transportation details from an ecosystem of suppliers to store shelves and end users may indicate potential food safety hazards.

Alternatively, [13] used “RFID and a wireless sensor network to measure the temperature and humidity of kimchi during its storage and shipping in South Korea. The proposed method assists in optimizing kimchi distribution, monitoring freshness, and improving consumer satisfaction”. “However, the full benefits of RFID can only be realized if all enterprises in the food chain use this technology” [14]. “The full application of RFID technology across the supply chain increases enterprise risks and expenses” [15]. Because of the intricacy of the food supply network and the fact that the majority of food enterprises are small and medium-sized, these requirements pose significant challenges to RFID adoption in the food supply chain.

2.1 Role of Robotics and Their Importance in Food Laboratories

Automation in food laboratories aims to reinforce aspects that are elemental to its sustenance are underachieving. Despite the laboratory being one of the largest, the greater dependence on human labor to execute repetitive functionalities has deflated its economy. The ratio of production to demand was very low. At times, this disrupts the demand-and-supply chain causing inflation in food grain prices and food shortages.

An effective solution to this crisis is the incorporation of robotics into food laboratories. Several food production companies in food production have taken decisive steps in this direction. Various levels of analysis can be made efficient using robotics in food laboratories. On the other hand, the integration of robotics development services can lead to the automation of processes that are performed manually, make production cost-effective, and minimize risks and errors.

2.2 Types of Some Robotics Used in Food Laboratories

2.2.1 Pickolo™ colony-picker

“Pickolo™ is a colony picker add-on for Tecan robots. The product enables advanced and fully automated microorganism colony picking from agar plates, both Petri dishes, and various multi-well plate formats, based on diverse criteria such as the size, shape and color of the colonies. The product was seamlessly installed on the robot for a few just a few minutes. The software is easily integrated into regular Tecan scripts such as Freedom EVO ware® software enabling colony picking downstream and upstream to other robotic tasks. The software generates automatic documentation of selected colonies" [16].

Features:

- Fast performance up to 800 colonies per hour
- Full automation with upstream and downstream applications
- Flexible selection criteria by color, size and more
- Easy to use and
- Simple to install

2.2.2 PetriPlater™ robotic spiral plating and streaking

"Automate dilution plating and spiral sample plating on Freedom EVO® 75 with SciRobotics' Petri Plater add-on. This provides state-of-the-art hardware and software to automate colony-picking experiments in an easy and cost-effective manner. The Robotic Manipulator Arm™ brings the source plate to the light table, and a high-resolution camera captures a photo. The Pickolo software then analyzes the image and selects colonies for selection according to your individual criteria. The template script provided makes it simple to set up the picking process while maintaining the freedom to define a variety of different colony selection criteria, microorganisms and agar types" [17].

2.2.3 FluHema™ hemagglutination analyzer

It can image an assay microplate, interpret the results and report them in multiple ways. The plates could be can be tilted for imaging at up to 65°. The results were are analyzed using advanced computer vision techniques to identify the positive and negative wells. The algorithm can be easily tailored by the user for a specific assay by providing typical examples. All results have been documented and can be easily reviewed by lab personnel.

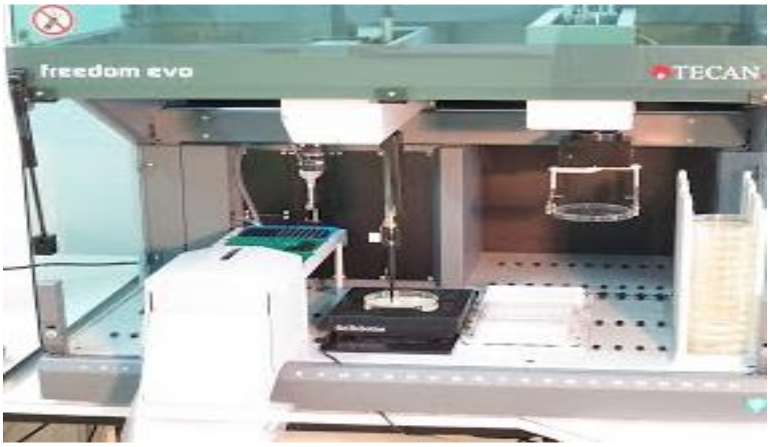

Fig. 1. Pickolo™ colony-picker

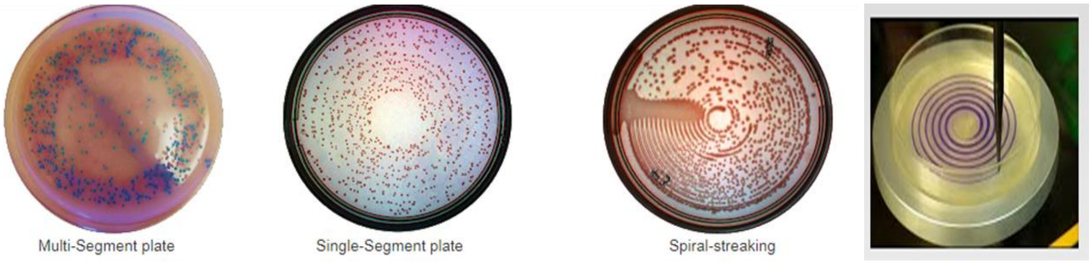

Fig. 2. Petri plater™ robotic spiral plating and streaking

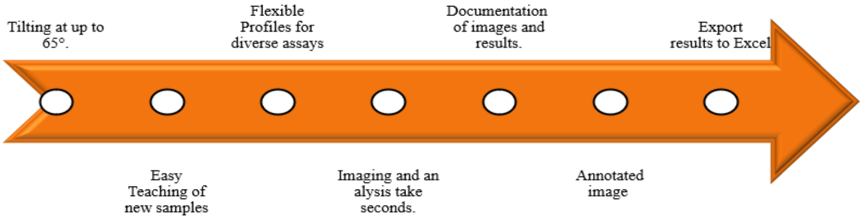

Fig. 3. Advantages

Table 1. Properties and performance of GFPickolo - GFP fluorescence colony picking

Properties	Performance
High-resolution industrial grade camera and lens (10MB)	Perform fluorescence imaging of colonies expressing GFP
Optical filter for the fluorescence imaging	Select the colonies based on sophisticated and flexible criteria combining properties from both back-light imaging and fluorescent imaging
Software controlled illumination	Screening and isolation of monoclonal mammalian cell lines such as Hybridomas, CHO cell lines microbial clones

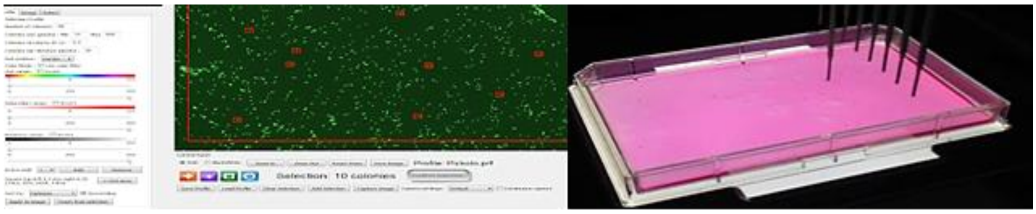

Fig. 4. GFPickolo - GFP fluorescence colony picking

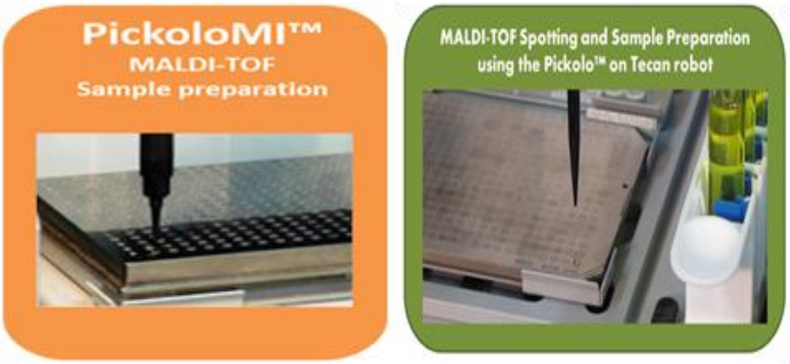

Fig. 5. PickoloMI™ - for MALDI-TOF microbial identification

2.2.4 GF pickolo - GFP fluorescence colony picking

These robots select the colonies with the strongest fluorescent signal or weakest fluorescent signal. They can use the average cumulative signal or even pick the colonies with the largest fluorescent signal to maximize protein secretion.

2.2.5 PickoloMI™ - for MALDI-TOF microbial identification

Advantages:

- ✓ Direct smearing: colony is smeared directly on MALDI target using disposable tip
- ✓ Smart algorithm: specifically designed for automatic colony selection for MALDI

- ✓ Sample tracking: Samples are automatically assigned to spots using a barcode reader
- ✓ Documentation: easy review of plate and colony images from previous runs
- ✓ Reports: Generate reports and sample file for Bruker's Biotype

2.2.6 PetriSel™: Petri-dish carousel add-on for tecan robots

This robotic arm takes the Petri plate directly from the carousel using special finger adapters to hold the petri dish on the robot. This automatic plate sensing enables easy operation and long walk-away time for Petri dishes driven tasks. This robot allows the carousel to work with no transfer station or shuttles and greatly speeds up the operation with an integrated storage solution for up to 180 Petri dishes, which includes 12 stackers containing up to 15 Petri dishes each.

2.2.7 PickoCell™ picking stem-cell colonies on tecan robots

"It is composed of a special dark field illumination table combined with a high-resolution camera and Pickolo versatile and flexible image analysis software. The solution provides both interactive and automatic colony selection based on diverse criteria for the desired colonies. By Using the robot tips, colonies covered with a thin layer of media were accurately and gently aspirated from the plate bottom and dispensed into a tube or collection plate while keeping the colonies viable and intact" [18].

2.2.8 Sensory robotics E-nose

"It consists of different polymer films, specially designed to conduct electricity. When a substance is absorbed into these films, the films expand slightly, which changes the amount of electricity that they conduct. Each electrode reacts with a particular substance by changing its electrical resistance in a characteristic manner" [19].

Each polymer changes its size, and therefore its resistance, by a different amount, making a pattern of the change. If a different compound had caused the air to change, the pattern of the polymer films' change would have been different.

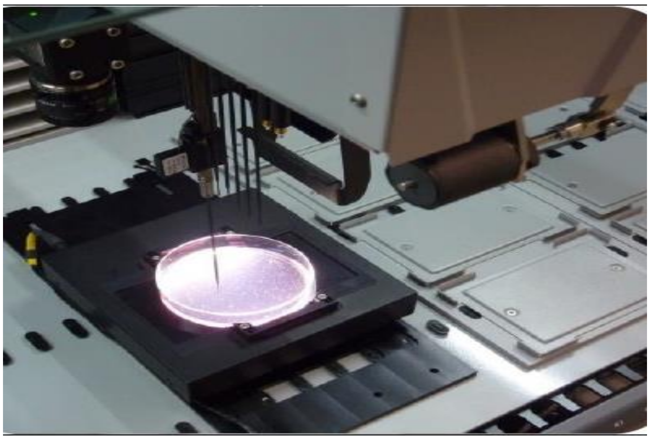

Fig. 6. PickoCell™ picking stem-cell colonies on tecan robots

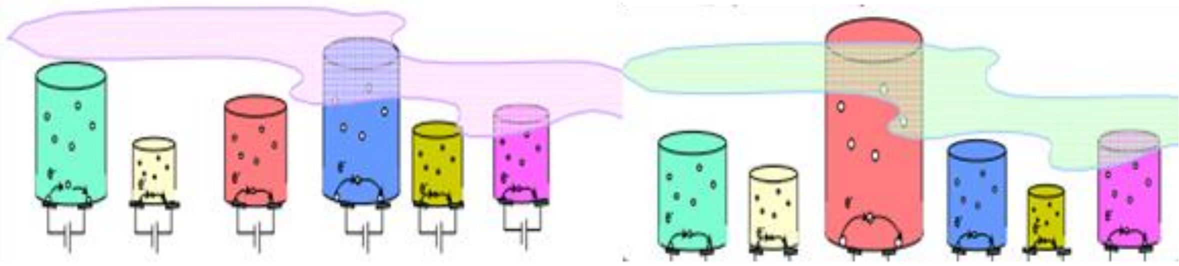

Fig. 7. Baseline resistance of the E-nose smelling properties

Table 2. Similarities between biological nose and E nose

Biological nose	E nose
Inhaling	Pump
Mucus	Filter
Olfactory epithelium	Sensors
Binding with proteins	Interaction
Enzymatic proteins	Reaction
Cell membrane depolarized	signal
Nerve impulses	Neural network

Source [20]

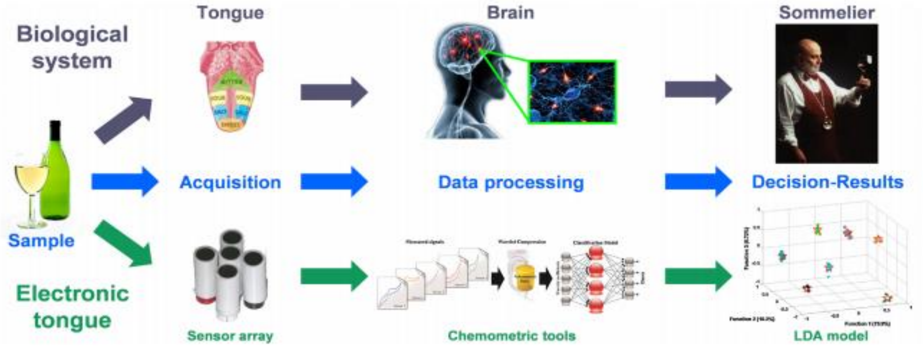

Fig. 8. How actually the E-tongue works

Table 3. Importance of E-tongue

Identify	E nose
Function	Identify chemical composition of liquids
Application	Wine industry
Principle	100s of microchip Sensors.
Colour change	Depends upon chemicals
Cost	20 USD
PROS	Effective qualitative results

Source [20]

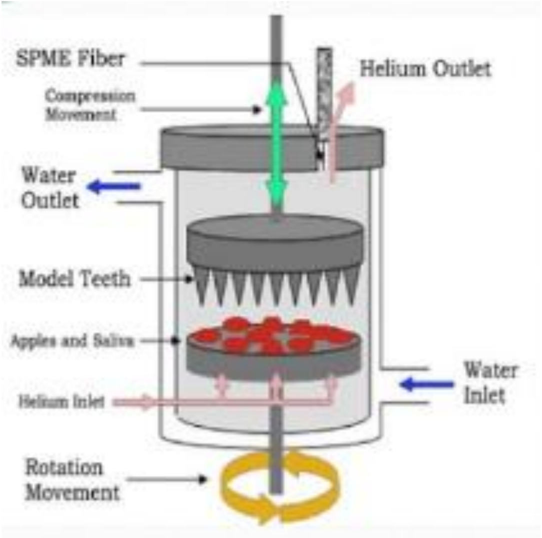

Fig. 9. Munch-o-matic- An artificial mouth

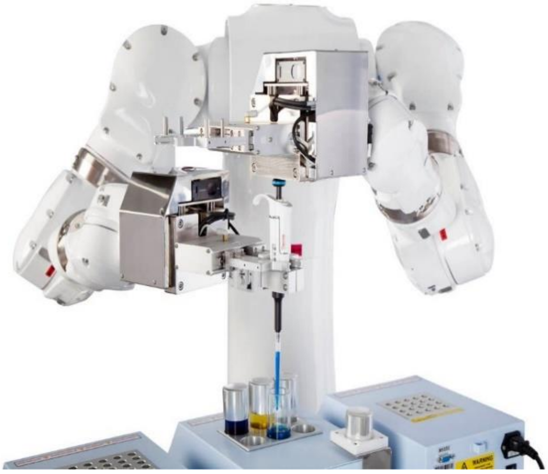

Fig. 10. Two-arm MOTOMAN CSDA10F robot

2.2.9 Sensory robotics E-tongue

An electronic tongue is a device made of sensors that respond to some taste (soluble) of foods through the transduction of a signal or a pattern of signals using a pattern-recognition software system. This is able to quantify bitterness or “spicy level” of drinks or dissolved compounds, quantify taste masking efficiency of formulations [20].

2.2.10 Munch-o-matic- An artificial mouth

“This reproduce the results of mastication by chewing the samples and the releasing saliva. The rate of food breakdown and the temperature all affect the flavor and smell of food before it is swallowed” [21].

2.2.11 Two-arm MOTOMAN CSDA10F robot

“Partial automation, in which the robot performs repetitive actions by the laboratory staff, thereby facilitating routines. This robot handles tasks, but process control remains with lab personnel or an automatic analysis system. The testing procedure was fully automated, including sample preparation, pipetting, test implementation and operation of all analytical equipment by the robot. This can independently carry out laboratory processes 24 h per day with the highest precision and repeatability” [22].

3. ROBOTICS AND WORKER SAFETY

Although the number of deaths caused by robots is very low, data have varied in the number of deaths or injuries caused by robots over the past few decades.

In 1942 Asimov created the Three Laws of Robotics, also known Asimov’s Laws, a set of principles robots should follow in the future towards human beings.

- A robot may not injure a human being or, through inaction, allow a human being to come to harm.
- A robot must obey the orders given it by human beings except where such orders would conflict with the First Law.
- A robot must protect its own existence as long as such protection does not conflict with the First or Second Laws.

“Through proper implementation of Robosts in manufacturing or production areas, musculoskeletal disorders, injuries associated with falls from higher places and other hazards that can cause harm to human beings can be decreased. Robots can also reduce overexertion and repetitive, monotonous tasks which are often associated with the food chain for example, bulk vegetable cutting. Robotics is ideal to work in harsh environments for example in freezers where temperatures reach -18℃ or below. Robots can also assist with heavy lifting, for example in a bakery lifting heavy bread tins, or arranging heavy food items in a dry store” [23].

4. CHALLENGES FACED BY THE IMPLEMENTATION OF ROBOTICS IN THE FOOD CHAIN

The implementation of robotics will initiate the unforeseen requirements of the policies and regulations related to the operation, usage and legalities of the business. However, the contemporary challenges in the implementation of robots in the food chain are as follows.

4.1 Policies and Regulations

Policies and regulations need to be in place to successfully guide collaboration between humans and robots. In many implementations, the policies and regulations that guide collaboration between humans and robotics are not in place once the implementation is completed. In the event in which it involved a robot, it create a new set of issues. “While OSHA (Occupational Safety and Health Administration USA) does not have regulations specific to robots in the workplace, employers would be wise to conduct job hazard analyses and evaluate any existing or potential robotic equipment installation, to abate any hazards posed by these machines.” Companies should have regulations in place for example regulations that protect their workforce from a human error involving robotics. A proper analysis should be performed for hazards that could arise from working next to a robot in certain areas. Robots and automation are complex, leaving the business owner with many questions associated with 'human' and moral values.

5. CONCLUSION

RAS is being rapidly developed and is thought to be a promising technology. The adoption of RAS in the food supply chain improves management and increases quality and efficiency. With rising labor cost and labor shortages due to uncertain political policies and disruption events, RAS might be one of the approaches to making food affordable. Although several areas of the food manufacturing sector will benefit from robotic devices; the robotic devices specifically designed for food production will help reduce the time and cost of production could make a great contribution to the food manufacturing sector.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of manuscripts.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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Peer-review history:
The peer review history for this paper can be accessed here:
https://prh.ikprress.org/review-history/12145