DOI: https://doi.org/10.21323/2618-9771-2024-7-3-491-504

Received 26.04.2024
Accepted in revised 28.09.2024
Accepted for publication 30.09.2024

Available online at https://www.fsjour.com/jour
Review article
Open access

SUSTAINABLE AGRICULTURE DEVELOPMENT FOR FOOD SAFETY AND NUTRITION

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KEY WORDS:
biodiversity, climate change, environment, food safety, sustainability

ABSTRACT

Sustainable agriculture is a type of agriculture which, in addition to producing food and agricultural products, is also economically advantageous for farmers, socially correct, respectful of nature and the environment. Sustainable agriculture contributes to improving the quality of life of both farmers and society. Climate change, economic development and social equity influence the sustainable agriculture and require complex and shared solutions on a large scale. Sustainable agriculture includes different meanings, such as environmental, social and economic perspective. The environmental perspective is related to the development of virtuous processes that respect the planet's resources, the healthiness of the soil and water, guaranteeing the maintenance of biodiversity and avoiding the use of pesticides and chemical agents. The social and economic perspective is the ability to meet the global demand of both industrialized and developing countries by ensuring the improvement of the protection of human rights and solidarity-based economic development, the quality of life of farmers, the ethical treatment of animals. The aim of this work is to discuss the implications and perspectives of sustainable agriculture in relation to food production.

Поступила 26.04.2024
Поступила после рецензирования 28.09.2024
Принята в печать 30.09.2024

https://www.fsjour.com/jour
Обзорная статья
Open access

РАЗВИТИЕ УСТОЙЧИВОГО СЕЛЬСКОГО ХОЗЯЙСТВА ДЛЯ ПИЩЕВОЙ БЕЗОПАСНОСТИ И ПИТАНИЯ

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КЛЮЧЕВЫЕ СЛОВА:
биоразнообразие, изменение климата, окружающая среда, безопасность пищевых продуктов, устойчивое развитие

АННОТАЦИЯ

Устойчивое сельское хозяйство — это тип сельского хозяйства, которое в дополнение к производству пищевых и сельскохозяйственных продуктов также экономически благоприятно для фермеров, социально корректно, уважает природу и окружающую среду. Устойчивое сельское хозяйство вносит вклад в улучшение качества жизни как фермеров, так и общества. Изменение климата, экономическое развитие и социальное равенство влияют на устойчивое сельское хозяйство и требуют крупномасштабных комплексных и общих решений. Устойчивое сельское хозяйство включает различные аспекты, такие как экологический и социально-экономический аспекты. Экологический аспект связан с развитием эффективных процессов, которые уважают ресурсы планеты, здоровье почвы и воды, которые гарантируют поддержание биоразнообразия и избегают применения пестицидов и химических веществ. Социально-экономический аспект — это способность соответствовать глобальному спросу как индустриальных, так и развивающихся стран путем обеспечения улучшения защиты прав человека и основанного на солидарности экономического развития, качества жизни фермеров, этического обращения с животными. Целью данной работы является обсуждение значения и аспектов устойчивого сельского хозяйства в отношении производства пищевых продуктов.

1. Introduction

"Sustainable development" is an economic and social term coined by the United Nations, outlining a roadmap for global environmental, social, and economic development. Its primary objective is to enhance living conditions for every individual within society and to develop means of production and their management in ways that do not deplete the natural resources of the Earth, thereby avoiding overburdening the planet beyond its capacity [1]. The comprehensive and general concept of sustainable development entails a holistic activity involving all international sectors, organizations, and institutions, whether public, private, or individual. It constitutes a process of developing and improving existing conditions through studying the past, learning from experiences, understanding the present reality, and striving to change it for the better. This is achieved through careful planning for the future by optimizing human and material resources, including information, data, and knowledge possessed by those engaged in the development process. It emphasizes the absolute importance of continuous learning, gaining experiences, and applying knowledge. Sustainable development is not limited to a single aspect or

FOR CITATION: **AlFadhly, N. K. Z., Al-Temimi, A. A., Alkanan, Z. T., Altemimi, A. B., Younis, M. I., Giuffrè, A. M., Abedelmaksoud, T. G.** (2024). Sustainable agriculture development for food safety and nutrition. *Food Systems,* 7(3), 491–504. https://doi.org/10.21323/2618-9771-2024-7-3-491-504

ДЛЯ ЦИТИРОВАНИЯ: **Альфадли, Н. К. З., Ал-Темими, А. А., Алканан, З. Т., Алтемии, А. Б., Юнис, М. И., Джуфре, А. М., Абедельмаксуд, Т. Г.** (2024). Развитие устойчивого сельского хозяйства для пищевой безопасности и питания. *Пищевые системы*, 7(3), 491–504. https://doi.org/10.21323/2618-9771-2024-7-3-491-504

field of life; rather, it encompasses social, economic, political, humanitarian, psychological, mental, medical, educational, technological, and other areas of development [2].

In the year 2015, all member countries of the United Nations adopted the Sustainable Development Agenda for 2030 as a shared plan for peace and prosperity for people and the planet. This agenda includes seventeen Sustainable Development Goals (SDGs), with the foremost goals being the eradication of poverty, the elimination of hunger, ensuring food security, achieving improved nutrition, and promoting sustainable agriculture [3]. Reports by experts from the Intergovernmental Panel on Climate Change (IPCC) have confirmed that human activities are responsible for air pollution, greenhouse gas emissions into the atmosphere, global warming, and manifestations of ice melting in the polar regions, accompanied by rising sea levels, posing severe threats of natural disasters [4]. The reason for this is attributed to climate variability, which poses a threat to the safety of the food chain in several ways, including the potential to exacerbate foodborne diseases due to the provision of conducive conditions for their growth and mutation, leading to mutations in some toxic biological entities. Additionally, food safety may be compromised due to the risks posed by various chemical substances, such as pesticides, mycotoxins, and heavy metals. Thus, abrupt climate fluctuations can lead to current, emerging, and future risks that could harm food safety [5]. The succession of systemic crises over the past two decades has profoundly impacted our lives, prompting the global community, represented by institutions headquartered within the United Nations, to encourage concerted efforts to address global challenges, particularly in the agricultural food sector, which is among the most relevant sectors to emerging societal challenges. There is now a clear need for new agricultural food policies to be implemented [2]. Sustainable development primarily calls for raising and enhancing the standard of living for individuals and ensuring a better livelihood for future generations. The emergence of the concept of sustainable development was a direct result of previous failed policies and strategies that persisted for decades. Therefore, stakeholders in sustainable development have aimed to correct the traditional path of development by reconsidering the components of the economic process (productivity) for societal wealth, whether natural, human, social, or industrial, to achieve its main objective, which is achieving intergenerational equity in the utilization of the same resources within a clean environment and economic prosperity for society [6].

Sustainable development aims to urge all countries, whether poor, rich, or middle-income, to work towards enhancing prosperity while considering the protection of the Earth. These goals emphasize that eradicating poverty must go hand in hand with strategies that promote economic growth, as well as address a range of social needs including education, health, social protection, and employment opportunities, while addressing climate change and environmental protection [7]. Furthermore, sustainable development aims to strike a balance within the economic system without depleting natural resources while considering environmental security. Given the human dimension of sustainable development, inherently tied to the environmental dimension, present generations have become responsible for preserving natural resources for future generations. Therefore, environmental concern is fundamental to development, as the wastage and depletion of natural resources, which form the basis of agricultural and industrial activities, will have detrimental effects on development overall. The concept of sustainable development emerged as a result of neglecting the environmental aspects of development, leading to international efforts culminating in the report of the World Commission on Environment and Development, which introduced the new concept of sustainable development [8]. Economists have been encouraged to depart from the mechanistic system approach. It has been observed that policies aimed at reducing carbon emissions may create pressures on biodiversity. Additionally, policies supporting biofuels could jeopardize food security [9,10,11].

Many natural resources that we harness for comprehensive development in our countries are constantly diminishing because they are non-renewable, especially energy sources, water, and raw materials. The world's consumption of these resources has been steadily increasing since the beginning of the industrial revolution. However, there has persisted a prevalent misconception that the Earth is a source of inexhaustible resources and an unlimited reservoir of energy [1]. Therefore, this study aimed to investigate the concept of sustainable agricultural development, its dimensions, and challenges in the current circumstances. It sought to understand the interconnection between food, climate, and energy, as well as to assess the reality of agricultural policies and their effectiveness in achieving sustainable development. Furthermore, it aimed to explore the impact of food on our lives and to identify applications in food systems that contribute to sustainable development.

2. Objects and methods

The sources of information were the following scientific databases: ScienceDirect, PubMed, Scopus, ResearchGate, and Google Scholar. The search strategy included the following keywords: biodiversity, climate change; environment; food safety; and sustainability. The following acceptance criteria for research characterization were considered: the implications and perspectives of sustainable agriculture in relation to food production. The parameters of the publications were as follows: publication from 1989 until 2023 (110 references were selected for this review); language: English. Exclusion criteria: no access to the full text articles. Based on the review, the authors compiled information on discussion of the implications and perspectives of sustainable agriculture in relation to food production.

3. Sustainable development

Sustainable development aims to meet current needs without hindering future generations' ability to meet their own. It advocates for a balanced approach to economic, environmental, and social progress. Initially defined by the International Commission on Environment and Development in 1987, this concept represents a transformative developmental philosophy that offers new perspectives on the future of our planet. Development seeks to achieve economic and social objectives through specific processes that enhance living standards in various contexts, but it does not always equate to economic growth. A lack of economic growth does not necessarily imply a lack of development within a society [12]. Perspectives on the environmental crisis and sustainable development vary. The strong sustainability movement emphasizes aligning development with environmental conservation, focusing predominantly on ecological concerns. However, the notion of unlimited growth is challenging given the Earth's finite resources and capacity to manage environmental impacts. Advocates of this view argue that without a radical rethinking of our approach to nature and economic progress, an environmentally sustainable future may be unattainable. In contrast, moderate environmental sustainability is currently more widely accepted, particularly among governments in industrialized nations, and is seen as a more practical approach to achieving greater global equality [13,14].

The term sustainable development refers to continuous and ongoing genuine development with its aim and purpose being human-centric, emphasizing the balance between the environment in its economic and social dimensions [15]. It contributes to the development of natural resources and human resources and induces transformations in industrial and technological bases on a scientifically planned basis according to a specific strategy to meet present and future needs [16]. Sustainable development, from an environmental perspective, focuses on the optimal use of agricultural land and water resources worldwide, leading to an increase in green spaces of Earth's surface [17]. From a social and humanitarian perspective, it entails striving for population growth stability and preventing or reducing rural-to-urban migration by improving the levels of educational and healthcare services in rural areas, while from an economic standpoint, it aims to achieve sustainability through the visions of industrialized countries on one hand and developing countries on the other [18].

Industrialized countries perceive sustainable development as necessitating continuous reductions in their energy and resource consumption to bring about radical transformations in prevailing lifestyles and refraining from exporting their natural and industrial development model globally. For developing countries, sustainable development means utilizing resources to raise the living standards of the most impoverished populations in the South. Technologically, sustainable development involves transitioning communities to an era of clean industries and technologies that utilize minimal energy and resources and produce the least amount of gases and pollutants that contribute to global warming and ozone depletion [19].

4. Natural resources as one of the fields of sustainable development

Economic development serves as a significant indicator of the extent of progress in the fields of sustainable development, which are linked to several crucial aspects such as education, health, finances, and average age expectancy for individuals in a specific region. This is achieved through raising awareness among individuals on how to preserve and protect natural resources from pollution, as well as their understanding of the necessity to achieve balance, diversity, and continuity in planning for the needs of current and future generations, and how to achieve mutual coexistence between humans and the environment [20,21]. Since the first United Nations Conference on the Environment in 1972, the world's population has nearly tripled to over 7 billion people, while the size of

the global economy has also increased more than threefold. Although this growth has lifted hundreds of millions of people out of poverty, the benefits have been unevenly distributed, placing a heavy burden on the environment. Future economic growth is accompanied by decent work and increased living standards, leading to human welfare improvement, all of which depend on preserving the natural resources upon which all livelihood and economic activities rely [22].

The increasing use of natural resources and the resulting pollution have led to a growing impact of water scarcity and loss of fertile land. This has accelerated the reduction of biodiversity and triggered climate change, exacerbating damage beyond sustainable levels. Consequently, addressing environmental challenges and finding swift and decisive remediation methods are imperative. However, such measures may hinder economic growth, thereby affecting job opportunities and exacerbating environmental disasters [22]. Freshwater scarcity is prevalent in many parts of the world, with the Organization for Economic Co-operation and Development (OECD) projecting that by 2050, the number of people living in severely water-stressed areas will exceed 2.3 billion, representing over 40% of the world's population. This impedes various economic activities, with industries, energy generation, human consumption, and agriculture increasingly competing for water resources, resulting in serious repercussions on food security. Irrigation accounts for approximately 70% of available water, and while intensive agriculture has increased crop yields through chemical fertilizers, it has degraded soil quality and polluted water resources. Consequently, water and food scarcity are increasing individual work burdens [10].

5. The significance of the agricultural sector in achieving food security and sustainable development in Iraq

The Food and Agriculture Organization (FAO), a United Nations agency, defines sustainable agricultural development as the management and conservation of essential natural resources, including institutions, technologies, and current and future human requirements. This strategy must work towards preserving land, water, and plant and animal resources while being technically and economically acceptable to society [23]. Food security is defined as a community's ability to provide basic nutritional needs for its population and ensure a minimum level of those needs. It consists of four pillars: food availability, access, utilization, and stability, with the food dimension being an integral part of food security [24]. Addressing food security is crucial in all countries, whether developed or developing, and agricultural nations have supported food security for general and specific purposes by making “eradicating poverty and hunger” one of the United Nations' Millennium Development Goals. These countries, including Iraq, hope to achieve this goal despite economic constraints affecting agricultural productivity, making it challenging to attain [25]. World patterns of social and economic development vary, resulting in significant surpluses and chronic food shortages, contributing to hunger and malnutrition. Therefore, maintaining food security may pose a significant problem for developing countries with low levels of per capita gross domestic product, including Iraq, which suffers from unsuitable agricultural conditions and inadequate infrastructure, often attributed to the lack of economic resources for food [26]. Wars, such as the Gulf War of 1990–1991 and the invasion of 2003, marginalized and weakened the Iraqi regime, leading to a significant deterioration in living conditions and a decline in food security in Iraq [27].

Iraqi agriculture faces a significant water problem that affects cultivated areas, agricultural production, farmers' income, and food security. However, the results achieved in rationalizing the use of irrigation water remain limited and do not meet the requirements necessary to address this serious challenge [28].

Agricultural policy is a significant tool adopted by countries to guide their economic and social activities by facilitating the appropriate delivery of agricultural goods to consumers in terms of price and quality, while simultaneously providing agricultural inputs to farmers at minimal costs. This approach aims to ensure profitability that sustains agricultural producers' continued participation in the production process with the same efficiency and effectiveness, thereby enhancing the agricultural sector's contribution to the gross domestic product (GDP) [29]. Achieving agricultural development is crucial for food security and forms the foundation for comprehensive economic and social growth. However, it requires various measures to overcome the obstacles and problems hindering the development of this economic sector, thereby enabling it to achieve food security, contribute to national economic development, provide workforce opportunities, and reduce reliance on external sources for food supplies. This can only be achieved through the highest degree of efficiency and economic resource mobilization. Consequently, most developed and developing countries alike strive to achieve sustainable agricultural development to meet current and future food needs, maintain productivity, and renew natural resource bases.

In the Iraqi economy, however, significant challenges hinder agricultural progress due to various overlapping obstacles. These include the destruction of infrastructure after 2003, land issues such as salinity and desertification, water problems, environmental pollution, decreased investment in the agricultural sector, cessation of country support for agriculture, rising prices of agricultural production inputs, declining use of agricultural technology, trade policy issues leading to flooding of Iraqi markets with imported agricultural products, and the financial, technical, and technological weaknesses of the private agricultural sector. These obstacles have had a detrimental impact on the agricultural sector. Therefore, effective solutions must be found to address the problems facing this vital sector, necessitating full support from the country, represented by the Ministry of Agriculture. This support should include providing production inputs such as improved seeds, fertilizers, mechanization, and water pumps, as well as supporting final product prices. These measures play a significant and influential role in achieving food security for a large segment of Iraq's population [30].

6. Food and its effect on sustainable development

Food is a fundamental aspect of human life, integral to our survival and daily routines. Beyond its necessity for nourishment, food also plays a crucial role in fostering social interactions and connecting individuals from diverse backgrounds. Dietary practices often reflect cultural identities, underscoring the richness of global diversity. Understanding the role of technology in food — both now and in the future — is therefore essential [31].

Food significantly impacts human behavior, health, and cultural practices. With advancements in social networks, mobile technology, and the internet, people frequently share and document food-related content, such as images, recipes, and cooking videos. This has led to an abundance of food-related data, providing valuable insights into nutrition and societal issues. Food computing utilizes diverse data sources to analyze, recognize, and recommend food, applying computational methods to address challenges in medicine, biology, culinary arts, and agriculture. Recent developments in computer science are revolutionizing the analysis of food data, driving progress in various food-related applications [32].

As we advance toward sustainable development goals, the adoption of innovative agricultural and food technologies is anticipated to grow. While these innovations promise to support multiple sustainability objectives, it is crucial to approach them with caution. One-size-fits-all technological solutions can be misleading. Understanding the broader impacts of technological advancements — such as those involving energy, health, and artificial intelligence — is vital. The interplay of different technologies can lead to both significant opportunities and unforeseen consequences. Therefore, careful consideration of these innovations is necessary to avoid negative outcomes and ensure alignment with principles of social justice. Collaboration on regulatory, social, and economic frameworks, as well as environmental and social management standards, is essential for achieving both human and planetary health [33–34]. Figure 1 illustrates improving crop management and its impact on sustainable development.

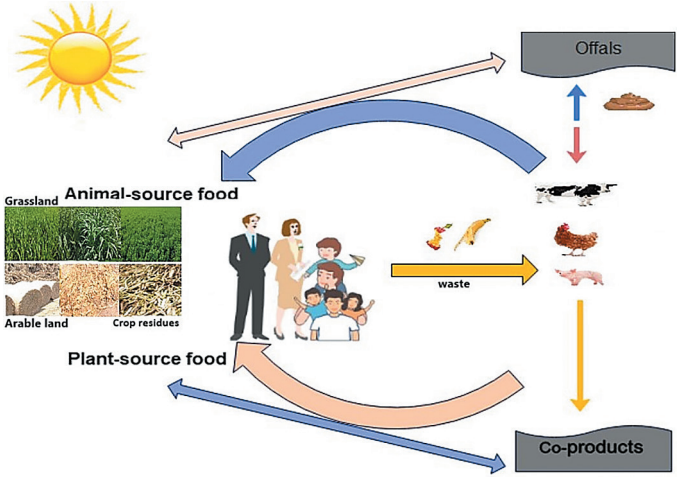

Figure 1. **Improving crop management and its impact on sustainable development**

Рисунок 1. **Улучшение менеджмента сельскохозяйственных культур и его влияние на устойчивое развитие**

Erdogan [35] pointed out the potential for implementing effective policy measures for sustainable development by identifying the health and environmental impact of producing long-lasting and perishable goods, such as the production and manufacturing of food items, which are impossible to reduce or eliminate due to their direct connection to daily individual life. Therefore, there should be a focus on not neglecting the environmental and health aspects and the negative effects resulting from long-term food production, including significant factors such as carbon emissions. However, it should be noted that statistical evidence has found a significant positive relationship between food production and life expectancy at birth, indicating that food production is a crucial determinant for sustainable development.

7. Malnutrition and its relationship to sustainable agricultural development

Four forms of malnutrition exist globally: energy-protein malnutrition, iron deficiency and anemia, vitamin A deficiency, and iodine deficiency disorders. These forms vary in their global impact, regional prevalence rates, affected age and gender groups, as well as their clinical and public health consequences. Recent advancements in quantitative measurement and monitoring at national and regional levels have improved understanding of these issues. Additionally, zinc deficiency, accompanied by decreased host resistance and increased susceptibility to infections, is also addressed [36]. The World Health Organization (WHO) identifies malnutrition as the greatest threat to global public health, with forty-five thousand children dying annually due to malnutrition-related causes [37].

Poverty and malnutrition are closely intertwined factors, with each depending on the other. Therefore, it is imperative to address both simultaneously rather than individually. The relationship between them is bidirectional, as each can be both a cause and a consequence of the other. Leaving this vicious cycle unaddressed poses a major concern for public health, necessitating immediate steps to confront it in order to achieve sustainable improvement.

Regarding nutritional outcomes, it is essential to address the challenges and obstacles that hinder poverty and malnutrition at all levels to achieve the primary goal of a healthier society. Despite advancements in social and economic development, malnutrition remains unacceptably high worldwide. This factor has been linked to a vital relationship between nutritional status and capital, as economic conditions negatively impact both nutritional and physiological/mental capacities of individuals, resulting in decreased productivity levels and making them and their countries more susceptible to poverty.

The eradication of poverty in all its forms is the first goal of the seventeen Sustainable Development Goals (SDGs), with ending hunger, achieving food security, improving nutrition, and promoting sustainable agriculture being the second goal. Additionally, at least twelve out of the seventeen SDGs include indicators closely related to nutrition [38].

The UNICEF framework outlines the underlying, basic, and direct causes of malnutrition, offering a comprehensive view of both direct and indirect pathways to mitigate malnutrition and enhance health outcomes. Sustainable Development Goal 2 seeks to “end hunger, achieve food security and improved nutrition, and promote sustainable agriculture”, which directly influences nutritional outcomes. Additionally, various other Sustainable Development Goals contribute to improving nutrition indirectly through their broader impacts [39].

In summary, there is a need to increase the utilization of emerging food innovations to achieve food security. Despite advancements in food sciences, the prevalence of malnutrition worldwide has not improved over the past decade. One of the Sustainable Development Goals emphasizes focusing immediate and long-term research and development efforts on: (1) adding value and increasing the use of crops rich in neglected and underutilized nutrients to enhance dietary diversity, (2) developing functional foods to address both undernutrition and overnutrition, and (3) applying knowledge of the food matrix to develop processing techniques that enhance the bioavailability of nutrients and reduce micronutrient deficiencies [40].

The Food and Agriculture Organization (FAO) of the United Nations has highlighted that addressing malnutrition and changing eating habits could significantly influence global food demand by 2050. Strategists should incorporate these factors to manage the food industry effectively. Plant-based dietary systems offer a practical approach to combating malnutrition, leveraging the nutritional properties of products at the point of delivery. Our proposed model can assist governments and non-profit organizations in mitigating the long-term effects of malnutrition. It provides food sector managers with valuable insights for designing an environmentally sustainable, responsive, and profitable supply chain. Key managerial insights from applying this model to a real-world case study include: 1) The critical role of agricultural production in creating a sustainable food system. 2) Prioritizing the nutritional quality of products over their deterioration rate to alleviate malnutrition while minimizing costs and environmental impact. 3) Enhancing the nutritional value of manufactured products is more crucial than construction and manufacturing costs for ensuring their inclusion in diets. 4) Achieving dietary diversity may increase overall costs by 14% [41].

8. Food and nutritional security and its relationship to sustainable agricultural development

Addressing food issues has become increasingly challenging in recent times due to the challenges posed by global agricultural development trends. The rate of food production and growth is significantly lower than the rate of demand, leading to a rise in chronic famine in many regions. Analyses of food shortages and the production of quality goods have been conducted, along with practical recommendations to overcome these challenges and expand the range of products [42].

Sustainable food systems aim to minimize environmental impacts while managing high costs, thereby supporting food security and nutrition. To achieve this, household income and expenditure survey data were analyzed using linear programming to develop optimal food systems for two objectives: maximizing the Nutrient Rich Food (NRF) index and minimizing costs. Goal programming was then applied to balance all objectives. This sustainable food basket, considering cultural preferences and recommended nutrient quantities, suggests portion sizes from various food groups based on the food pyramid. Adhering to this basket results in a 23% cost reduction and a 7% increase in the NRF index. To align with sustainable consumption patterns, policy interventions are necessary to boost intake of dairy products, fruits, vegetables, grains, poultry, and vegetable oils while reducing consumption of bread, rice, pasta, meats, fish, eggs, legumes, saturated fats, and sugars. Enhancing food availability, access, and public awareness are crucial, as economic downturns and rising food prices exacerbate food insecurity. Strategies for achieving a sustainable food system include economic incentives, food assistance, reducing waste, and developing relevant guidelines [43].

Seaweed offers a nutritious, low-fat food option rich in minerals, fiber, unsaturated fatty acids, sugars, vitamins, and biologically active compounds. Seaweed by-products present unique opportunities for creating functional foods and can significantly contribute to climate change mitigation by sequestering carbon, reducing agricultural emissions, and providing materials for biofuel and livestock feed. Seaweed farming also aids climate adaptation by absorbing wave energy, protecting coastlines, and mitigating ocean acidification and oxygen depletion. Despite its benefits, challenges include making seaweed products affordable, nutritionally balanced, and appealing to consumers. Developing seaweed-based foods that can compete with current human diets is essential for its broader adoption [44].

Environmental pressures such as salinity, drought, temperature fluctuations, and increased diseases threaten crop production and nutritional value, complicating global food security. Projections for 2100 include a rise in carbon dioxide concentrations to 950 parts per million, temperature increases of 3.5 to 8 degrees Celsius, and sea level rises of over 2.4 meters. These changes could increase drought risk and affect rainfall patterns, leading to higher water vapor levels. Rice cultivation may play a crucial role in achieving food and nutritional sustainability, providing essential nutrients and biologically active compounds amidst these environmental challenges [45].

9. Food security in Iraq and its relationship to water security and sustainable agricultural development

Food security in Iraq is intricately connected to its water security, a crucial consideration for any sustainable development strategy in the country. Addressing this link requires incorporating “virtual water trade” into these strategies, as it helps bridge the gap between available water resources and the water needed to produce essential food products. This approach can mitigate the risk of famine and reduce reliance on external aid. To effectively implement this strategy, it is important to classify food products based on their water footprint and prioritize crops with medium and low water requirements while excluding those with high water footprints from agricultural plans. Additionally, importing products with high water footprints to provide “virtual water” should be a standard practice, ensuring that the country can sustainably meet its food needs.

Iraq relies heavily on water from the Tigris and Euphrates rivers and their tributaries. However, decreasing river flows are leading to a significant water shortage problem, which is expected to worsen in the coming decades. With the population projected to reach around 70 million by

2050 and approximately 90 million by 2070, future water availability will likely be insufficient to meet the country's food security needs, including both agricultural and animal products [46].

To address this challenge, water management must be based on scientific principles to tackle both current and anticipated issues. Key strategies include analyzing the virtual water footprint of various food crops to optimize the use of available water resources and minimize shortages. This involves maximizing the use of desalinated water, recycled sewage water (grey water), and reducing reliance on surface and groundwater irrigation (blue water) and rainwater (green water). Additionally, a comprehensive strategic plan should incorporate elements beyond food security, such as community development and policies to manage population growth, which currently stands at 2.97% annually.

Implementing awareness and education programs on water and food security is essential to highlight the critical nature of food security for Iraq's survival and sustainability [47].

10. Goals set by the international community as main components of sustainable development

One of the primary challenges in achieving sustainable development is eliminating poverty while fostering balanced production and consumption patterns that do not overly depend on natural resources. Sustainable development indicators provide a structured scientific approach, focusing on six key areas: international trade, investment, economic policy, climate change, energy, natural resource management, and communication technology. These indicators serve as a comprehensive framework to guide policies and actions toward sustainable growth [48]. Figure 2 depicts the key components of sustainable development.

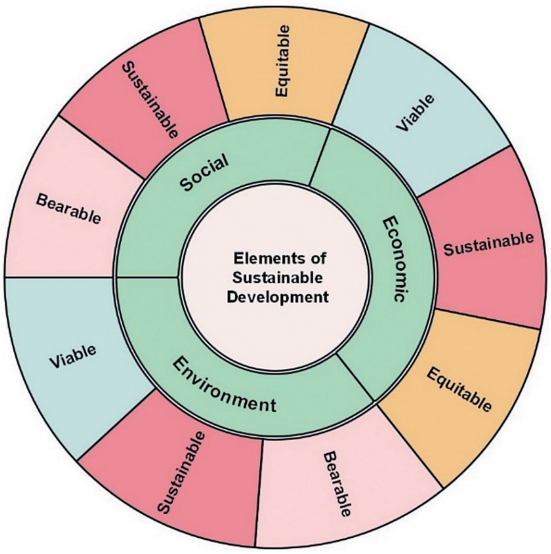

Figure 2. **Elements of sustainable development**
Рисунок 2. **Элементы устойчивого развития**

10.1. Ending poverty

Poverty extends beyond the mere absence of income or resources; it encompasses a lack of sustainable livelihoods and is manifested in forms such as hunger, malnutrition, limited access to education and basic services, social discrimination, societal exclusion, and a lack of participation in decision-making. Addressing poverty in all its dimensions is a central focus of the seventeen Sustainable Development Goals (SDGs) for 2030. These goals aim to eradicate extreme poverty, implement social protection programs, and promote gender equality in access to economic resources. The overarching aim of the SDGs is to combat poverty by "ensuring the provision of significant resources from diverse sources, including enhanced developmental cooperation for developing countries" [49].

Protected areas are the most effective places for conserving biodiversity, and the services provided by well-functioning ecosystems in protected areas are of great value to humans, ensuring livelihoods, health, and overall well-being. However, human activities may intersect with protection efforts, causing a sharp decline in biodiversity if social and economic development exceeds the carrying capacity of protected areas. Protected areas may have positive or negative effects on local social and economic development, as numerous studies have demonstrated the impact of protected areas on local development using quasi-experimental methods and constructing poverty indices. Cases have shown that protected areas have positive effects on poverty alleviation [50,51].

Protected area systems have been established to achieve a balance between poverty alleviation and the preservation of sustainable regional development. Several studies have indicated that protected areas tend to be biased towards low-productivity and low-economic-value locations, while the wide distribution and spread of populations are used as indicators of threats or pressures on natural ecosystems. Multidimensional poverty is widespread, affecting more than four out of every ten households and children. Although the incidence of household poverty appears modest at the regional level, it does not paint a complete picture, as the proportion of the population in poverty reaches 13.4%, approximately 38.2 million individuals [52].

10.2. Ending hunger

The Sustainable Development Goals (SDGs) for 2030 serve as a global framework for fostering international collaboration to advance sustainable development. Nutrition is a key element within the second SDG, "Zero Hunger", which focuses on achieving food security, improving nutrition, and promoting sustainable agricultural practices [3]. The nutrition-related targets of the SDGs aim to enhance health outcomes, foster sustainable food systems, and secure global food availability. While malnutrition poses a minimal issue in European Union member states, rising trends in childhood obesity remain a significant concern, with progress falling short of the desired goals. Notably, improvements in European food production systems have positively impacted various environmental factors in recent years. However, there is still a lack of a comprehensive regulatory framework to achieve environmental and climate goals towards addressing all forms of malnutrition while maintaining environmental sustainability through the production of good food and food systems [53].

Eliminating hunger, achieving food security, improving nutrition, and promoting sustainable agriculture encompass addressing malnutrition, improving agricultural production, ensuring sustainable and resilient food production, correcting trade practices, and ensuring functioning food markets. The Sustainable Development Plan for 2030 pledges to move away from escalating inequalities, environmental degradation, and mass extinction of plant and animal biodiversity, waste, and depletion of abundant natural resources to practices that respect and protect our resources within the common environment. It aims to move away from activities that expose hundreds of millions of people to harmful effects such as global warming and its consequences on climate risks. Priority is given to eradicating poverty, hunger, and malnutrition in all its forms in the 2030 plan, with nutritional interventions aimed at reducing child malnutrition (stunting among children under 5 years old) by about 30 million at an average cost of approximately US $5 billion annually. Additionally, taking all measures to reduce hunger together could potentially decrease the number of children suffering from stunting by about 40 million without any additional increase [54].

Industrial science and technology can play a crucial role in combating hunger, addressing malnutrition, improving food security, and ensuring food safety. Through the Food and Agriculture Organization (FAO), many industrialized countries utilize advanced agricultural practices and develop nutrition programs to ensure stable food supplies [23]. Their efforts contribute to achieving the second United Nations Sustainable Development Goal of eradicating hunger and all forms of malnutrition by 2030. Healthcare professionals and scientists employ advanced industrial techniques to study various forms of malnutrition, from undernutrition to obesity. The findings of their research assist policymakers and experts in developing programs and policies to address hunger and malnutrition. These initiatives include food fortification programs focusing on producing nutrient-rich foods, calorie reduction programs to combat obesity, as well as programs aimed at assisting mothers in breastfeeding and improving their children's nutrition. Hunger is one of the manifestations of poverty, with one in every nine individuals worldwide suffering from malnutrition. This leads to weakened health and immunity, making individuals more susceptible to various diseases. It is evident from research findings that malnutrition is linked to low educational attainment. Consequently, poverty leads to malnutrition, which negatively impacts learners [53]. Education, decent work, and economic growth have been linked to improved diet quality, though the causal relationship remains unclear. The preference for low-quality, energy-dense, and nutrient-poor foods among lower socioeconomic groups may be influenced by limited access to, or the unaffordability of, healthier food options, along with other contributing factors [55].

10.3. Good health and well-being

Promoting healthy lives and well-being for all individuals at every stage of life involves several key objectives, including reducing maternal mortality, preventing child deaths, combating diseases such as HIV/AIDS and other communicable diseases, and ensuring access to universal

health coverage. This also includes the availability of affordable essential medicines, sexual and reproductive healthcare, vaccine research, and access to medicines. Economic sustainability focuses on boosting productivity through preventive healthcare measures and enhancing workplace health and safety. Social sustainability emphasizes enforcing standards for air and water quality, as well as managing noise pollution to safeguard human health and provide primary healthcare to the poorest populations. Environmental sustainability, in turn, is dedicated to protecting biological resources, ecosystems, and life-support systems to ensure a healthy planet. This entails everyone enjoying healthy lifestyles and well-being at all ages by achieving comprehensive healthcare, providing opportunities to access medications, vaccines, appropriate treatment, regular check-ups, addiction treatment, ensuring complete nutrition and clean drinking water, suitable housing, and, above all, providing preventive protocols against infectious diseases, especially endemic ones such as malaria, AIDS, and others. This ensures the provision of good health conditions for mothers, guaranteeing the birth of generations that enjoy both physical and mental health and their ongoing monitoring from a health perspective [3]. Nutrition plays a key role in the Sustainable Development Goals (SDGs), serving as a vital element in the global effort to promote sustainable development by 2030. All countries, whether low-, middle-, or high-income, are encouraged to collaborate in achieving these 17 goals. Notably, the second SDG, "End hunger, achieve food security and improved nutrition, and promote sustainable agriculture", is the only one that explicitly emphasizes the concept of "nutrition" as a central focus [3]. Despite a significant reduction of nearly 50 million in the number of children under the age of five affected by stunting over the past 20 years, an estimated 150 million children are still stunted. Additionally, 50 million children under five suffer from wasting, and approximately 20 million newborns are born with low birth weight. Although these numbers are much lower in Europe, in Southeast Europe, stunting prevalence may be up to 10% among children under the age of five [53].

11. Simultaneous combatting of climate change and poverty

Civil society organizations are essential in advancing sustainable development and climate action, both locally and globally. In collaboration with the Green Climate Fund, they contribute significantly to achieving Goal 13 of the Sustainable Development Goals, which focuses on combating climate change. These organizations encompass non-governmental institutions, non-profit organizations, associations, academic organizations, youth groups, women's groups, and environmental organizations. Civil society organizations work on raising awareness and education regarding environmental and climate challenges, and they encourage community participation in implementing principles and goals related to sustainable development and climate action. These organizations implement local, regional, and international projects and initiatives to promote sustainable development and adapt communities to climate change. Additionally, there is an emphasis on the need to enhance adaptation in developing countries to climate change. Developing countries face particular challenges due to the impacts of climate change, necessitating the provision of funding, technology, and training to enhance their adaptation and increase their ability to address risks and climate-related transformations. There is a close relationship between sustainable development and climate action, and understanding their mutual impacts and promoting integration between them is necessary to achieve sustainable development and protect the environment. Strong cooperation and effective coordination among the United Nations, civil society organizations, governments, the private sector, are required to effectively and comprehensively address climate change challenges to achieve a balance between economic and social development and environmental preservation for current and future generations [2].

Eliminating poverty and addressing climate change require a broader reliance on well-funded social protection programs, which can be easily scaled up in times of disasters, alongside robust data and the ability to identify and provide support to the poor. Moreover, the widespread provision of financial services enabling the poor to save and borrow is essential for their swift recovery from shocks. Additionally, access to healthcare and education is crucial for rebounding from shocks and mitigating the effects of poverty [56].

Climate-related actions can bring about new income opportunities through increasing the workforce, such as reforestation efforts and soil fertility restoration, and by encouraging innovative industries that consider the environment. Climate change provides a significant opportunity for retraining in economic activities and trade patterns diversification, represented by the growth of pastures and the construction of sustainable cities. Climate change is a fundamental factor in exacerbating land drought, as rising temperatures can accelerate the process of water transfer from the Earth's surface to the atmosphere. As a result, drought can severely impact water resources in the future, influencing population growth, increasing pollution, lowering living standards, shifting dietary habits, altering agricultural practices, and reducing both industrial and economic activities. The rising demand for water and energy presents a significant challenge in the face of climate change, which will consequently affect agriculture and food security, leading to hunger and poverty, particularly in regions with high levels of malnutrition and extreme vulnerability to climate change. Global food demand is projected to rise by 59% to 98% by 2050 [56].

12. Challenges of sustainable agricultural development

12.1. Food security and nutrition

Economic sustainability focuses on boosting agricultural productivity and output to ensure local food security, whereas social sustainability aims to enhance the productivity and profitability of small-scale farming to achieve household food security. Environmental sustainability, in contrast, is dedicated to the responsible use and preservation of lands, forests, water, wildlife, and fish resources. The Arab Sustainable Agricultural Development Strategy includes 19 main sub-programs covering most agricultural development areas, as well as addressing all Sustainable Development Goals for 2030 related to the agricultural sector. These main programs focus on technology transfer, increasing and sustaining production and productivity, agricultural yield, governance of agricultural resource management systems, and enhancing the competitiveness of agricultural products, improving the investment environment and agricultural trade, plant and animal health, and food safety [2].

It is worth mentioning that achieving many of the Sustainable Development Goals (SDGs) is of paramount importance for achieving the nutrition goal. "Nutrition" is a fundamental element for achieving many other SDGs, and malnutrition is influenced by several social and economic factors, including food insecurity attributed to poverty (the first goal of the SDGs) [3]. Approximately 800 million individuals worldwide suffer from hunger due to poverty, with 43 million people in the European Union unable to afford regular high-quality meals every two days. This inability stems from the incapacity to bear the costs of high-quality foods. Another factor is food choice, which is crucial for maintaining good health, representing the third goal of the SDGs [3]. The term "double burden" describes the simultaneous occurrence of malnutrition, which is linked to higher risks of cancer and infectious diseases, and overweight/obesity, which is associated with an increased risk of non-communicable diseases. This global issue affects approximately 4 billion people across both developing and developed nations. Since 1990, there has been a notable rise in overweight and obesity rates among children and adolescents. Countries such as Greece, Italy, Malta, and Spain have seen particularly high rates, with about 18% to 21% of children affected by obesity. In contrast, Ireland, Latvia, and Norway have reported much lower obesity rates, ranging from 5% to 9%. Maintaining a healthy body weight remains crucial for overall health [53].

12.2. Poverty and food wastage

The Oxford Poverty and Human Development Initiative (OPHI) introduced a new concept of poverty termed Global Multidimensional Poverty (GMP), [57] launching the Global Multidimensional Poverty Index (MPI) in 2010 in collaboration with the United Nations Development Program (UNDP). This initiative utilizes statistical data from the Human Development Reports to analyze available statistical data for the Global MPI alongside the Sustainable Development Goals. The Global Multidimensional Poverty Report for 2019 covered approximately 7.5 billion individuals, equivalent to 77% of the world's population, living in 105 countries, including those experiencing poverty according to three indicators: health, education, and living standards, across ten dimensions as illustrated in Figure 3.

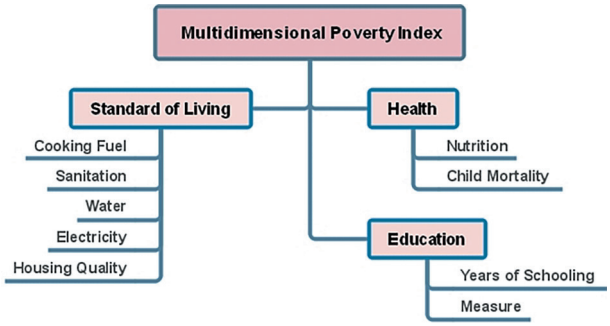

Figure 3. **Multidimensional poverty index**
Рисунок 3. **Индекс многомерной бедности**

In 2019, the aforementioned institution added a numerical classification to the Multidimensional Poverty Index ranging from 0 to 1. According to this classification, Iraq scored 0.032, reflecting a low level of multidimensional poverty [57].

The risks arising from unemployment, which increase poverty rates, have doubled. According to the United Nations Development Program (UNDP), approximately 1.75 billion people suffer from multidimensional poverty that affects health, economic opportunities, education, and living standards. With an additional 27 million unemployed since 2008, there are still 200 million unemployed individuals waiting for opportunities. This unprecedented level of unemployment coincides with the entry of 400 million youths into the global labor market over the next decade in search of employment opportunities. Considering that 75 million individuals aged between 16 and 25 are unable to find employment, youth account for more than one-third of the total unemployment rate [2].

In order to generate sustainable growth while simultaneously maintaining social cohesion, the world must rise to the high challenge of creating 600 million productive jobs over the next decade. In addition to the widespread phenomenon of unemployment and the poor quality of jobs, challenges are exacerbated by the prevalence of poverty among workers, with approximately 900 million workers, or around 30% of the total workforce, living with their families below the poverty line, earning daily wages not exceeding $2 USD, particularly in developing countries where labor is weakly organized. A significant proportion of these workers are employed in sectors that pose risks due to excessive use of natural resources and climate change, such as agriculture and fisheries, which together employ over a billion people. Furthermore, securing basic income for individuals through sufficient social security coverage to meet individual needs and access to healthcare is essential. This serves as an attraction to increase productive employment and break the cycle of multidimensional poverty [2].

Despite humans' adaptation to their primary environment, they sometimes appear ill-prepared for the developed environment, leading to mismatches between biological predisposition and the new food environment [58]. Some researchers and institutions advocate for the inclusion of a fourth dimension in sustainable development, arguing that the existing economic, environmental, and social dimensions do not fully capture the complexities of modern society. In this context, the 21st-century agenda for culture and the United Cities and Local Governments (UCLG) Executive Bureau emphasize the need for a policy statement on culture and sustainable development. This statement, prepared for the third World Conference in Mexico City, underscores the importance of integrating culture into sustainable development strategies. It proposes a dual approach: developing strong cultural policies and incorporating a cultural dimension into all public policies. This approach identifies four areas of sustainability: economic, environmental, political, and cultural. Information technology is also recognized as a key enabler of sustainable development, offering potential benefits across economic, social, and environmental domains by promoting technology-driven sustainable practices (see Figure 4) [59].

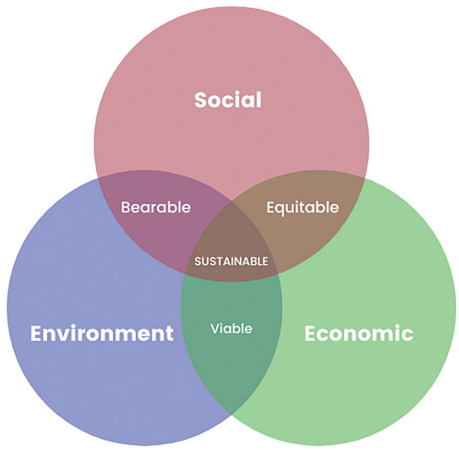

Figure 4. **Circles of sustainability**
Рисунок 4. **Круги устойчивого развития**

13. Food loss and waste and its relationship to food security and sustainable development

Food loss and waste represent major issues in the food industry, affecting all stages of the food supply chain. They are associated with environmental degradation, economic losses, and increased hunger. Figure 5 illustrates the amount of food waste for available food commodities in the European Union [60]. The Food and Agriculture Organization [23] defines food loss as a reduction in the quantity of food originally intended for human consumption, while food waste refers to discarded food as waste. The term "food waste" encompasses both concepts despite differences between them. Food classification helps distinguish between food types based on intrinsic characteristics, including seasonal production, quantity, and quality, relying on biological diversity and quality constraints at each step of inventory depletion risk, transportation and storage requirements, temperature, waiting time, and other requirements. Fruits, vegetables, and grains contribute the most to food waste, with the fruits and vegetables sector being the most susceptible to insect attacks. Meanwhile, edible food waste (about 35%) mainly consists of fresh meat and bakery products [61].

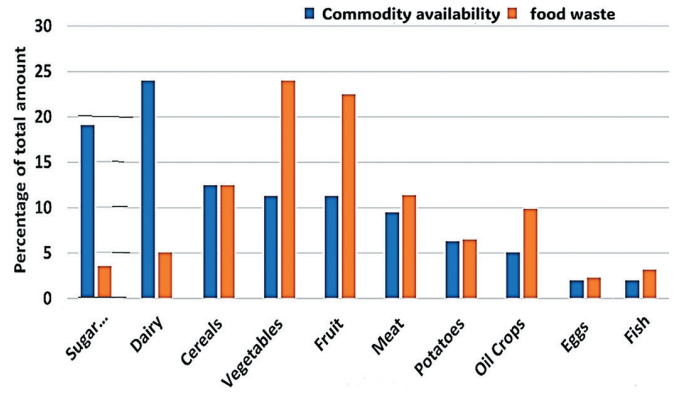

Figure 5. **Total amount of food waste in the European Union [60]**
Рисунок 5. **Общее количество пищевых отходов в Европейском Союзе [60]**

The relationship between food loss and waste and food security is a crucial topic in societal discussions, highlighting the challenges linked to the ongoing and unsustainable development of agricultural food systems. Addressing this issue involves identifying, assessing, and managing how food loss and waste impact food security. Food loss and waste represent inefficient use of resources such as water, energy, and food, which adversely affects food security. To mitigate these impacts, implementing policy measures to reduce food loss and waste across various stages of food production and supply chains is essential. Future research should focus on exploring the complex interactions between food loss, waste, and food security, drawing from multiple disciplines including agricultural sciences, agricultural economics, development economics, environmental sciences, and engineering. This research should aim to provide evidence-based insights into how different supply chain domains interact and how resource management can be optimized through circular and green economy principles — primarily reducing, reusing, and recycling. Future studies must also address environmental protection and natural resource conservation to develop strategies that promote a circular economy and minimize food waste. Actions to reduce food loss and waste include preventing loss during processing by identifying waste causes and training employees, improving production practices, and supporting farmers in converting perishable raw materials into shelf-stable products. Enhancing storage and cold chain facilities, improving transportation, and extending shelf life through innovative packaging and labeling are also crucial. Additionally, redirecting food to consumers via food banks or markets, using food for animal feed, or converting food waste into compost or renewable energy are sustainable alternatives. The food sector is increasingly producing biofuel from waste streams, reflecting a shift towards a more circular food system (see Figure 6) [55,62].

Addressing global food security necessitates the development of new strategies to tackle challenges such as climate change, depletion of natural resources, and the need to protect ecosystem quality and biodiversity. Food loss and waste directly impact food security, nutrition, and the sustainability of food systems. Quantifying the negative effects of food waste is a complex, multidimensional task that requires a comprehensive approach, considering economic, environmental, and social factors. Effective management of food loss and waste throughout the food supply chain depends on implementing sound, standardized practices and measures [63]. According to the European Waste Framework Directive, waste is defined as "any substance or object which the holder discards or intends or is required to discard." Food loss specifically refers to food discarded after harvest. Table 1 provides details on the degree or percentage of food loss and waste across different food groups and stages of the food processing chain [60].

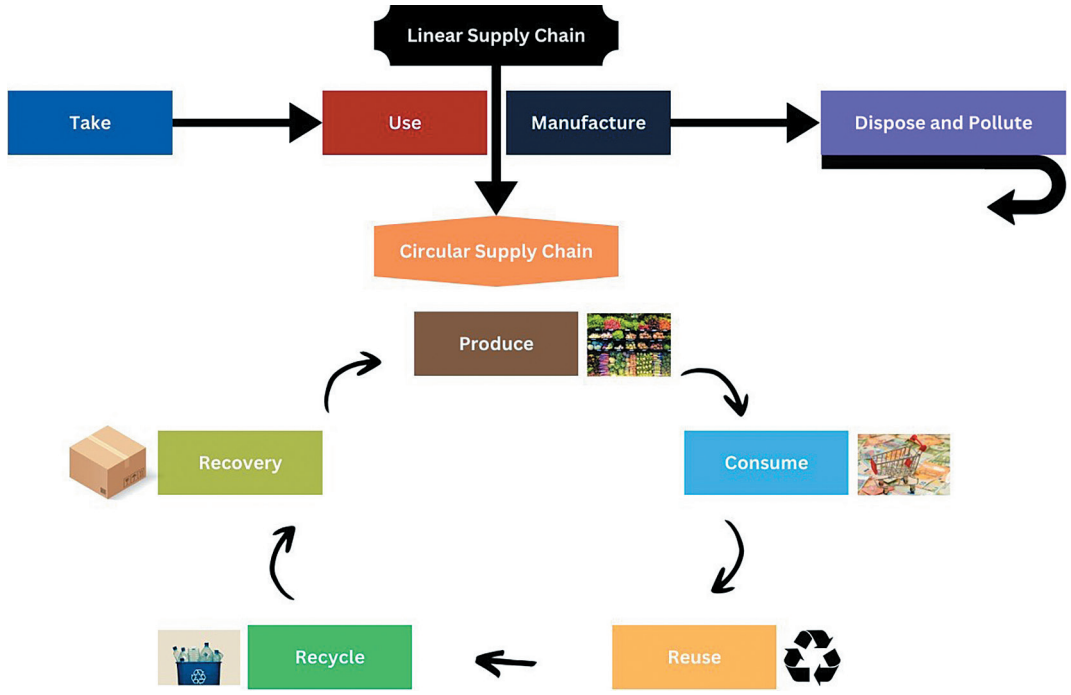

Figure 6. **Transition from a linear forming chain to a circular forming chain**
Рисунок 6. **Переход от линейной цепочки к замкнутой цепочке**

Table 1. **Degree or range of food loss and waste (%) for each food group and stage of the food processing chain [60]**
Таблица 1. **Степень или диапазон продовольственных потерь и пищевых отходов (%) для каждой группы пищевых продуктов и стадии цепи переработки пищевых продуктов [60]**

Food supply chain stage	Food Groups							
	Eggs	Fish	Dairy	Roots and tubers	Oil crops	Meat	Cereals	Fruits and vegetables
Consumption	2	8–22.6	9.8–15	13.3–25.5	4–5	11–14.6	13–27	17.9–26.2
Distribution	1.6–2	9	0.3–0.8	0.3–1	0.7–7	2.8–4	2–3	1.2–10
Processing	0.5–1.6	6	0.7–1.2	4.9–15	5–28.2	4.7–5	3.2–10.5	2–6.4
Storage and handling	1.9	0.5–7.9	0.5–1.7	7.6–9	1–1.2	0.7	3.9–4	5–7.3
Primary production	4–4.8	9.4	0.3–3.5	2.8–20	2.5–10	0.8–3.2	1.5–4.3	18–20

The study by Principato et al. [64] emphasizes the crucial role of reducing food waste in creating a more sustainable food system. To support this, the United Nations Sustainable Development Goals have set a target to cut per capita food waste in half by 2030. The study highlights that employing digital tools for monitoring and managing food inventory in warehouses can lead to more sustainable food service operations within industrial settings. By analyzing longitudinal data from 2018 and 2019 collected from a major Italian food production company's cafeteria, the study found a decrease in both food loss and waste over time, which resulted in notable environmental benefits. The analysis also revealed significant differences between food lost during meal preparation and food left uneaten on employees' plates. The findings suggest the importance of implementing educational programs and using digital tools to share food-related data among employees, kitchen staff, and procurement teams to enhance awareness of behavioral practices. The study proposes new interventions at both the kitchen and customer levels to further address food waste, as illustrated in Figure 7, which depicts the food waste management routine applied in company warehouses.

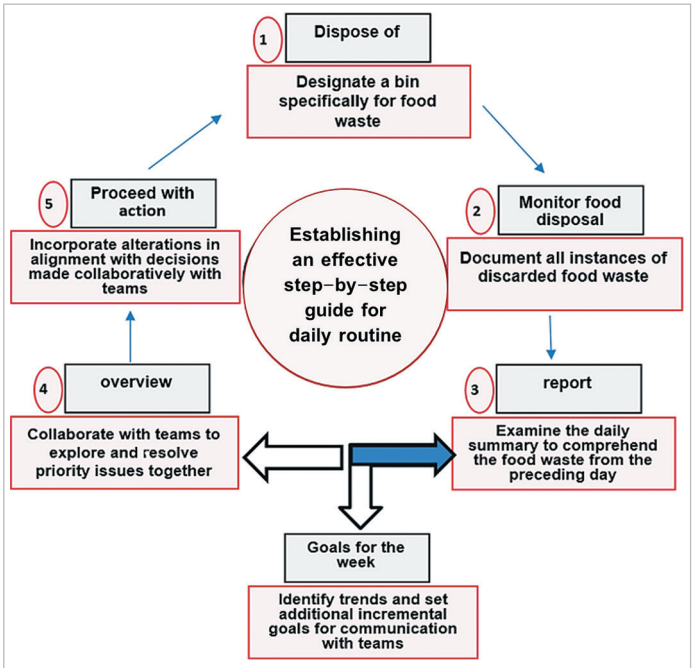

Figure 7. **Food waste management routine and its application in work company canteens**
Рисунок 7. **Обычный порядок менеджмента отходов и его применение в столовых производственных предприятий**

14. Sustainable food systems

Global progress towards food security and nutrition has been sluggish in many areas, with some experiencing regression. Given the changes in population composition, income, technology, climate, and other influential factors, pressures on food systems have become immense. When designing and implementing future interventions to achieve these goals, leveraging insightful knowledge to anticipate and prepare for various potential scenarios becomes highly necessary. Overcoming current and emerging challenges, as well as seizing available opportunities, requires continuous efforts to provide robust analyses. The latest insights from studies focus on three key aspects within the food system. Firstly, consumer demand and the changes it undergoes are significant factors

shaping the food system itself, alongside nutritional and environmental outcomes. Secondly, inequality in distribution and exchanges within the food system has been identified as a major challenge to address to counteract the negative health effects of the current food system. Thirdly, due to the COVID-19 crisis, efforts to enhance the resilience of the food system are escalating as it faces increasing exposure to multiple risks [65].

Lab-grown meat is a novel concept in food biotechnology that combines tissue engineering and cellular agriculture, involving the production of edible biomass through the cultivation of stem cells extracted from live animal muscles, using the self-organization method. This type of meat is considered an efficient, environmentally friendly, and safer method for general food safety and security. Additionally, it is deemed an ethical approach to meat production. To achieve any significant change in various social, economic, and environmental domains, marketing this technology is essential, and it must be cost-effective like traditional meats while being widely accepted by consumers. New challenges, such as increased meat demand due to population growth, can be met by establishing large-scale lab-grown meat production and enhancing its popularity. Industrial-scale adoption of lab-grown meat production will lead to achieving self-sufficiency in advanced economies [66].

Soybeans currently provide fats for human dietary needs mostly in the form of soybean oil, which is one of the primary plant oils. Soybean oil is generally considered healthy due to its relatively high content of alpha-linolenic fatty acid (n-3), and soybeans are legumes capable of nitrogen fixation directly from the atmosphere (using nitrogen-fixing bacteria). Peanut, like other legumes, has the ability to fix nitrogen in the soil, making it a sustainable option for fat production. Furthermore, tree-grown nuts such as almonds and walnuts have been proposed as significant sources of fats in sustainable diets due to their ability to sequester carbon and their potential use in agroforestry systems. However, it is worth noting that water availability poses a constraint on the cultivation of these nuts. Currently, peanuts play a vital role in providing fats in areas with low consumption. There is significant potential to increase peanut productivity in Africa. Tree-grown nuts offer another sustainable option but require sufficient water supply for success [67,68].

Milk is the second-largest source of fat globally. In many countries, dietary recommendations encourage the consumption of low-fat dairy products, leading to increased consumption of skimmed milk and other low-fat dairy products. However, unlike lard and tallow, the fats remaining from low-fat products like butter and cream are fully utilized in other food products [69]. The Organisation for Economic Co-operation and Development (OECD) and the Food and Agriculture Organization (FAO) anticipate an increase in butter demand in the future. Changes in future dietary recommendations may lead to increased demand for dairy fats, which could be detrimental from a sustainability perspective due to the greater environmental impact of dairy fats compared to plant oils. It is worth mentioning that dairy production results in a significant amount of beef as a joint product, so careful consideration must be given to the relationship between these two sources [70].

Legumes have been valued as vital nutrient sources in both human and animal diets for thousands of years, initially appreciated for their benefits to soil health and agricultural productivity. However, over time, their popularity as a human food declined due to various factors, including their perception as “poor man's meat”, occasional gastrointestinal issues, and longer preparation times compared to other plant foods. The rise in meat consumption in the latter half of the 20th century further reduced the role of legumes as a primary protein source. This decline was mirrored by a decrease in legume production, particularly in Europe, where legumes now occupy only a small fraction of agricultural land. Recently, there has been a renewed focus on sustainable dietary practices, leading to a revival of legume production and consumption in Europe. This resurgence is supported by policies and initiatives aimed at reintegrating legumes into modern diets. Today, legumes are being incorporated into a variety of products such as beverages, grain bars, bread, meat alternatives, snacks, and flours, and are featured in resource-conserving agricultural systems, including organic farming and intercropping. The increased production and consumption of legumes are seen as significant contributions to addressing global health and environmental challenges. Dried legumes offer excellent nutritional benefits, providing protein, amino acids, fatty acids, fiber, and carbohydrates with a low glycemic index. They also contribute to ecosystem services by reducing the need for synthetic fertilizers, promoting soil conservation, and enhancing agricultural biodiversity [71].

15. Utilizing food waste to achieve a circular economy

Achieving sustainable development through the concept of the circular bioeconomy can only be realized through the adoption of advanced techniques for valorizing food waste. Valorizing food waste opens up new avenues for economic growth, making waste a suitable raw material for biological processes to produce bioproducts from a biological source in a circular loop. Advanced techniques such as ultrasound-assisted extraction, microwave-assisted extraction, enzymatic reactors, and enzyme-assisted extraction alleviate global concerns resulting from poor food waste management. Decomposing food waste below zero level using advanced techniques transforms food waste into bioproducts such as biologically active compounds (antioxidants, pigments, sugars, polyphenols, etc.), biofuels (biodiesel, biogas, biohydrogen), and bioplastics. The circular bioeconomy allows for the best use of organic resources in the most productive and economical way. There are many advanced techniques and their combinations to enhance the value of food waste for premium goods, attracting significant interest from researchers. Food waste reclaims a variety of bioproducts that open up numerous opportunities in future bioeconomics. The circular bioeconomy is a fast-growing sector contributing to increased material and energy production with minimal environmental impact [72]. Anaerobic digestion (AD) is a well-established technology for converting food waste into biogas. Despite its effectiveness, a substantial amount of undigested material remains, highlighting the need for sustainable management and recycling of nutrient-rich anaerobically digested food waste (FWD). Closing the resource loop and achieving circular economy goals necessitate exploring the potential of FWD as a substrate for cultivating microalgae and producing biofuels. Emerging technologies, such as thermal conversion methods (pyrolysis and hydrothermal treatment), offer promising avenues for transforming FWD into value-added products like biochar and hydrochar, which have diverse applications. Additionally, hydrothermal carbonization represents an effective technique for managing high-moisture digestion, providing benefits such as enhanced water drainage, functional carbon materials, and solid fuel production. Integrating anaerobic digestion with subsequent valorization techniques can significantly advance circular economy objectives [73].

Waste management remains a critical environmental issue, and traditional methods such as landfilling are merely temporary fixes rather than solutions. Effective waste recycling is economically advantageous, reducing reliance on raw materials and minimizing environmental impact. Sustainable waste management practices, including those based on circular economy principles, are vital. For instance, universities can recycle food waste into fertilizers for campus gardens, thereby reducing waste and food costs, which aligns with circular economy goals. Addressing waste generation and minimizing food waste through innovative recycling methods can significantly reduce treatment costs and contribute to a cleaner environment [74].

The rapid population growth and lifestyle changes have led to a dramatic increase in food waste from industrial, agricultural, and household sources, with approximately one-third of produced food wasted annually. This not only depletes resources but also poses environmental and health risks. Food waste, rich in biologically active compounds such as polyphenols, dietary fibers, proteins, fats, vitamins, and minerals, can be transformed into value-added products. Advances in extracting these compounds are fostering new uses for food waste in sectors like food, bioplastics, bioenergy, and organic fertilizers. The development of innovative techniques for extracting and utilizing these compounds is crucial for reducing waste, conserving resources, and promoting sustainability. Emerging research emphasizes the potential of food waste in creating functional food components, cosmetics, and dietary supplements, and highlights the opportunities for incorporating waste-derived materials into active packaging and other industrial applications. Evaluating factors such as storage stability, practical application, and cost will be essential for enhancing the industry’s adaptability to these sustainable practices [75].

16. Waste recycling is the way to achieve food security and sustainable development

The concept of “shallow environmentalism” contends that there is a need to expand the resource base through the development of renewable resources, finding alternatives to non-renewable resources, and optimizing current resource use. It suggests that technological advancements will enable humans to control the land to meet their growing demands, with any emerging problems being addressed through technological advancement. It posits that the root causes of the environmental crisis, such as pollution, resource depletion, biodiversity loss, poverty, and inequality, stem from ignorance, greed, and incorrect environmental practices, rather than the values of the dominant modernity model centered around humans, its standards, institutions, or practices [56].

Ecological modernization considers the compatibility between the environment and development not only possible but beneficial for the business sector, suggesting that sustainable development can take a step

forward. It emphasizes that the industrial society will not only survive but can adapt well and fruitfully to environmental pressures. Pollution reflects inefficiency and thus adds further costs to the business sector, whereas working within cost, effectiveness, and efficiency boundaries [56].

Circular economy is defined as an organized approach to economic development and the triple dimension of sustainable development, a result of the application of the industrial revolution by reducing environmental accumulations that pose a threat to the environment through recycling until waste is fully exhausted and converted into new materials useful for consumers. Hence, researchers have become more interested in the circular economy as an alternative to the linear economy, which turns consumed materials into waste and leads to their accumulation in the environment. The main goal of the circular economy is to achieve economic prosperity [76]. There is currently a growing interest in manufacturing food products containing nutrients that enhance health, prevent nutrition-related disorders, improve sensory and natural characteristics, prevent spoilage and unwanted changes.

16.1. Benefiting from fish waste to achieve sustainable development

There are huge amounts of fish waste, including inedible parts such as skeletal structures, internal organs, heads, scales, and skin, as well as fish unsuitable for consumption and processing due to their color, size, type, and damage during handling and processing. These waste products are usually discarded or directly used as fertilizer. Due to the large quantities of waste and economic pressure, among other factors related to obtaining useful materials, a device has been designed to extract oils from fish waste using infrared radiation to utilize fish waste from carp (*Cyprinus carpio*) with its massive quantities, low cost, and high nutritional value [77]. The oil is used in margarine production and serves as feed for fish farms. The by-products of oil extraction are protein concentrates, which are used in fish farm feed and fertilizers, as all by-products are utilized in addition to the extracted oil. Fish waste oils can be used for human consumption purposes and animal feed by blending them with natural feed as they are a rich source of vitamins A and D. Alternatively, they can be used in linoleum sealing, detergent production, rubber, decorative materials, printing ink, cosmetics, and leather production [78].

Rustad [79] noted that approximately 20 million tons, equivalent to 25% of total fish production, are disregarded as by-products or waste, causing environmental pollution. However, these waste products can serve as a source of enzymes and fats [80,81,82]. The oil content in fish waste ranges from 1.4% to 40.1% [83], with fish oil being one of the best sources of essential fatty acids (omega-3) [84], which are among the most effective anti-inflammatory agents with minimal usage and no negative side effects compared to chemical medications that may be lethal [85].

16.2. Extracting hyaluronic acid from animal waste

The by-products of slaughterhouses can be utilized in biotechnology and polymer applications, given the thousands of tons produced from fish eyes, poultry heads, and other waste materials, which pose numerous environmental and health problems. They can be employed in the cosmetics, medical, pharmaceutical, and food industries [86]. An example of this is the extraction of pure hyaluronic acid from poultry waste, such as rooster combs, using cost-effective methods suitable for industrial production [87].

16.3. Using by-products of oil presses in preparing bread

Activating what is known as the circular economy and sustainable development involves maximizing the utilization of waste or by-products from oil mills, including sesame, flaxseed, anise, black cumin, coconut, and sunflower residues after oil extraction. These by-products contain important nutrients and natural antioxidants such as numerous minerals, vitamins, essential and non-essential amino acids, as well as saturated and unsaturated fatty acids, phenols and flavonoids. Addition of these by-products to various foods, such as bakery and meat products, can improve the nutritional and functional properties of the final products [88]. Dahdah et al. [89] demonstrated that partially replacing wheat flour with olive pomace enhanced the nutritional, functional, biological, and sensory qualities of bread while having minimal impact on its technological properties.

16.4. Using feather and wool waste to prepare antioxidant protein hydrolysates

Recent attention has been directed towards peptides resulting from protein degradation as an excellent source of natural antioxidants, replacing synthetic antioxidants that have negative effects on human health. It is possible to produce biologically active peptides from proteins that have various physiological functions in living organisms, such as antioxidants, antimicrobial agents, blood pressure and cholesterol-lowering agents, immune system enhancers, and metal chelators [90–91]. Due to the significant abundance of slaughterhouse residues, including chicken feathers and sheep wool, which are disposed of into the environment without being utilized and are unable to degrade, they are considered a source of environmental pollution. However, they can be used in the production of biopolymers, such as keratin, which has a potential for application in many fields. Keratin in various forms (powders, micro/nanoparticles, films, hydrogels, sponges, nanofibrous materials) can be applied for purification of air and water, drug delivery and packaging, as well as in production of animal feed and fertilizers [92].

16.5. Use of bioactive carotenoids extracted from shrimp shells as antioxidants in food systems

Recent scientific trends in the field of food science emphasize the utilization of functional properties of foods and their active components to make food ingredients that inhibit the growth of microorganisms and act as antioxidants [93]. The need to use astaxanthin as a natural antioxidant for food preservation arises in line with the advancement of modern manufacturing techniques in the food industry to meet increasing nutritional requirements and move away from artificial additives to ensure the human health aspect. There is an attempt to leverage marine biowaste, which is wasted in hundreds of tons, containing biologically active compounds crucial for food preservation [94]. Applied studies have been conducted to test the effectiveness of carotenoid compounds extracted from shrimp shells of *Penaeus semisulcatus, Penaeus japonicus* and *Exopalaemon styliferus* species obtained from local markets as antioxidants in sesame oil. The extract also contributed as a 1% antioxidant in sesame oil by stabilizing the values of peroxide and thiobarbituric acid [95].

16.6. Using onion, potato and lemon peels as antioxidants and including them in the manufacture of meat products

During food processing of fruits and vegetables, significant quantities of waste are generated, causing serious environmental issues. Therefore, it is necessary to recycle and utilize them [96]. The peels of these materials contain numerous active compounds, including polyphenolic compounds, which are natural antioxidants that prevent the formation of free radicals in the body. These important active compounds were obtained from potato, onion, lemon, and clementine peels [97,98,99,100]. The addition of plant peel extracts as functional components, antioxidants, and antimicrobial agents preserves food products, including meat and meat products, enhancing their oxidative stability, maintaining quality, prolonging shelf life, and obtaining natural and safe products. This approach replaces the addition of chemical and synthetic substances with toxic and harmful effects on consumer health, such as synthetic antioxidants, nitrates, and nitrites, which are added to stabilize the color of processed meat products and prolong their storage life [101].

17. Nanotechnology applications in achieving food security and sustainable development

17.1. Nanotechnology applications in food packaging

The issue of food security represents a fundamental problem in light of the linear increase in population numbers. Achieving food security and sustainable agricultural development requires the utilization of all modern technologies related to food and nutrition. Several studies have indicated that food production will be affected by numerous variables over the next two decades due to water issues, energy crises, rising prices, and unfavorable climate variations. Specialists may resort to using modern technologies, including nanotechnology, to address these needs. It is expected that such technologies will contribute to increasing food production globally. By the year 2040, nanotechnology is projected to be incorporated into the production of most food items, as it does not affect the chemical composition, taste, or texture of food products [102].

Applications of nanotechnology in the food industry include nanocapsules and nanoparticles, which are utilized to enhance food flavor, treat various plant sterols, and remove chemical substances and pathogens from food. Nanotechnology has become widely used in the manufacturing, packaging, and processing of food products [103], with an expected utilization that will be expanded across various industries in the coming years. The production of effective and intelligent packaging capable of extending the shelf life of food products is a significant goal for many companies involved in the production of food packaging materials. These packages are characterized by their ability to minimize the impact of changes in external environmental humidity and temperature on the contents through the fine pores they contain. Furthermore, such packaging can clearly indicate the potential contamination of consumed food [104].

Nanotechnology can contribute to the development of antibacterial and antifungal properties on the surfaces of packaging materials to inhibit the growth and spread of microorganisms in food. Additionally, it

can increase the sensitivity of these surfaces to any chemical changes that occur in the food substance, expressing them clearly. Currently, there are between 400–500 nanoproducts of food packaging materials available in the global markets, and it is anticipated that nanotechnology will be used in the production of approximately 25% of packaging materials on a commercial scale over the next two decades [105].

17.2. Improving the bioavailability of nutrients using nanotechnology

Nanotechnology refers to a collection of techniques that manipulate matter at the molecular and atomic levels, which are not visible under an ordinary microscope, with dimensions typically around 1/1000th the width of a human hair. What makes this technology promising is that food substances remain unchanged in their chemical composition, unlike genetic modification techniques. Nanotechnology works solely by reducing the size of food particles without altering the substance itself. By working on particles smaller than the food material, new properties such as electrical conductivity, elasticity, increased strength, color variation, and enhanced reactivity can emerge. These properties are not evident at the macroscopic or even microscopic levels of the material [106]. In recent years, human understanding of this technology has grown alongside the increasing capacity to find applications for sustainable development in the food manufacturing industry. However, further time is needed for commercial-scale application of this technology in food manufacturing [103].

There is a possibility that this technology will have a significant impact on the selection of suitable raw materials for manufacturing, and it may also unexpectedly alter the extent of food's effect on human body structure. For instance, German chemical laboratories like BASF produce nano-sized lycopene (a type of carotenoid pigment) as an additive for manufacturing fruit juices, cheeses, and margarine. Carotenoids are known antioxidants that convert into vitamin A in the body. BASF reports that the body absorbs carotenoids produced by nanotechnology more easily, and foods containing these manufactured carotenoids remain fresh for longer periods [107].

Furthermore, nanotechnology has been utilized in the Nutralease program in the Applied Chemistry department to develop compound liquids that transport nano-sized nutritional elements to the body's cells. These particles are emulsifying agents containing essential nutrients such as plant-based carotenoids and sterols. These liquids facilitate the easy entry of these elements into the bloodstream through the small intestine. These liquids can also be used to manufacture clear beverages free from impurities, loaded with these important nutrients processed using nanotechnology, and unaffected by heat treatments such as pasteurization [108].

One of the prominent benefits of this new technology is its ability to enhance the bioavailability of food substances. For example, in China, a nanotechnology company utilized particles smaller than 100 nanometers to release plant elements into green tea solutions, which would otherwise be inaccessible. This paved the way for various nano-enriched tea products rich in selenium, which helps absorb or attract free radicals that destroy cells, thereby reducing cholesterol and blood fat levels. The same Chinese company also applies nanotechnology to maximize the beneficial properties of coffee [109].

One of the applied research studies in this field involves extending the shelf life of pasteurized milk by adding Chitosan Nanoparticles (CNP), derived from chitosan through ionotropic gelation and sonication methods. It has been found that CNP compound at a concentration of 0.3% w/v inhibits the growth of *Bacillus cereus* vegetative cells in stored pasteurized milk at 5 °C, prolonging its shelf life from two weeks to 30 days. Additionally, it does not affect the physical and chemical properties of pasteurized milk, such as acidity and color [110].

18. Potential hazards and risks associated with nanotechnology

Nanotechnology, while promising, poses several potential hazards and risks that necessitate thorough investigation. The increased use of engineered nanoparticles (NPs) across various products raises concerns about their safety throughout their lifecycle. Key exposure routes include inhalation, dermal contact, and ingestion. Inhaled nanoparticles can deposit in the respiratory tract, potentially causing oxidative stress and inflammatory reactions, with some evidence linking them to tumor formation in rats under overload conditions. There is also concern about their ability to cross into the brain via the olfactory epithelium and their potential translocation into systemic circulation, although evidence on this is inconsistent [111].

Dermal exposure to nanoparticles, such as those in sunscreens, has not shown significant systemic absorption through intact skin. However, the adequacy of existing skin testing protocols is debated. Oral exposure to nanoparticles is utilized intentionally in food and pharmaceuticals, but the implications for systemic uptake and safety are still under evaluation [111].

Environmental concerns are also significant. The large-scale production of nanomaterials raises the risk of environmental release through various pathways. Current data on the bioaccumulation, bio-toxicity, and biodegradation of nanoparticles in environmental species are limited. Preliminary studies suggest that while some nanomaterials, like fullerenes, may exhibit toxicity to aquatic organisms, others, such as single-walled carbon nanotubes (SWNT), show limited bacterial toxicity. Thus, comprehensive, case-by-case assessments are needed to understand the environmental and health impacts fully. Despite these uncertainties, nanotechnology holds potential for environmental benefits, such as in bioremediation and enhancing renewable energy technologies, which could reduce dependence on fossil fuels [111,112].

19. Conclusion

In conclusion, sustainable agriculture emerges as a multifaceted approach that balances the production of food and agricultural products with broader economic, social, and environmental considerations. This review underscores the importance of sustainable practices in enhancing the quality of life for farmers and society at large. By addressing climate change, economic development, and social equity, sustainable agriculture provides a framework for achieving long-term agricultural viability. The environmental perspective emphasizes the need for processes that conserve natural resources, promote soil and water health, and protect biodiversity while minimizing reliance on harmful chemicals. Meanwhile, the social and economic dimensions highlight the necessity of meeting global food demands, supporting human rights, and fostering ethical treatment of animals. As this review illustrates, integrating these perspectives is crucial for developing effective, shared solutions that advance sustainability in agriculture. Continued exploration and application of sustainable practices are essential for addressing the complex challenges facing modern agriculture and ensuring a resilient and equitable food system.

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Conflict of interest	**Конфликт интересов**
The authors declare no conflict of interest.	Авторы заявляют об отсутствии конфликта интересов.