From Farm to Fork: Developing Holistic Food System by Using Engineering, Nutrition and Sustainable Agricultural Practices

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Abstract

The food system globally faces many challenges environmental changes, soil degradation, food insecurities due to food wastage and overpopulation, nutritional loss during processing, and nutritional deficiencies. Many engineers, technologies, nutritionists, and organizations are working to make innovative methods and policies that overcome these challenges. The purpose of this study is to develop a holistic system from farm to fork using integrated engineering, sustainable agriculture practices, smart packaging, and nutritional considerations. This system utilizes sensors, drones, smart farming, vertical farming, genetic engineering, climate-smart agriculture, bio-fertilizers to increase yield by efficiently using the resources. Novel thermal methods such as ohmic heating, microwave heating, and radio frequency heating are used as there are less nutritional loss, no fouling, and less energy is used. Proper packaging increases the shelf life of food products and saves the energy that is used on unpacked products during processing, handling, and transportation. Smart packaging includes sensors, QR codes, RFID, NFC, Time-Temperature Indicators, biodegradable materials, IOT technology, and block-chain technology help to monitor the whole food chain these techniques help to manage the food chain which improves the food system and increase customer trust in the product as they can easily get the information from origin to proper handling during transportation with just one tap. Acknowledge the food insecurities and promote the sense of taking proper nutritional value through different organization policies like WHO in 2024.

Keywords: Sustainable agriculture, Novel thermal methods, Smart packaging and distribution management

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Introduction

Globally 9.8 percent population faced food insecurity. 75 percent refugee population was affected by food assistance cuts in Ethiopia, Kenya, and Somalia regions in 2021. In recent years, many engineers, nutritionists, and scientists worked together to find solutions of these problems. The objective of this chapter is to explore innovative solutions for these problems with food engineering, nutritional considerations, and sustainable agriculture practices.

Multifaceted challenges in food production and consumption can only be overcome by developing a holistic food system. Food systems have revolutionized from simple agricultural and conventional food handling practices to complex networking that includes engineering, sustainable agriculture practices, processing using advanced methods, making nutritional values standards, and proper packaging methods. By developing such a system, we can overcome many issues which include food insecurity due to climate changes and overpopulation, malnutrition, inefficiencies in food processing and distribution management.

Methodology

1. Sustainable Agriculture Practices

Sustainable agriculture practices are very important to overcome the challenges of climate change, environmental degradation, food security, economic feasibility, and social equality. Sustainable agricultural practices significantly help protect the environment by reducing pollution, conserving the water and minimizing erosion of soil thus enhancing soil health, this also promotes biodiversity and reduces the carbon footprint of framing (Tilman et al., 2002). Other agricultural practices like agroforestry, cropping cover and adopting tillage practices will decrease the amount of carbon and help to reduce the emission of greenhouse gases (Lal, 2004). It makes the food system strong against other challenges and encourages local food production which helps in enhancing food security (Godfray et al., 2010).

Techniques used for sustainable agriculture practices:

- Sensors
- Drones

- Smart farming
- Vertical farming
- Genetic engineering
- Climate-smart agriculture
- Biofertilizers

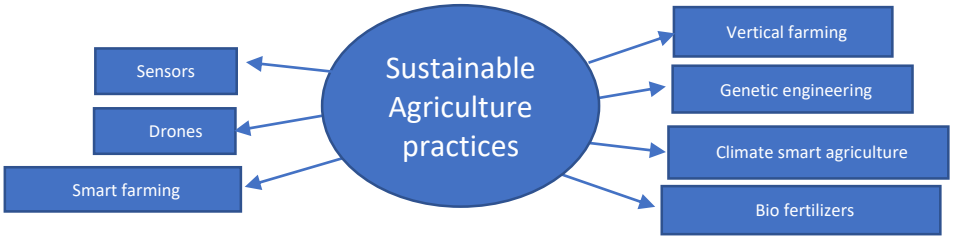

Fig. 1: Different techniques used for Sustainable agriculture practices

1.1. Sensors

Help in optimizing the field level management in crop farming. They reduce the input cost, minimize the environmental effects, and increase the yield in the end (Zhang et al., 2002). There are different types of sensors which include soil monitoring to pest control. Four main parameters are monitored for soil management which are moisture, temperature, pH, and nutrients. Weather sensors help in collect the data of temperature, humidity, wind speed, rainfall and direction of the wind. Sensors for Crop health monitoring collect the data of nutrients, detect the primary signs of stress, diseases, and other factors affecting the health of crop (Yadav et al., 2023) .

1.2. Drones

They are used for monitoring the crop heath and also used for applying fertilizers. This method reduces crop destruction, and proper distribution of fertilizers and gives real-time data to improve input accuracy and reduce labor cost. Different countries use drones for good agriculture practices. Their preference level changes due to cost, privacy concerns, and affordability (Nazarov et al., 2023). The following graph is the country-wise analysis of using drones. The graph is between different parameters like adoption, benefits, and challenges of different countries vs scores or levels.

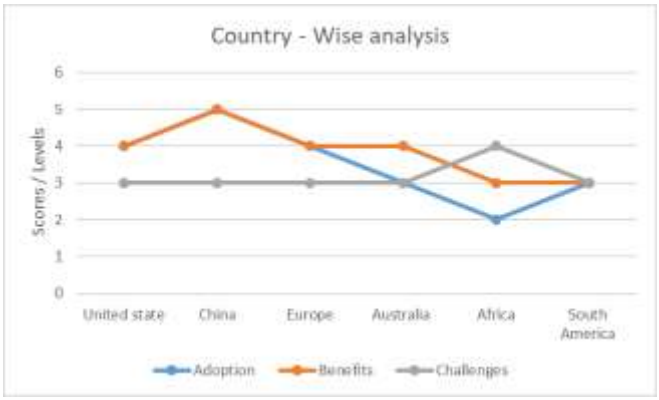

Fig. 2: Analysis of different countries using drones in agriculture

1.3. Smart Farming

Smart farming includes automation and artificial intelligence. Technologies used in smart farming are variable rate technology, sensors for proper water monitoring, pest monitoring and nutrient monitoring of crops, and rate controllers (Rasool et al., 2023). The adoption of smart framing increased as we moved from scientific research to commercial products. Farmers face difficulties due the environmental changes which can only be overcome using smart farming technologies (Balafoutis et al., 2020). Engineers develop innovative solutions for it, which result in a better food chain and enhanced efficiency from field to final products (Bacco et al., 2019). Adopting smart farming techniques increased the management efficiency and reduce the labor need. Different innovations used for precision agriculture include drones, block chain and autonomous tractors (Karunathilake et al., 2023).

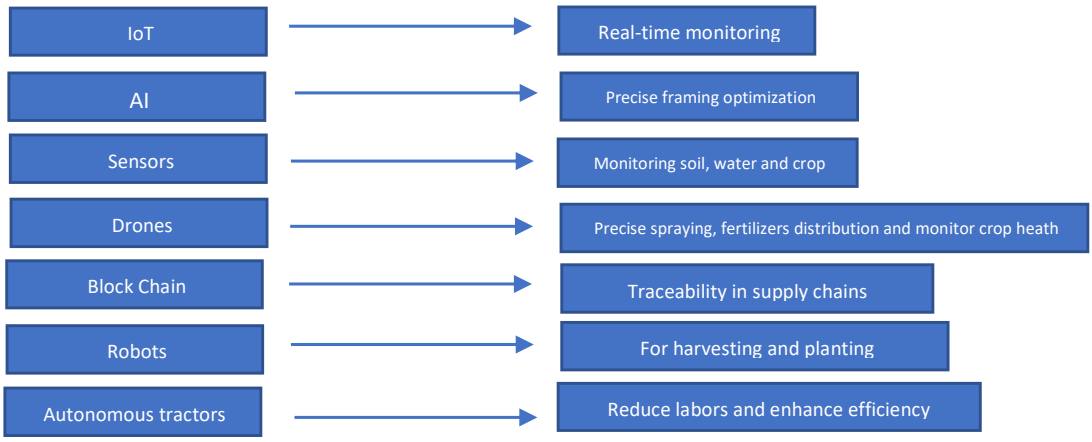

Fig. 3: Technologies used in smart framing for better yield production

1.4. Vertical Farming

Challenges like urbanization, climate change, and food security can be overcome using vertical framing as a sustainable practice in agriculture. There are different types of vertical farming:

- Hydroponic
- Aeroponics
- Aquaponics

1.4.1. Hydroponics

In this method, nutrients are used instead of soil with water. In this method less water is used and the resulting yield has more nutrients (Supraja, 2022). Hydroponic vertical farming uses 10% water (Shrouf & Alshrouf, 2017).

1.4.2. Aeroponics

In this method plant roots are suspended in air and nutrients are sprayed on them. This method uses less water than the hydroponic method. The aeroponics method uses water up to 2% and reduces the use of pesticides by 100% (Shrouf & Alshrouf, 2017).

1.4.3. Aquaponics

Combination of hydroponic and aquaculture. Fish waste provides organic nutrients to the plants whereas plants clean the water for fish.

- These types increase their efficiency using IoT and other AI technologies.

1.5. Genetic Engineering

CRISPR technology is used for precisely editing the plant genome making it more pest resistant and increasing the nutrients. This method helps to withstand the environmental stresses and provide sustainable agriculture (Jamil et al., 2023). Some nitrogen-fixing bacteria inside the cells of plants can provide the nitrogen that plants need. This is rarely found in plants. Scientists see this as an opportunity to improve the nitrogen by transferring this trait (Yang et al., 2018).

1.6. Climate-smart Agriculture

Climate-smart agriculture means developing systems that effectively respond to climate change. The objectives of using these systems are a sustainable increase in the agriculture production yield, reduced greenhouse gas emissions, and improved food security. Table 01 gives the information of food security rank of Pakistan, the percentage of undernourishment, and the policies (Chaudhury & Ayub, n.d.).

Table 1: Data from Climate Smart Agriculture in Pakistan

Food Security Rank	78th out of 113 countries in the Global Food Security Index
Food Insecurity	60% population is food insecure
Undernourishment	22 % population
Policies	Scaling up nutrition initiatives to improve food security

2. Innovative Technique in Processing

In processing there are many innovative techniques that are energy efficient and also less nutritional value loss. Novel thermal methods is one of these innovative techniques.

2.1. Novel Thermal Methods

Novel thermal methods include direct and indirect heating. These methods are used instead of conventional heating as it results in reduce fouling and efficient heating. Ohmic heating is direct heating in which electrical energy is directly converted into heat energy. Ohmic heating is mostly used when we need uniform heating. Microwave and radio frequency heating is indirect heating method in which electrical energy in converted into electromagnetic waves then in heat energy (Lajnaf, 2023).

2.1.1. Ohmic Heating

Conventional methods of heating causes fouling on the surface of heat exchangers, due to which heat cannot transfer efficiently and cause non- uniform heating in the milk and milk products. Fouling also causes a pressure drop in the heat exchanger which leads to an increase in cost. Therefore, ohmic heating is now adopted instead of conventional heating uniform heating, a less time-consuming process and less nutritional loss of milk and milk products.

Principal of Ohmic Heating

When electrical current passes through the milk product milk product act as electrical resistance due to which the temperature of milk product rises.

Fig. 4: Electrical current passed through the milk product

Ohmic Heating Effect in Different Types of Milk

Commonly thermal evaporation is used for the concentration of milk which results in loss of aroma, flavor, and color changes. The study

focuses on exploring the abilities and benefits of ohmic heating for milk concentration like rapid & uniform heating and produces high quality products (Asrar et al., 2023. The sample is placed in an ohmic heater and the sample from 4°C to the boiling of milk sample. The voltage gradient was kept constant at 13.33V/cm and the time for this whole procedure was 75 minutes. Voltage decreases from 200 V to 195V for cow milk and mixed milk but for buffalo milk, this voltage increases up to 202V.On the other hand, current was increased from 4.6 A to 16.8 A within 30 minutes during processing then decreased which may be due to the electrodes foul. Results show that conductance decrease as high amount of non-polar fat content in cow milk and buffalo milk were standardized to 3.5 and 6.0 percent of fat content. Almost all the compositional parameters were increased except the PH values of a sample which decreased with the time of heating. FFA (free fatty acid) increased due to the destruction of protein and phospholipids during heating. Physio-chemical properties like total solids, fat content, protein content, ash content, lactose content and titratable acid, and FFA increased while values of pH decreased over time of heating. The color of samples moves toward yellow, red, and yellowish red from white color during ohmic heating. Milk samples that were concentrated by ohmic heating will be less white as compared to conventional heating. An increase in total solids caused an increase in consistency coefficient (k). Where Flow behavior index (n) decreased with total solids increased. The score for sensory properties is from 9 scores. So, the flavor score is maximum in mixed milk sample, buffalo milk shows maximum body and appearance in conventional heating. The effect of microbial properties is very good as there was decrease in standard plate count and due to ohmic heating the Yeast & Mold and coliform bacteria were completely absent after ohmic heating (Parmar et al., 2018). Table 02, 03, 04, 05, and 06 shows change in different properties of different types of milk due to ohmic heating.

Table 2: Electrical properties of Milk during ohmic heating

Sample	Voltage (V) Initial	Voltage (V) Final	Current (A) till 30 minutes	Current (A) after 30 minutes	Power consumed (kWh)	Temperature (C°) at 75 minutes
Cow milk	200	195	4.6 - 16.8	<16.8	2.4	100
Buffalo milk	200	202	4.6 - 16.8	<16.8	2.5	100
Mixed milk	200	195	4.6 - 16.8	<16.8	2.5	100

Table 3: Physio-chemical properties of milk during ohmic heating

Sample	Total solids (%)	Protein contents (%)	Fat contents (%)	Ash contents (%)	Lactose contents (%)	Titratable acidity (% L.A)	PH	Colour
Cow milk	12.03±0.6 To 22.08±0.92	2.91±0.11 To 5.37±0.3	3.45±0.15 To 6.35±0.25	0.64±0.04 To 1.19±0.09	5.03±0.2 To 9.17±0.5	0.16 To 0.46	6.62 To 6.56	Yellowness
Buffalo milk	15.30±0.8 To 28.36±0.86	3.02±0.2 To 5.61±0.29	6.05±0.25 To 11.15±0.3	0.61±0.0 To 1.13±0.003	5.61±0.2 To 10.47±0.5	0.18 To 0.46	6.70 To 6.58	Redness
Mixed milk	13.52±0.5 To 24.37±1.23	3.04±0.2 To 5.48±0.38	4.80±0.20 To 8.55±0.25	0.62±0.03 To 1.15±0.05	5.06±0.26 To 9.19±0.39	0.17 To 0.47	6.60 To 6.55	Yellowish red

Table 4: Rheological properties of milk using ohmic heating

Models	Ostwald			Herschel–Bulkley			Bingham	
Sample	K (Pa.s)	n	(R)^2	K (Pa.s)	n	(R)^2	K (Pa.s)	(R)^2
Cow milk	0.189-0.477	0.449 - 0.28	0.98 - 0.852	0.265 - 0.721	0.524 -0.428	0.995 - 0.981	2.58 - 5.18	0.973 - 0.581
Buffalo milk	1.374-1.374	0.114 - 0.12	0.63 -0.971	0.351 - 0.972	0.487 - 0.143	0.988 - 0.998	4.00 -11.17	0.812 - 0.807
Mixed milk	0.105-0.782	0.525 - 0.27	0.99 - 0.954	0.480 - 0.941	0.565 - 0.244	0.992 - 0.973	3.10 - 6.52	0.964 - 0.998

Table 5: Sensory Properties of milk during ohmic heating and conventional heating

Sample	Flavor	Body and texture	Colour and appearance	Overall acceptability
CCM	> 7.11	>7.61	>7.51	>7.21
CM75	7.3	>7.41	7.5	>7.41
CBM	7.3	7.8	7.3	>7.51
BM75	7.8	>7.51	>7.81	>7.61
CMM	>7.510	>7.81	>7.61	>7.61
MM75	7.7	>8.01	>8.11	>8.11

Table 6: Microbial properties of milk during ohmic and conventional heating

Sample	SPC (log CFU/mL) initial	Y&M (log CFU/mL) initial	Coliform (log CFU/mL) initial	SPC (log CFU/mL) final	Y&M (log CFU/mL) final	Coliform (log CFU/mL) final
Cow milk	7.89	4.1	3.75	4.4	____	____
Buffalo milk	8.3	4.27	3.36	4.44	____	____
Mixed milk	8.27	4.25	3.39	4.46	____	____

Factors Affecting the Ohmic Heating are

- Electrical conductivity
- Particles orientation characters
- Field strength
- Product characters

2.1.2. Microwave Heating and Radio Frequency Heating

Microwave heating is used at the domestic level for quick heating. The frequency of microwaves is more than the radio frequency heating and has smaller wavelength. Due to high frequency and smaller wavelength microwave heating rapidly heat the milk product as compared to the conventional heating method in which there is improper and non – uniform heating. Radio frequency heating penetrate in the food product due to large wavelength (S. Wang & Li, 2023).

Table 7: Wavelength and frequency of microwave and radio wave

Type	Wavelength	Frequency
Microwave	$10^9 - 10^6$	$3 \times 10^9 - 3 \times 10^{12}$
Radio wave	$>10^9$	3×10^9

Factor affecting the heating:

- Frequency
- Product characters

3. Packaging

Packaging extends the shelf life of the product, which helps the rural producers to generate income by selling their products to different areas. More than 25% of food waste due to poor packaging. Therefore, packaging play a crucial role for keep the product in good condition by protect it from both environmental damage and physical damage during the transportation. Packaging elements have different impact on customers. Proper handling and techniques enhance the interest of customers regarding the specific product (Kuvykaite et al., 2009).

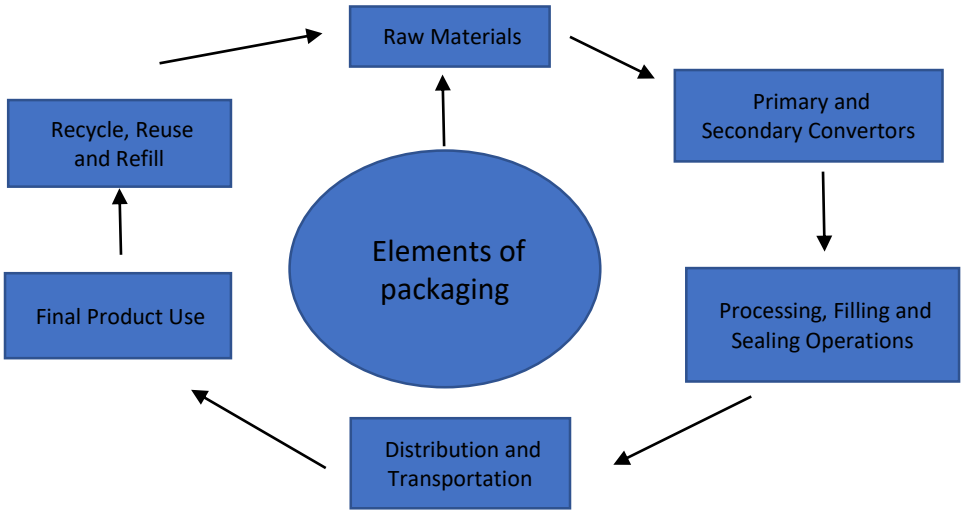

Fig. 5: Elements of packaging

Functions of packaging include protection, containment, communication and convenience. Packaging also save energy used during the transportation and processing in food products to make it fresh (Lindh et al., 2016). These function helps to meet all the requirements of costumers and food safety regulations.

Smart Packaging

Smart packaging revolutionizes the food market by providing innovative techniques to explore product quality and ensure food safety (Qureshi et al., 2020). These technologies increase the customer interest by providing different techniques due to this, they can easily purchase the product with confidence. This increased the product image and also demand in the market.

Types of Smart Packaging Technologies:

- Sensors
- QR Code
- RFID
- NFC
- Time-Temperature Indicators
- Biodegradable Materials

- IOT Technology
- Block-chain Technology

3.1. The Role of Sensors in Smart Packaging

Certainly, sensors are of immense significance in smart packaging. They are capable of recording temperature, humidity, pH and oxygen content in the system in real time. Other aspects of smart packing like IT enabled systems or sensor networks also allow to ingest a 'smart' controller in the form of sensors or other IT enabled devices. Monitoring of food ingredients and materials' compatibility, storage conditions, level fluctuations such as temperature and humidity conditions are also some key benefits (Kuswandi et al., 2011). This helps manufacturers assist in tracking the status of their products from the time they are manufactured all the way to the end when they are consumed by customers. For instance, temperature sensors aim at detecting increased temperature readings which sometimes indicate contamination as well as other forms of spoilage. Similar, humidity measuring sensors aim at maintaining the humid levels in order to hinder the potential of mold formation.

Some of the Benefits Derived from these Sensors Include

- Real time monitoring which is an added advantage, is continuous monitoring of conditions such as temperature and humidity that are sensitive and impact the safety of the product.
- They sense and detect damage caused by spoilage or pollution early which can impact a large portion of food and increase health related dangers.
- Shows Quality and Continues to maintain the frozen goods' quality regardless of how long it takes to reach the end consumers.
- Through measurements, saves food by ensuring it does for longer periods of time.
- As the sensors allows to collect information that can be made available when industry, investors, potential customers some information, which will increase trust in the level of the purchased product.
- Early alter on small issues which can be large recalls leads to increase in the cost saving and at the same time increase the brand image.

3.2. QR Codes Role in Smart Packaging

They provide information of product, track the supply chain, verify the product authenticity and improve the marketing efforts by personalizing and loyalty programs (Rotsios et al., 2022). This ensures that the product is safe to consume and it leads to an increase in engagement and trust.

Benefits of using QR codes:

- These are used to give information about the ingredients and authenticity of products. They also use this to inform about allergens.
- These codes give manufacturing information about products like the expiry date.
- In Asia Pacific, particularly China and Japan, QR codes make a bridge between the physical and digital worlds, offering innovative applications.
- There was about an 83% usage increase in the APAC region from 2014 to 2018 because it built strong customer trust.
- Brands like Coca-Cola use QR codes for special experiences and give gifts and other loyalty packages to build customer interest.
- They help in analyzing the data and in managing the supply chain thus reducing the cost and improving product production performance.
- They offer personalized marketing, loyalty programs, usage alerts, and reviews, increasing customer satisfaction and retention.
- To increase the customer's satisfaction and retention some companies use QR codes for reviews and offer personalized marketing.

3.3. RFID (Radio Frequency Identification):

The increase in the functionality, safety and convenience of products is benefiting from RFID technology (G. Wang et al., 2016) .

Advantages Pointed to RFID Enabled Smart Packaging

- RFID tags update on condition/location product state, place, and originality.
- Improve the supply chain management by tracking the product across the supply chain and also improve trimming losses.
- These tags give full information to the customers and increase their shopping experience.
- Helps to prevent replica thus ensuring that the product is real.
- Help in sustainable sorting and grading.

3.4. NFC (Near Field Communication):

The product is equipped with a near field communication (NFC) tag that allows consumers to tap their NFC-enabled phone on the packaging, which takes them directly to more information about the products they bought. This will increase the customer's digital experience and thus enhance their interest in the brand (Đurđević1 et al., 2018).

Benefits

- Enhanced Traceability
- Consumers and retailers would know when their favorite food or drink item was about to expire with NFC technology.
- Recall management is done effectively.
- Helps in managing the supply chain.

3.5. Time-Temperature Indicators (TTIs):

Time-temperature indicators are the sensors which are small labels on the food package, these sensors help the customer to easily examine the product quality such as change in color based on how long it is exposed to high temperature (Pavelková, 2013).

Benefits of TTIs in smart packaging:

- Increase food safety.
- Helps in maintaining the freshness of food which leads to extending the shelf life of food.
- Provide sustainable practices by reducing food spoilage and waste.
- Optimize the transportation and storage conditions.
- Building consumer trust by providing visible indicators of product quality and safety.

3.6. Biodegradable Materials

Utilization of biodegradable polymers in smart packaging for sustainability and food safety. Biodegradable smart packaging is improved using essential oils and plant extracts that keep the food fresh and it is environment friendly (Amin et al., 2022).

Benefits of Biodegradable Materials

- Environment friendly packaging.
- This will reduce the plastic use.
- Improvement in food security.
- There is less waste of packaging materials.
- Customers who are eco-conscious demand for this type of packaging.

3.7. IOT (Internet of Things) Technologies

IOP technologies such as temperature and moisture sensors, RFID and NFC tags, and GPS tracking devices are known to IOT.GPS tracking of products throughout the supply chain increases the cost saving and reduces the damages or replication problems.

Benefits

- Enhance connectivity
- Increased user engagement and satisfaction ·
- Sensors and monitoring tools identify hazards
- If a company is good at collecting data and acting on it in real time, they are better off going with Cloud front.

3.8. Blockchain Technology

GPS Tracking Devices GPS tracking devices gather data from satellites, cell towers, and WiFi networks to help pinpoint products and shipments (Y. Yang et al., 2024).

Benefits

- The fact that data in blockchain is immutable means it cannot be changed hence preventing people from committing fraud and indulging into unauthorized activities.
- Real-time tracking and data science can help in speeding up the operating practices of any supply chain; thus minimizing delays to a great extent, giving long-term efficiency.
- Smarter package where the blockchain technology interacts with packaging, providing consumers with more knowledge about their product launch.

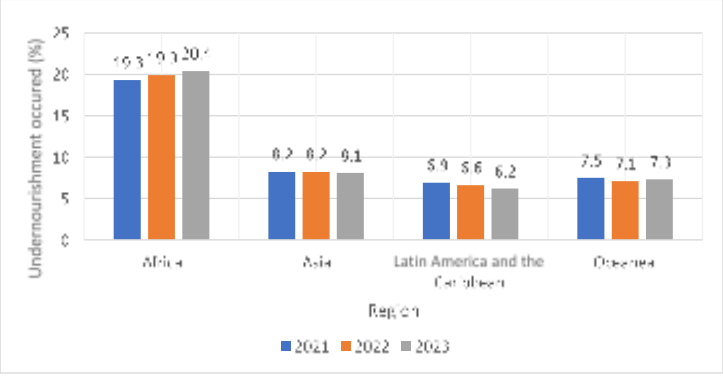

Fig. 6: Percentage of undernourishment in different region of world from 2021 to 2023

4. Nutritional considerations and Policies

About 9.1% global population faced hunger in 2023, while Africa has the highest percentage in it. Globally 29.8% population faced food insecurities in 2023. Food insecurity in higher among women as compared to men. The cost of a healthy diet increased due to which 35.4 % population was unable to afford a healthy diet. 22.3% of children are short due to malnutrition, 6.8% are too thin caused by poor health or lack of food and 5.6% of children are overweight. Obesity in adults increased from 12.1% to 15.8% up to the 2022 year. Problems of undernutrition is declined but problems like overweight and obesity in increasing in all age groups.

Key challenges include climate change, economic downturns, not following the proper diet secludes and inequalities. Policies that should be made by the

government are scale up the investment, increase technical efficiency and shifting the private investment to a sustainable and health project and establishing of "Food and Nutrition Security" as a policy objective ("The State of Food Security and Nutrition in the World 2024," 2024).

Conclusion

The development of a holistic food system helps to overcome the challenges that the global food system is facing. By using engineering innovations, advanced technologies, sustainable agriculture practices, smart packaging, and nutritional considerations, this system will increase the yield, reduce wastage rate, improve food security, increase economic growth and enhance customer trust. Further, the government should make different policies like scaling up the investment, promoting sustainable agriculture practices and innovative techniques in processing, enhancing the use of smart packaging, and starting different projects for promoting nutritional value which will decrease problems like overweight and obesity which cause diabetes, increase cholesterol level and hypertension.

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