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*Review*

# Sustainable Agro-Food Systems for Addressing Climate Change and Food Security

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**Abstract:** Despite world food production keeping pace with population growth because of the Green Revolution, the United Nations (UN) State of Food Security and Nutrition in the World 2022 Report indicates that the number of people affected by hunger has increased to 828 million with 29.3% of the global population food insecure, and 22% of children under five years of age stunted. Many more have low-quality, unhealthy diets and micronutrient deficiencies leading to obesity, diabetes, and other diet-related non-communicable diseases. Additionally, current agro-food systems significantly impact the environment and the climate, including soil and water resources. Frequent natural disasters resulting from climate change, pandemics, and conflicts weaken food systems and exacerbate food insecurity worldwide. In this review, we outline the current knowledge in alternative agricultural practices for achieving sustainability as well as policies and practices that need to be implemented for an equitable distribution of resources and food for achieving several goals in the UN 2030 Agenda for Sustainable Development. According to the UN Intergovernmental Panel on Climate Change, animal husbandry, particularly ruminant meat and dairy, accounts for a significant proportion of agricultural greenhouse gas (GHG) emissions and land use but contributes only 18% of food energy. In contrast, plant-based foods, particularly perennial crops, have the lowest environmental impacts. Therefore, expanding the cultivation of perennials, particularly herbaceous perennials, to replace annual crops, fostering climate-smart food choices, implementing policies and subsidies favoring efficient production systems with low environmental impact, empowering women, and adopting modern biotechnological and digital solutions can help to transform global agro-food systems toward sustainability. There is growing evidence that food security and adequate nutrition for the global population can be achieved using climate-smart, sustainable agricultural practices, while reducing negative environmental impacts of agriculture, including GHG emissions.

**Keywords:** agriculture; biotechnology; development; emissions; environment; farming; nutrition

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## 1. Introduction to Agro-Food Systems

Agriculture has been a crucial part of human civilization since its emergence and continues to play a significant role in our lives. Approximately 80% of the population in developing countries reside in rural areas, where agriculture is the mainstay of livelihood [1]. Agriculture encompasses cultivating plants, animals, and fungi to produce food/feed, fiber, and energy products, and it employs more than 3 billion people worldwide [2]. Food and agriculture are part of a broader social, economic, cultural, and environmental system and are a vital component of the global economy and its driving force [3,4]. As more people move into urban areas, an inevitable change in lifestyle is also occurring; diets change, and land use patterns and agricultural production are intensified. As a result, the agricultural industry has become an interwoven global activity that produces and exports commodities worldwide, providing food to city dwellers who constitute more than half the world's population [5,6].

The Green Revolution, with its high-input and technology-dependent approach, was able to feed the growing world population in the last several decades. It ensured food security and helped to reduce food imports, particularly in developing nations. However, long-term impacts are now evident: degraded soils, reduced groundwater levels, contaminated water bodies, and reduced biodiversity. High crop yields cannot be sustained without increased fertilizer use. Increasing fertilizer and other input costs and fragmentation of land holdings resulting in reduced farm incomes push many farmers towards non-farm economic activities. Climate change science has shown that intensive agricultural systems brought about by the Green Revolution are both a contributor to and a victim of climate change [7–9].

The agro-food sector will become more critical in future decades. It connects strongly with the natural environment and affects every part of our lives and economies, spanning society, politics, culture, employment, faith, communities, and families. At the same time, it is influenced by these aforesaid factors [10]. The contemporary agro-food system includes the infrastructure and processes connected with the planting, harvesting, processing, packing, transporting, selling, consuming, and disposing of food. [11,12]. Some 3 billion people are involved in this process, providing labor, management, research and development, and education [2].

With increased awareness of environmental challenges in the current agro-food systems in recent years, much research has gone into different aspects of managing various components of agro-food systems more sustainably toward reducing the carbon footprint of our food. This research encompasses cultivar development, cultivation methods and systems, improved harvesting, storage, processing, packaging, transport, and food waste management. On the other hand, food insecurity and disparity in food availability, even in countries producing sufficient food, even in excess for export, has attracted much attention from researchers working on the socio-political aspects of agro-food systems. Thus, we find that most of the research is compartmentalized in specific areas, including plant genetics, crop and animal sciences, soil fertility and fertilizer management, food science, social and political studies. In this review, we attempt to address some of the key biological, physical, and social aspects of agro-food systems to better understand the complexities in our attempts to make them more sustainable, environment-friendly, equitable, and fair.

## 2. Impact of Climate Change on Agriculture and Food Security

The primary changes to the earth's atmosphere can be due to either natural changes or anthropogenic activities. Significantly, anthropogenic activities, such as pollution, urbanization, industrialization, agricultural activities, change in land use patterns, and deforestation leads to an increase in the atmospheric concentrations of water vapor and carbon dioxide ($CO_2$) and all the other greenhouse gases (GHGs), further accelerating the rate of climate change. An increased level of GHGs ($CO_2$, water vapor, nitrous oxide [$N_2O$], methane [$CH_4$], sulfur hexafluoride ($SF_6$), hydrofluorocarbons, and perfluorocarbons) due to anthropogenic activities are gradually contributing to the overall increase in the Earth's temperature, thereby leading to global warming [13,14]. The GHGs are all very good at absorbing infrared radiation energy. The Earth's surface absorbs a certain percentage of incoming solar radiation. However, the earth does not re-radiate heat in the visible part of the spectrum, but as long waves in the infrared range, GHGs can trap that radiation in the atmosphere resulting in the greenhouse effect [15,16].

### *2.1. Agriculture Needs to Transform to Mitigate Climate Change*

A quarter of global warming is due to $CH_4$ and $N_2O$, arising from fossil fuel burning and agriculture (Figure 1). Agriculture currently contributes approximately 12% of global GHG emissions [13,16]. $CH_4$, which is 25 times more harmful to the climate than $CO_2$, is produced by the activity of micro-organisms in the soil. In the circular economy of organic farming, it is mainly taken up again by other bacteria, and GHG emissions are up to 50% lower than in conventional agriculture [17]. Moreover, spreading sewage sludge also releases $CH_4$ [15,16]. Approximately 37% of the $CH_4$ emitted worldwide comes directly or indirectly from ruminant livestock. $N_2O$ is approximately 300 times more harmful to the climate than $CO_2$ and is released from artificial fertilizers [18]. $CO_2$ is also produced by the long transport routes involved in food distribution (Figure 2). In agriculture, however, the significant emissions are not $CO_2$, but $CH_4$, which is produced mainly in animal husbandry, and $N_2O$ is produced by nitrogen fertilizers [19].

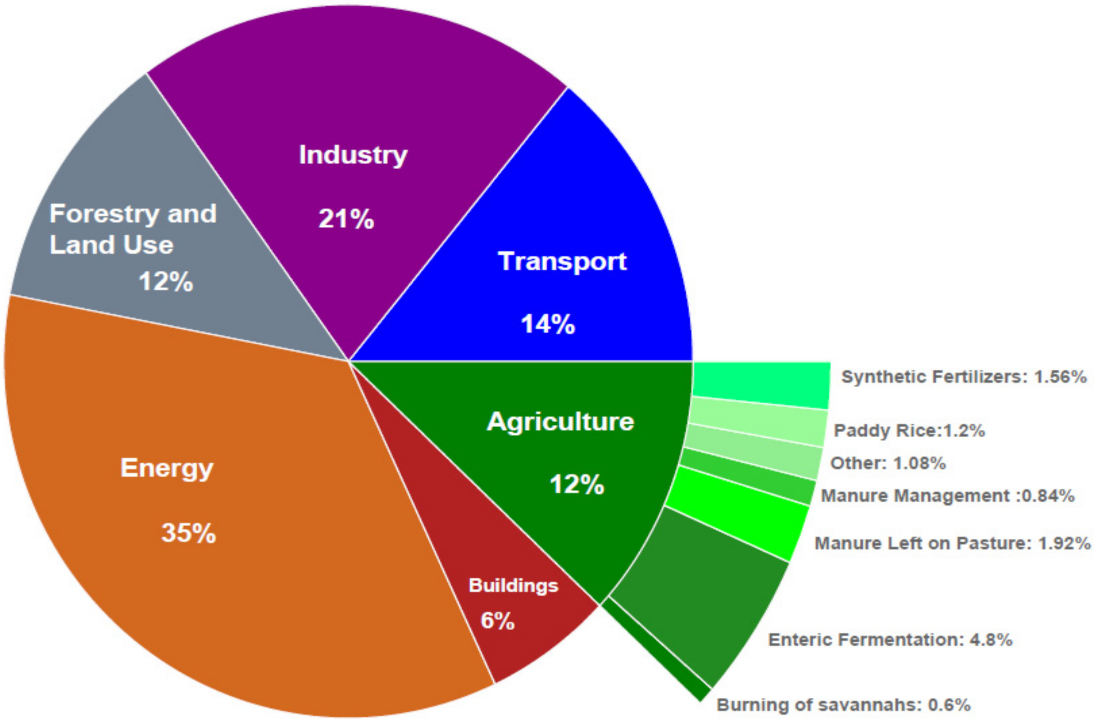


**Figure 1.** Contributing factors to greenhouse gas (GHG) emissions. Agriculture, forestry, and land use currently contribute approximately 24% of global GHG emissions; half of this is from agriculture, and the other half is from forestry and other forms of land use. The figure was created using data from the International Fund for Agricultural Development (IFAD) report [20].

The production of plant-based foods contributed $5109 \pm 1436\,TgCO_2eq\,yr^{-1}$; 29% of total emissions in agriculture, consisting of 19% $CO_2$, 6% $CH_4$, and 4% $N_2O$. Paddy rice is responsible for most of the GHG emissions from crop plants, followed by wheat, sugarcane, maize, and cassava. On the other hand, animal husbandry results in higher emissions ($9796 \pm 850\,TgCO_2eq\,yr^{-1}$), contributing 57% of the total, consisting of 30% $CO_2$ and 20% $CH_4$, and 7% $N_2O$ emissions. Beef production is responsible for the most GHG emissions in animal husbandry, followed by cow milk, pork, and chicken meat (Figure 3) [21]. Thus, the choice of our source of protein and even staple food has a powerful effect on GHG emissions. The GHG emissions from agriculture grew 1.6% annually after 2000 and reached 9.3 billion tons of $CO_2$ equivalents by 2018, with livestock activities and synthetic fertilizers being the most significant contributors [19].

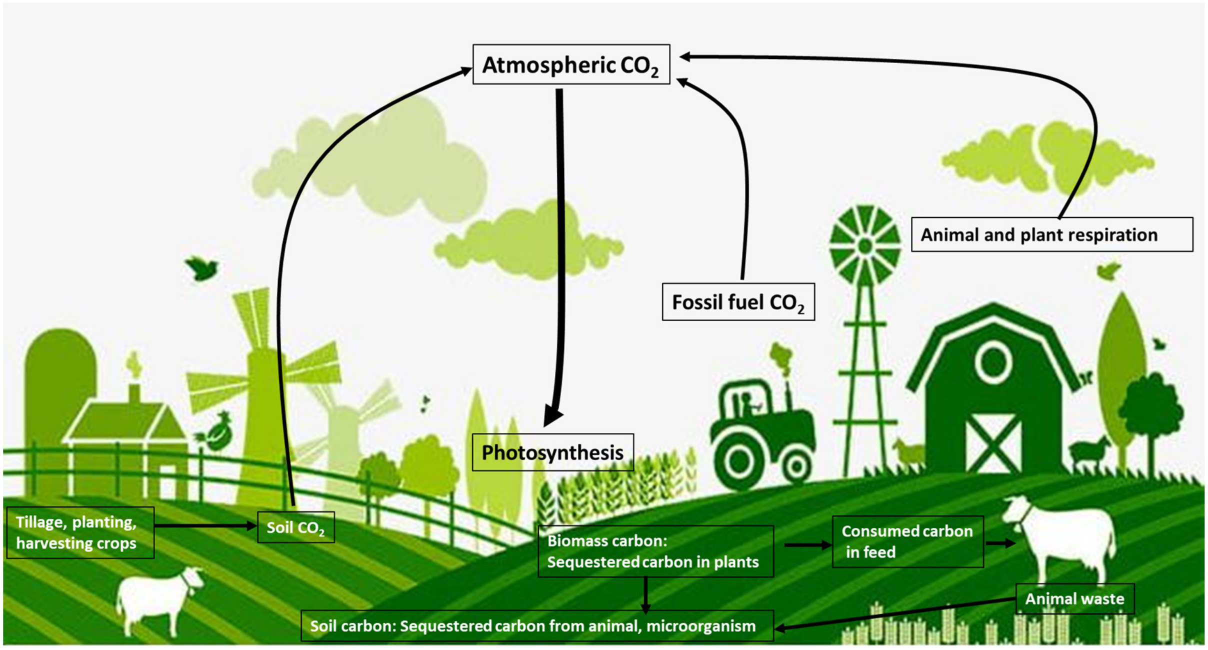


**Figure 2.** Carbon cycle demonstrating both additions to and removal of atmospheric carbon dioxide ($CO_2$). $CO_2$ is also produced by the long transport routes involved in food distribution.

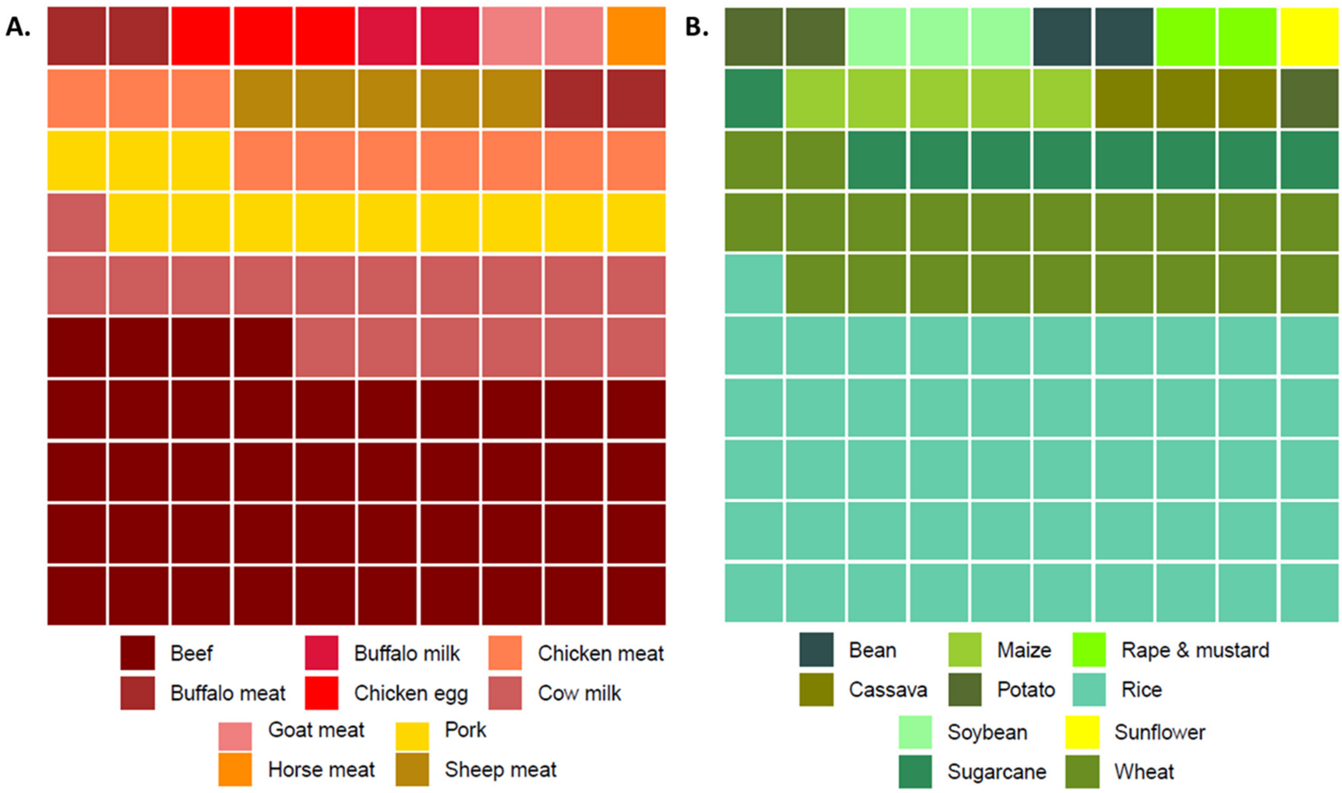


**Figure 3.** Top-contributing commodities for greenhouse gas (GHG) emissions by (**A**). animal-based foods and (**B**). plant-based foods. The figure was created using data from the study of Xu et al., 2021 [21]). The waffle plot shows the percentage of GHG emissions of the top ten plant-based and animal-based food commodities, where one tile represents 1%.

The earth's temperature has increased over the last few decades in parallel with the increased GHG emissions, mainly $CO_2$ (Figure 4), the primary driver of climate change. Despite pledges at world summits by the largest emitters of GHGs to reduce emissions, the amount keeps increasing each year, except in 2008, during the economic downturn [22]. A few countries are responsible for most emissions, with three countries accounting for 30% of total agricultural emissions [19,23].

The global annual mean $CO_2$ level in 2019 was 410 parts per million (ppm), marking a 47.5% increase from the pre-industrial concentration of 278 ppm in 1750. This new record represents an increase of 85 ppm in the last 55 years [24], at approximately 1.55–2 ppm $CO_2$ per year. Even more alarming is that $CO_2$ stays in the atmosphere for hundreds or thousands of years. This milestone is a wake-up call that our response to climate change needs to match the persistent rise in $CO_2$ [24]. Thus, cumulative emissions of $CO_2$ will largely determine the speed and magnitude of global warming during this century and beyond. The major crisis facing humanity and life on Earth is that doubling $CO_2$ levels will lead to a temperature rise of 2.6–4.1 °C [25]. Nevertheless, the Intergovernmental Panel on Climate Change and the United Nations Framework Convention on Climate Change are guided by the optimistic hope of limiting warming to a 1.5–2 °C rise by 2100.

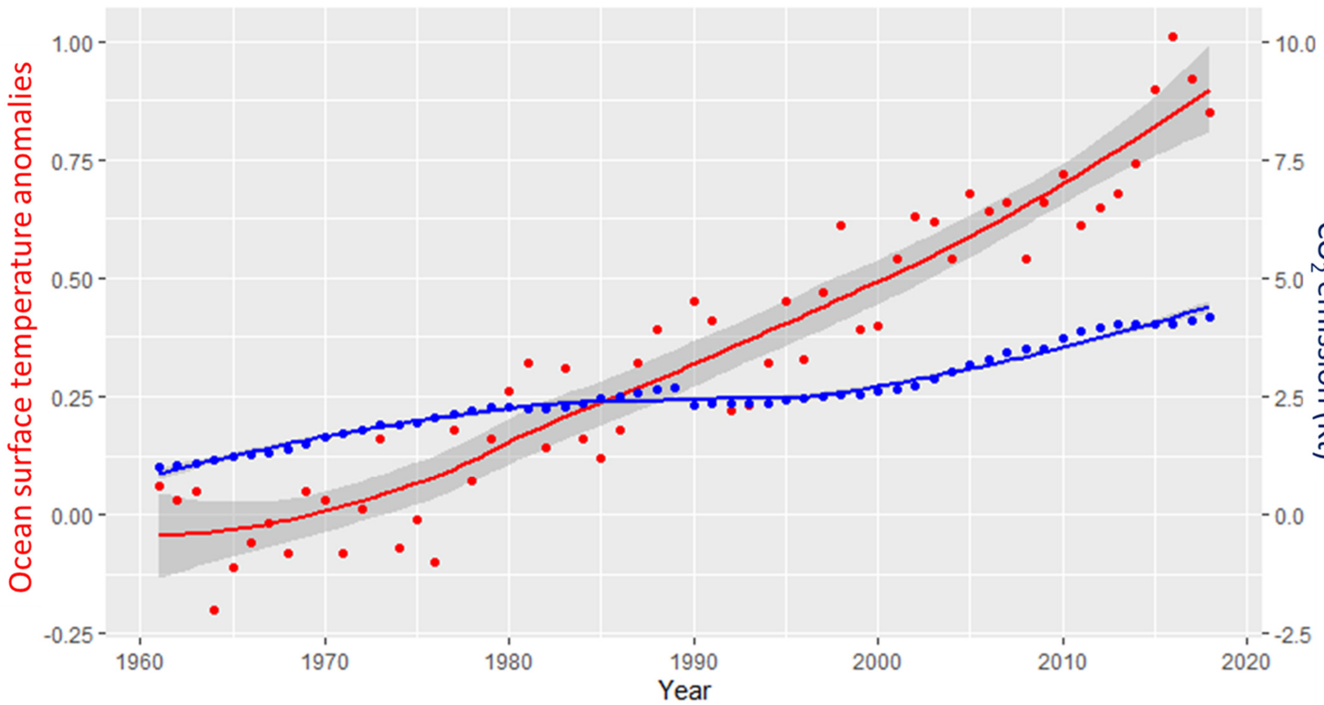


**Figure 4.** Annual atmospheric carbon dioxide ($CO_2$) emissions (blue) and annual ocean surface temperature anomalies (red) over the last six decades. Annual anomalies in ocean surface temperature data were retrieved from the National Oceanic and Atmospheric Administration [26], and $CO_2$ emissions data were retrieved from the Global Carbon Project Source link [19].

Climate change is a significant threat on the horizon, while we are presently dealing with the devastating socioeconomic consequences of the COVID-19 pandemic and the Ukraine conflict [27]. As a result, acute food insecurity globally continues to escalate, with 193 million people facing crisis or worse levels (Integrated Phase Classification (IPC) Phase 3 or above) of acute food insecurity across 53 countries or territories in 2021, an increase of 40 million compared with 2021. Another 49 million people in 46 countries are in IPC Phase 5, at risk of famine or famine-like conditions [28]. However, hunger rose because of poverty, a growing population, disease, conflict, and climate change even before the pandemic. Furthermore, extreme weather events resulting from climate change jeopardize global harvests and magnify food systems' challenges [29]. Therefore, strategic actions by governments are needed to build resilient food systems with intelligent ways to produce, distribute, consume, and dispose of food.

### *2.2. Water, Land, Soil, and Agriculture Are Intricately Woven Together*

Since the 1960s, world grain production has achieved unprecedented growth. World cereal production increased by 430%, from 6.8 billion metric tons in 1961 to 29.5 billion metric tons by 2018. While in the same period, the world population grew by 260%, from 3 billion to 8 billion, and agricultural land use increased by 134%, from 386 million sq. km to 510 sq. km. Notably, $CO_2$ emissions increased by 420%, from 76 Gt to 319 Gt (Figure 5). Further, $CO_2$ emissions positively correlated with agricultural land use, cereal production, population growth (Figure 5), and gross domestic product [30].

The current global population of 7.7 billion is expected to reach 9.7 billion by 2050 and 11 billion by 2100. Along with China, developing countries account for almost 85% of the world population [31]. Global agricultural production has to increase by approximately 60–70% from the current levels to meet the increased food demand in 2050 [32,33]. Increasing economic growth and income levels in emerging nations drive consumers to consume more animal proteins and dairy products. This involves generating more feed for animals in intensive-feeding systems—animals are inefficient feed converters. Therefore, improving the amount of arable land is the fundamental solution to boosting food production. However, this development may come at a high cost, such as deforestation, which causes severe ecological disruptions and releases more carbon held in soils into the sky. Over the last 40 years, one-third of the world's arable land has been endangered by erosion, saltwater incursions, and contaminants that degrade soil health and biological production [34,35]. As most fertile land is already under crop production, expansion of arable land will be possible only in some regions.

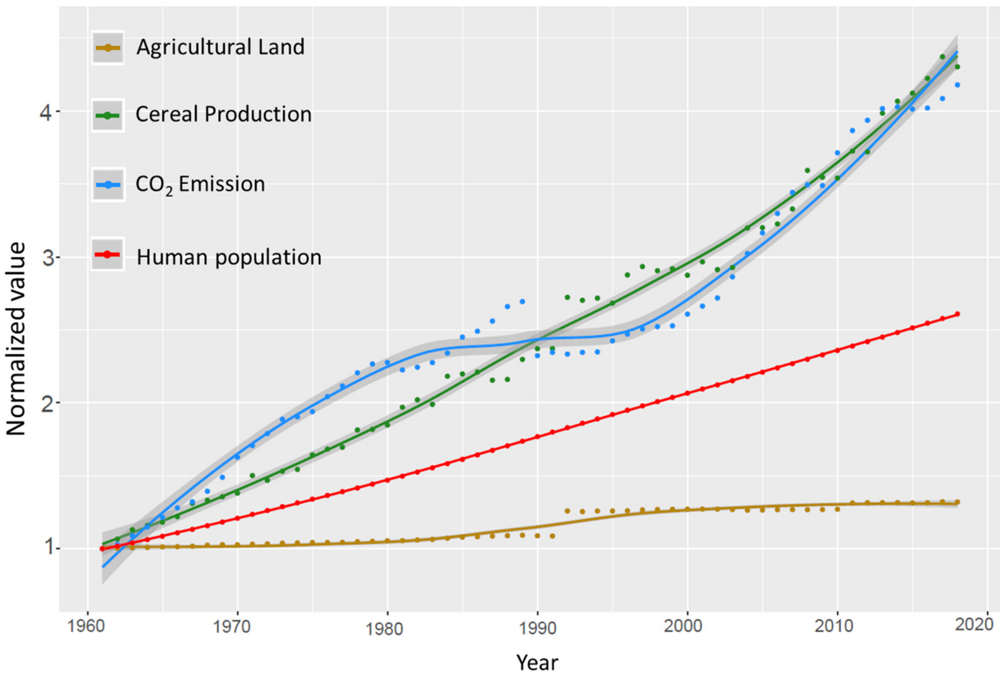


**Figure 5.** Global agricultural land use, cereal production, carbon dioxide ($CO_2$) emissions, and population data over the period 1961–2018 normalized to a value of unity in 1961, showing the positive relationship between cereal production and population growth with $CO_2$ emissions. Produced using freely available data from the World Bank data bank [36].

Climate change will significantly and profoundly impact the planet's soils and water, which in turn will adversely affect food production. Soils are vital in storing carbon, buffering the climate, and supporting plant life. As the earth's climate changes, the soil is vulnerable to degradation by increased temperatures or fluctuations in precipitation [32,37,38], making water supplies more scarce. With increased heat, there is more evapotranspiration and less rainfall to replenish soil moisture, resulting in an increase in dust storms, salinization of croplands, and desertification. These soil changes can make it even more difficult for plants to access sufficient nutrients for growth. Such unpredictable weather conditions will also lead to decreased crop productivity due to interference with plant-growth processes caused by drought, heat stress, flooding, and pests and diseases [32,38,39]. This is already evident in different parts of the world [37–41].

$CO_2$ emissions from agricultural soils comprise complex processes and correlate with precipitation, temperature, and soil moisture. Soil tillage also greatly influences $CO_2$ emissions. The deeper the soil is plowed, the more $CO_2$ it releases. However, some studies show less influence by tillage and demonstrate a strong relationship between soil temperature and daytime $CO_2$ emissions [42]. A high correlation between soil moisture content and $CO_2$ emissions has also been shown [43]. The decomposition of organic matter and soil respiration are more intense when the temperature is moderate (approximately 25 °C) and soil moisture is between 60% and 80% of the maximum retention capacity [44,45]. Indeed, moisture is a crucial factor in the activity of soil biota that breaks down organic matter, the process by which $CO_2$ is released.

### 2.3. Agriculture and Nutrition in a Changing Climate

In 2012, the World Health Assembly (WHA) Resolution 65.6 endorsed a comprehensive maternal, infant, and young child nutrition plan for implementation. Six global nutrition targets were specified, targeting 2.2 of the SDGs to "end all forms of malnutrition" [46–48]. To align with the 2030 SDG agenda, the WHA targets were extended to 2030 [49]. In addition, they included a target to halt the rise in adult obesity and reduce the risk of noncommunicable disease mortality [50]. Approximately 690 million people, or 8.9% of the global population, are undernourished [51], and the diets of over two-thirds of the world's population lack one or more essential minerals [52]. Asia (381 million) and Africa (250 million) have the most malnourished, followed by Latin America and the Caribbean (48 million). Furthermore, according to the Joint Malnutrition Estimate 2021, stunting (low height for a child's weight) has affected 149.2 million (22%) of all children under five years of age [53].

Unfortunately, climate change makes food less nutritious when crops are exposed to $CO_2$ at levels predicted for 2050. At these $CO_2$ levels, the plants lose as much as 10% of their zinc, 5% of iron, and 8% of protein content, making it challenging to address world malnutrition [54,55]. In addition, recent studies have shown that warming soil temperature can lead to yield reduction and increased arsenic levels in rice grain [56,57]. Nevertheless, through agronomic and genetic approaches, the bioavailability of mineral elements in our food crops is being successfully improved.

### 2.4. Measures of Food Security and Food Security Indicators

Food security is an indicator driver of inclusive economic growth and sustainable development. In the new definition of food security, quantitative security has been expanded to include the qualitative aspect. Although the two concepts are complementary, analysts keep them separate when they speak of quantitative and qualitative food security [58,59]. Therefore, food security must be viewed against the complex socio-economic background and is closely linked to poverty alleviation and economic growth.

In a changing climate scenario, food security, preservation of biodiversity, and resource effectiveness and efficiency are seen as central challenges of the 21st century [60]. Access to food must be possible both physically and economically, and nutritional needs and food preferences must be considered. Although a variety of individual or composite indicators of food security have been developed and used, there is general confusion regarding which dimensions (availability, access, utilization, or stability), levels (from global to individual), or components (quantity, quality, safety, cultural acceptability, and preferences) of food security these indicators are meant to reflect [61].

There are four dimensions of food security according to Burchi and De Muro (2016) [58]: food availability, food access, utilization, and stability. Food security measurements that have been developed include:

(1) Dietary diversity and food frequency:
  (i) Food Consumption Score;
  (ii) Household Dietary Diversity Scale;
  (iii) Spending on food; and
  (iv) Undernourishment [62,63].

(2) Consumption behaviors:
  (i) Coping Strategy Index;
  (ii) Reduced Coping Strategy Index;
  (iii) Household Food Insecurity and Access Scale;
  (iv) The Household Hunger Scale; and
  (v) Self-assessed measure of food security [64].

### *2.5. Climate Change and Food Security*

The right to adequate food was part of the 1948 *Universal Declaration of Human Rights* [65]. Against the background of famines in India, Bangladesh, the Sahel zone, and the explosion in food prices on international markets, the FAO defined food security in 1974 as the ability to have an adequate amount of staple food at all times to satisfy consumption and compensate for fluctuations in production and price [60]. Four broad concepts fit food security's definition: food availability, food access, utilization, and sustainability. The definition of food security was adopted at the World Food Summit in 1996: "*Food security exists when all people, at all times, have physical and economic access to sufficient safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life*" [66].

The State of Food Security and Nutrition in the World (SOFI), a report jointly published by five UN bodies, had already put the world on notice that the food security of millions—many children among them—is at stake [51]. In the first global assessment of the pandemic era, SOFI states, "Unfortunately, the pandemic continues to expose weaknesses in our food systems, which threaten the lives and livelihoods of people around the world." Thus, it will take a tremendous effort for the world to honor its pledge to end hunger by 2030 [51].

Despite doubling the world's population, it was possible to increase the amount of food per capita from 2200 Kcal/person/day in 1960 to more than 2800 Kcal/person/day by 2009 [67,68]. Although enough food is produced today to feed everyone living on this planet, it is not distributed evenly. A fairer food distribution worldwide is primarily a matter of political will and international solidarity.

Approximately 2 billion people were already at risk of moderate to severe food insecurity when the COVID-19 pandemic, followed by the start of the Ukraine conflict [27]. These have further escalated the challenge to achieve the SDG on 'zero hunger'; WHO warns that the situation can worsen as experts predict it will take longer before the impact of these events diminishes [51]. Loss of incomes, disruption in food supply chains, and social protection have worsened and have resulted in significant food price fluctuations [69,70], leading to wastage as demand drops. Poor farmers with inadequate infrastructure to store food lost their produce and income [71]. The countries with greater food insecurity were worse affected [72]. In addition, food production cycles that relied on migrant labor were affected due to travel restrictions and the closing down of work facilities to contain the outbreak [73]. Malnutrition and overnutrition cause the immune system to weaken, making people vulnerable to COVID-19 and creating a vicious cycle of illness and hunger [74]. Although efforts are being made to reverse these negative trends, even the UN Food Systems Summit held in 2021 seems to follow a trajectory in which efforts to govern global food systems in the public interest have been subverted to maintain colonial and corporate forms of control [75].

Food price increases due to the Russia-Ukraine conflict also jeopardize food security worldwide. Russia and Ukraine, called the 'breadbasket of Europe,' are top producers and exporters of several important grains and account for 29% of global wheat exports and 62% of sunflower oil. This war is exacerbating food price inflation in emerging markets and developing economies and is impacting some of the poorest and most vulnerable countries. According to the FAO, 26 countries rely on Ukraine and Russia for at least 50% of their wheat imports. These include countries in Africa's Sahel region, where 6 million children are malnourished, and 16 million people in urban areas are at risk of food insecurity [76–78].

## 3. Meeting Food Demand in the Face of Climate Change

### *3.1. Influence of Political Stability and Land Use Practices on Food Security*

Food security is a highly complex phenomenon that depends on social, cultural, and political systems and environmental factors, such as land topography and location, weather, soil conditions, and water availability [79–81]. However, the availability of plentiful food in a particular country or throughout the world does not guarantee that people will have access to adequate food supplies [79,82], as the factors mentioned earlier play a significant role in determining food security for individuals, families, and communities.

Food distribution systems are primarily shaped by political and economic forces and can facilitate or prevent food from getting to the most needed [75,79]. Thus, food availability does not necessarily address the problem of accessibility to food; famines occur—and have occurred—in countries where food is readily available and plentiful. Historically, significant malnutrition and famines have been caused by the disruption of food supplies through wars, civil strife, and poor economic policies and management. Additionally, higher food prices often generate political unrest and influence political stability even in countries where dissent is firmly repressed. Thus, food security and political stability are often mutually dependent and reinforcing.

Governments and institutions in fragile regions often lack the political and institutional capacity and desire to effectively implement measures that halt deforestation for land expansion, even when external programs provide economic incentives [83,84]. Incentives targeted at local and regional scales than national governments might be more effective, especially when combined with measures for securing land tenure for small-scale farmers, women, and indigenous communities [85,86]. For instance, in many countries where forests are "a property of the state", governments allocate large forested areas to agribusiness and other large-scale actors, potentially perpetuating unsustainable agricultural practices, land expansion, deforestation, and food insecurity at the household level [86].

### *3.2. Promoting Equity and Social Integrity*

Women comprise most smallholder farmers and food producers [87]. However, female farmers face structural, gendered disadvantages in land rights, access to technology, and social capital investment. A 45-country survey found that COVID-19 has created a food insecurity crisis that negatively affects a cross-section of women in smallholder farming and food production [88]. Any rise in food prices, job losses, higher home care duties, and less opportunity for women can lead to long-term gender inequity [89,90]. Therefore, it is essential to understand how the pandemic affects food security and agriculture more broadly to ensure optimal gender-sensitive social protection responses.

Unequal access to education and economic opportunity leaves women without much power to make decisions about food at home [91]. When women participate in household decisions, they produce and earn more, and family income increases by 20% [92]. Ensuring that girls can go to school and that women receive the chance to make a livable income increases their ability to make better nutritional choices for themselves, their families, and the community [93–95]. Agricultural credit, for instance, is critical for farmers to manage the seasonality of agricultural income and expenditures and invest in technologies and long-term farm improvements [96]. A strong link exists between increasing women's land rights and poverty reduction. Land rights can also be critical in rural households seeking economic migration [97]. Funding women farmers, electing women leaders, promoting equal education for girls, providing access to maternal and child health care, and ending harmful practices, such as child marriage could empower women and girls to fight hunger [98].

Land tenure refers to rules, norms, and institutions that govern how, when, and where people access land or are excluded from this access. Land rights, affected by these tenure rules and practices, regulate how people access, manage, and benefit from land under different tenure arrangements. Consequently, land rights significantly influence women's ability to decide over land and their security of tenure [99–101]. Women have less access to credit than men and less control over financial resources. For example, African women access only 1% of available credit in the agricultural sector because they often do not have the necessary collateral [102].

Further, only 10% of rural women own the land they cultivate in North, West, and Central Africa and in the Middle East [103]. This lack of credit and land ownership limits their ability to purchase agricultural tools, seeds, fertilizer, or hire labor that could increase production. Applying gender transformative approaches allows for identification of the barriers to recognizing women's land rights and the mechanisms to enhance their exercise of rights [104–106].

The United Nations (UNs) SDG 5 calls for equal rights for women in terms of economic resources, ownership and control of land, and their access to resources [49]. However, women in many countries continue to be disadvantaged by lack of recognition and insecure rights to land and resources and by exclusion from decision-making and governance systems from local to national levels. These barriers include inadequate legal frameworks, ineffective policy implementation at local and national levels, and discriminatory norms and practices at institutional and community levels, including social and religious practices [107,108]. If these barriers are not recognized and proactively addressed, investments and development initiatives in the agricultural sector can exacerbate gender inequalities. These inequalities can be overcome by identifying factors that enable and catalyze transformation to achieve a more equitable involvement of women and girls in decision-making, control of resources, and control of their labor and future [105].

### *3.3. Economic Access to Food*

Food prices have risen at 2% and 3% annually since 2001 [109]. In the short term, many factors, such as supply and demand, weather, disease outbreaks, war, and natural disasters, affect food prices, making them volatile. However, in the long term, five underlying forces tend to drive up food prices: high oil prices, climate change, government subsidies, World Trade Organization (WTO) limits on stockpiles, and relying on animal-based products. Oil by-products are a significant component of fertilizers, and high fuel prices also raise their shipping costs [110]. Government subsidies can also affect food prices. For example, the US government subsidizes corn for biofuels by taking corn out of the food supply and raising prices. In 2000, only 6% of the US corn crop was used for ethanol production. This proportion has now increased to 37% [109]. The US, the European Union, and some developing countries heavily subsidize their agricultural industries. As a result, farmers in those countries receive an unfair trade advantage. The WTO limits stockpiling to lower this edge. However, it also reduces the amount of food available in a shortage, increasing food price volatility [111]. Meat consumption takes away land for grain production to feed the animals that could have been planted with crops for human consumption. Higher demand for meat means higher grain prices.

There has been an 82% increase in acute food insecurity compared with the pre-COVID period. Moreover, since the COVID-19 pandemic in January 2020, food prices have risen faster than the overall consumer price index across all world regions, with 51.1 million people food insecure in Southeast Asia and the Pacific alone [112].

### *3.4. Food Consumption Habits*

Changing from meat to plant-based foods automatically leads to a reduction in the burden on the climate. However, the higher energy consumption and the higher $CO_2$ emissions from animal foods pollute the climate [19,21]. Both in liquid and solid forms, $CH_4$ and $N_2O$ are produced during animal manure storage. Ruminants, such as cattle, buffalo, sheep, and goats, also emit $CH_4$, which is produced by the microbial breakdown of food in the rumen [113]. Therefore, our current food systems represent one of the most significant challenges for our planet and the continued existence of humanity on Earth [24].

Livestock farming provides only 18% of the total food energy but consumes 83% of the agricultural land and is responsible for 60% of the GHG emissions in agriculture [114,115]. Therefore, foregoing or significantly reducing meat and dairy from the diet is the most significant individual contribution that one can make to stabilize the climate. For example, forests in Central and South America are cleared for cattle farming, causing 12 times more GHG emissions and consuming 50 times more land than keeping cattle on natural pastures. If meat and dairy products are eliminated from our diet, the land can be used for cropping plant-based foods and reforestation; the planet will be much greener. The switch even to a plant-rich, Mediterranean diet, containing only a quarter of meat, will save half of the fertilizers and reduce other climate-active gases [114].

## **4. Sustainable Agricultural Development for Food Security and Nutrition**

### *4.1. Current Trends in Food Security and Nutrition*

As of 2017, satisfactory progress has been made towards SDG target 2.1 (universal access to safe and nutritious food) and SDG target 2.2 (end all forms of malnutrition). The Prevalence of Undernourishment (PoU) is defined as the percentage of the population whose consumption falls below the Minimum Dietary Energy Requirement and is one of the indicators for the prevalence of undernourishment (SDG 2.1.1). PoU increased to 9.9% in 2020 compared with 8.4% in 2019, and this increase has occurred across all the regions around the globe. This may compromise the SDG target of ending hunger by 2030.

The COVID-19 pandemic affected each food system's drivers, thereby aggravating food insecurity. Government measures to counter the COVID-19 spread have dealt devastating blows to global food security and nutrition. The supply-side of food systems has been affected by border closures, travel restrictions, and quarantine measures. These disruptions to the supply chains have limited the access of large sections of the population to nutritious food. Such measures have resulted in an urgent humanitarian crisis in 55 countries. The economic shocks were the critical drivers of food insecurity in 17 countries and affected approximately 40 million people. Before the pandemic in 2019, only eight countries had food insecurity due to economic shocks [51].

Apart from the factors triggered by the COVID-19 pandemic, climatic and environmental factors also affected food security across the continents [112]. For example, locust outbreaks in East Africa and South Asia [116,117]; hurricanes Eta and Iota requiring emergency response due to acute food insecurity in Central American countries [118,119]; droughts, cyclones, and seasonal flooding in South Sudan and the Democratic Republic of Congo [120,121] were significant. Developed economies were not spared either by the effects of climate change. Filkov et al. (2020) estimate that it will take many years to restore the economy and infrastructure in New South Wales, Victoria, and South Australia affected by the recent wildfires, including the recovery of animal and vegetation biodiversity [122]. The estimates of the economic cost of 2018 wildfires in the western US totaled US$148.5 billion, with $27.7 billion (19%) in capital losses, $32.2 billion (22%) in health costs, and $88.6 billion (59%) in indirect losses [123]. One of the direct influences of these events has been on food security.

Despite some improvements, most nations have a long way to go towards achieving the agreed global nutrition targets for reducing child malnutrition, improving exclusive breastfeeding rates, and reducing anemia in women of reproductive age [54,124–126].

Moreover, shifting to healthy diets with sustainability considerations with lower "hidden costs" can reduce health and climate change costs by 2030 [51].

Reaching the 2025 and 2030 global nutrition targets remains a challenge. An estimated 22% of children under 5 years of age were affected by stunting, 6.7% by wasting, and 5.7% by being overweight. In addition, nearly 30% of women aged 15 to 49 years were affected by anemia in 2019. Asia and Africa account for more than 9 out of 10 children with stunting and wasting, while approximately 20% worldwide are overweight, mainly because of unhealthy diets and heavily processed foods [51].

### 4.2. Dietary Diversity

Diversifying agricultural production is vital for food security, dietary diversity, and improved nutrition and depends on agricultural biodiversity. Through interactions, the various components of agricultural biodiversity sustain agroecosystems' functions, structure, and processes [127,128]. Although human migration has increased dietary diversity in the last few centuries, particularly after European discovery and colonization of America, the Green Revolution, and mechanization of agriculture since the 1960s have had a negative impact on dietary diversity [72]. Our dietary diversity has narrowed to such an extent that we depend on just four crops (wheat, rice, potatoes, and maize) for over 60% of our calorie intake, and 30 crops supply 95%. The Green Revolution promoted monocropping and introduced chemical fertilizers and pesticides, new, high-yield cereal grains, and the growing use of large farm machinery and irrigation systems. Although this helped double crop production, it also accompanied the depletion of soil micronutrients and reduced crop biodiversity [129]. Mono-cropping decreases the diversity of beneficial insects and birds, making it harder to control pests and diseases without increased use of pesticides [129]. These chemicals and synthetic fertilizers pollute water bodies, further damaging the ecosystem. Monocropping makes the food systems more vulnerable to detrimental effects from climate change, disease, and pest outbreaks. Today, agricultural landscapes are becoming increasingly homogeneous as the number of crops and crop varieties on farms diminishes [130], and either homozygous lines or clones represent the varieties. Crop diversification can influence dietary diversity through personal consumption and improved household income for food access from markets [131]. Therefore, diversification of farm production is recommended as a potential strategy to improve rural households' dietary diversity, nutrition, and food security [132,133].

Gender also plays a vital role in crop and dietary diversity. A review of 15 studies found more robust links between agricultural biodiversity and dietary diversity in female-headed households than in those headed by males [134]. Empowering women could mitigate the adverse effects of low diversity in maternal and child nutrition through traditional and local awareness of agricultural biodiversity, participatory processes, cultural factors, and tourism associated with agricultural landscapes. These are essential for preserving biodiversity and maintaining sustainable livelihoods [135,136]. Dietary diversity is considered a measure of food security, mainly at the individual or household level. Still, it can also provide information about food availability in the community and reflect seasonal changes in dietary patterns, an aspect of the sustainability of the food supply. Household food security, consumption, and dietary diversity are interrelated. The household dietary diversity score (HDDS) and individual dietary diversity score are the most common dietary diversity measures [137,138].

Previous studies have shown that dietary diversity positively correlates with household energy intake [139] and micronutrient intake [140]. While confirming this association, Wiesmann et al. (2006) used HDDS as a predictor of household level per capita dietary energy in Bangladesh, Philippines, Sri Lanka, Malawi, and Mali, which was poor to fair [62]. In Vietnam, women with a dietary diversity score of eight or more had a significantly higher nutrient adequacy ratio for energy [141]. Thus, dietary diversity and energy intake show a positive, significant relationship. Another study revealed a relationship between dietary diversity and micronutrient intake [140]. Thus, increasing dietary diversity at household and individual levels are related to increased energy and nutrient intake.

### *4.3. Food Systems Approach*

The agro-food sector is critical for achieving economic, environmental, and social sustainability. Therefore, developing strategies for a sustainable food system for all parts of the food chain is essential. However, food systems stand on a fragile balance between humans wanting more than their actual needs and the environment. Therefore, urgent reforms to the food systems are critical to tackling the climate emergency.

In the food systems approach (FSA), relationships between different components of the food systems are analyzed regarding socio-economic and environmental or climatic outcomes. Thus, it is an interdisciplinary conceptual framework for research and policy aimed at sustainable solutions for the sufficient supply of healthy food. In the systems approach, feedback loops are characteristic, occurring cyclically between different components of the agro-food sector with varying socio-economic and environmental outcomes [4,142]. The FSA explains non-linear processes in the food system and possible adjustments between policy objectives. The systems approach has the overarching broad perspective for identifying and resolving the root causes of problems, such as malnutrition, poverty, unemployment, and climate change.

Addressing the following aspects is the cornerstone of achieving sustainable food systems:

1. An environmentally sustainable agro-food sector that is resilient to climate change;
2. Practical and adaptable primary producers with enhanced well-being;
3. Safe food with high nutritional value that meets the traditional and cultural needs of the consumer;
4. Innovation through competition and use of novel, advanced technology;
5. New ways to live on and with the land, and respect and care for the sea.

Efforts to reduce and eliminate malnutrition in its different forms should be stepped up by implementing policies to reduce the cost of nutritious food by channeling investments for their production, value-addition, and distribution. Programs and policies on nutrition should be targeted at all sectors beyond health and agriculture [143–145]. At global and regional levels, nutrition targets need to be set that are inclusive, sustainable, and efficient, delivering nutritious food to all at a low cost for the poor. In addition, social protection measures that improve access to healthy and nutritious food need to be implemented in rural and urban settings [146]. By targeting social protection measures toward farmers and vulnerable and marginalized workers, food systems can better meet the nutritional needs of the total population, thus strengthening the resilience of food systems. In addition, women play a crucial role in the family's nutrition. Therefore, the participation of women in implementing these policies will be central to improved nutrition and food security. Finally, we must look at food systems holistically because they do not operate in isolation. A game-changing action in one domain can cause adverse effects in another domain. Therefore, food systems modeling is essential to quantify trade-offs and synergies.

## 5. Trends in Sustainable Agriculture

### *5.1. Agroecology and Agroforestry*

Climate change, land degradation, loss of biodiversity, depletion of water resources, and pollution have tremendous impacts and contribute to the quality of our food, land, and water systems, exacerbating vulnerability to extreme events. Agroecology addresses practical aspects of resilient and sustainable food production systems, including natural resource management, environmental impacts, and the governance and social challenges facing current food and farming systems. There are many benefits of agroecological options, which have been demonstrated in specific contexts. As a result, agroecology is gaining increasing attention in agricultural research and socio-economic studies, including politics. However, its largescale implementation is limited by a lack of enabling mechanisms [147] and political will.

In many settings, socio-political and economic conditions have favored agricultural practices that have undermined these systems, with 40% of arable land degraded; 64% of agricultural land contaminated by agrochemicals [148]; and forest and biodiversity loss affecting our healthy diet and livelihood options [149]. In recent decades, the environmental costs of intensifying conventional agriculture have begun to cause serious concern. Ecological intensification has been proposed as a nature-based alternative that complements or partially replaces external inputs [150]. Perennial plants are vital components that offer previously unattainable levels of ecological intensification in agriculture, reducing environmental impact [151]. Compared to annual crops, perennials are more robust, protect the soil from erosion, improve its structure, and increase the retention of nutrients, organic carbon, and soil moisture[152,153]. Therefore, perennials will contribute to the adaptation and mitigation of climate change and can help to ensure long-term food and water security.

Agroforestry cultivates trees and shrubs on farmland and pastures for more sustainable food production [154]. Agroforestry practices can help with climate change mitigation, food security, and income generation. In addition, an agroforestry system promotes carbon sequestration by planting trees on farms [155]. Agroforestry has been practiced for centuries, but researchers have only recently begun understanding how these practices can help to combat climate change [156].

### 5.2. Organic Agriculture

Organic agriculture emphasizes using renewable resources, conservation of energy, soil, and water, recognition of livestock, and environmental maintenance and enhancement, while producing optimum quantities of produce without synthetic fertilizer or chemicals [157,158]. In 2017, global organic farming increased from 11 million hectares in 1999 to 69.8 million hectares. In Austria, the share of the land area under organic production reached 24.0%. The volume of production in organic enterprises is higher than in conventional enterprises in Ukraine. Organic agricultural production has gained more popularity recently due to changes in customer tastes and income. In 2017, organic agriculture was licensed in 181 countries, and approximately 2.4 million farmers were engaged in organic production [159]. In a study that calculated how the climate footprint of England and Wales would change if they were converted entirely to organic farming, it was found that agricultural production would decrease by up to 40% and that these lower yields would require a lot more food imports [160]. Bhutan's experience of converting to organic agriculture reveals that organic crop yields were 24% lower than conventional yields [161]. Nevertheless, using examples from South America, Africa, and Asia as well as from developed countries, Leu (2004) argues that with education and the use of best practices, organic agriculture can even surpass the yields of conventional alternatives, at the same time ensuring high levels of economically, environmentally, and socially sustainable production [162]. The EU's recent "Farm to Fork" (F2F) initiative for a fair, healthy, and environmentally-friendly food system, agreed upon in October 2020, calls for 25% of Europe's farmland to be converted to organic agriculture by 2030.

Organic farming combines land use and livestock management within the same system [163]. Cyclical processes and circular economy determine the environmentally friendly production of high-quality food and secure the long-term natural production bases, such as soil, biodiversity, water, or climate [163–165]. Furthermore, the diversity of cultivated crops and animal species maintains and strengthens the stability and resilience of the agricultural ecosystems. In this way, organic farmers provide positive ecological services for society. With organic agriculture, the natural resources in the ecosystems are used but preserved [166]. No agronomic system is closed because minerals and energy are removed from the farm with the economic harvest. However, organic farming is practiced as a semi-closed system to minimize agronomic practices', external inputs, or impacts [166]. This means external inputs are severely restricted or entirely prohibited, as in synthetically produced nitrogen fertilizers, synthetic chemical pesticides, and growth regulators [166].

Organic farms require significantly less energy per hectare than the conventional and thus emit fewer GHGs. However, since organic farming has lower yields than intensive farming, the benefits for the climate are reduced if emissions are related to production volume. Concerning environmental pollution, organic farming is superior to conventional farming [167]. Soil organic matter is generally higher in organic farming systems and contributes positively to agro-biodiversity and natural biodiversity [168]. In their meta-analysis, Hole et al. (2005) identified 66 cases where organic agriculture had a positive effect, against 8 with a negative and 25 with a mixed or no effect across different taxa. Three general practices in organic farming that are of particular benefit to farmland biodiversity include (1) prohibition/reduced use of chemical pesticides and inorganic fertilizer; (2) sympathetic management of non-crop habitats and field margins; and (3) preservation of mixed farming [168]. Nevertheless, due consideration needs to be given to the problem of antibiotics in the environment when animal manure and other organic products are used as fertilizers [169].

### *5.3. Integrated Agriculture*

Integrated agriculture focuses on integrating crop and livestock production principles to create sustainable farming and food systems [170,171]. This links livestock and crops, fish and crops, and trees and livestock. Integration is a much more effective form of farming that conserves the natural resource base. A recent study found that integrated farming systems can increase crop yields of maize, pea, and wheat by almost 50% and farm net returns by 39.2%, decreasing the environmental footprint by 17.3% compared with monocropping [172]. Thus, integrated farming with intercropping increases food production and diversity, while reducing the environmental footprint. However, currently available integrated farming models are better suited for small and marginal landholders toward ensuring better income and secured livelihoods. Applying this practice to large-scale farming is a challenge that needs to be urgently addressed.

### *5.4. Regenerative Agriculture and Permaculture*

Both regenerative agriculture and permaculture are based on similar principles. One of those principles is that humans should work with nature instead of against it. They provide a different approach to farming. It adopts some of the principles of organic farming [173,174]. This form of agriculture uses natural inputs, such as cover crops, composting, and crop rotation to improve soil quality [25] and natural processes to restore the topsoil, water, biomass, biodiversity, and other resources.

These two terms are often used interchangeably, but they have different meanings. Regenerative agriculture uses techniques to produce food without depleting the soil or harming the environment; the soil is enriched with bio-fertilizers, and diverse crops are planted in a way that helps them to be as effective as possible. Pioneered in Australia by Bill Mollison and David Holmgren in the 1970s, permaculture is a design principle for sustainable living and farming [175–177]. In permaculture, the land is not tilled or plowed. Instead, it is layered with different plants so they can help each other to grow. Permaculture practices are based mainly on environmental observations and ideas about nurturing relationships between the land and people. The original concept of achieving "permanent agriculture" has now evolved to signify design and practices for "permanent culture" to achieve sustainability. In permaculture, an attempt is made to replicate growth patterns occurring in the natural environment so that crops are made to grow in configurations resembling their progenitors. 'Design permaculture' is the extreme form and uses the connections and underlying ecological principles observed in naturally functioning ecosystems to plan all human activities and habitation [173]. Transitioning from an annual extractive to a perennial model is the best chance we have of creating a truly regenerative food future. Research has progressed rapidly in this direction in the last decade [151,178]. For biological and anthropological reasons, almost all cereal, legume, and oilseed crops, including potatoes, were domesticated as annuals, although most of their progenitors were perennial. Rapid neo-domestication is now practiced on many crops that started with perennial sunflower [179], and high phenotypic gains in such programs, reaching 320%, are encouraging[180]. Toward this objective, many countries have launched programs to develop perennial cereals, oilseeds, and legumes [181].

### 5.5. Digital Agriculture

The global agro-food system sustains the world's ever-growing population. Although billions of people are engaged in agro-food systems, the current system does not fit its purpose and stresses the environment by generating up to 24% of global GHGs. While there is an overabundance of food, 820 million people are undernourished worldwide. The main reason is that the global agro-food system is being held back partly by transaction costs and information asymmetries that prevent profitable transactions [148,182]. The agro-food system is complex, and it takes dozens of stakeholders and transactions to bring food from the farm to the table. In addition, business partners incur costs to find each other and determine sales conditions, such as volume, quality, price, and return policies [183]. However, with emerging digital technologies and access to data, the world's agro-food system can overcome these obstacles and develop sustainable and healthy networks within and between sectors. The digital revolution in global agro-food systems has the potential to create societal gains with economic efficiency. This can be achieved through (a) farmers being able to access multiple markets and reduce the cost of production through improved price discovery; (b) buyers conscious of product origin, traceability, and quality control, including the inclusion of smallholder farms and marginalized populations; (c) environmental sustainability through reducing food waste using better resource management and rewarding environmentally friendly practices; and (d) governments and institutions being able to identify shortcomings in supply systems and intervene in a timely manner.

Access to data allows new ways to evaluate small-scale farms and agribusinesses. Creditworthiness improves their access to rural finance and enables the design of affordable insurance products, and digital technologies allow efficient government policy designs, implementation, and environmental outcomes monitoring. However, digital agriculture also has risks, such as marginalizing people who are deprived of access to and knowledge of digital technology. Therefore, governments need to improve digital literacy in society and physical infrastructure for data and technology use throughout the food system. Furthermore, policies need to support innovative approaches to digital agriculture through open data, digital platforms, digital entrepreneurship, digital payment systems, and digital skills. These are critical for ensuring an equitable environment for digital services providers and users. Furthermore, it is essential to implement policies that protect data, ensuring that agriculture policies maximize digital agriculture's potential for environmental sustainability through digital transformation. A food system optimized for sustainability with the implementation of the right policies can result in a healthier population, restoration of damaged ecosystems, and healthy economies for humankind.

### 5.6. Biotechnology

The use of modern biotechnological tools, including genetically modified (GM) crops, has dramatically changed agriculture and food production. Agricultural biotechnology has a significant role in transforming global agriculture to meet the UN's goal of ensuring zero hunger by 2030. In addition, evidence abounds that biotechnology positively impacts agriculture in meeting the UN's SDG 2 [184,185].

The economic and environmental benefits of adopting GM crops globally have been significant. These have contributed to reduced insecticide and herbicide applications, reduced $CO_2$ emissions, and higher crop yield and quality, resulting in increased farmer income and improved consumer health [186–189]. For example, adopting Bt eggplant in Bangladesh has resulted in a six-fold increase in farmer income due to the durable resistance of the crop to destructive fruit and shoot borer [190].

Staple foods, such as rice, that have improved nutritional content need to be made available to smallholder farmers to impact diet quality immediately. Recently, the Philippines approved Golden Rice, a genetically engineered rice with increased beta-carotene levels, which the body converts into vitamin A. It is the first country to give the final biosafety approval for Golden Rice. The estimated average requirement (EAR) for vitamin A intake is very low in the Philippines, with only 20% of households meeting this requirement. One cup of cooked Golden Rice contains 30–50% of the EAR of vitamin A for children aged six months to five years, the most vulnerable and high-risk group [191].

Another successful implementation of a GM crop is the approval in October 2020 by Argentinian authorities of "HB4" wheat modified to express the transcription factor *HaHB4*, from sunflower for drought resistance [192]. Argentina is the eighth largest exporter of wheat in the world (5.1% of total exports). Prolonged drought in the country in recent years has resulted in significant crop losses. The drought-resistant "HB4" has been planted in 55,000 ha in 2021/22 summer with an expected production of 200,000 mt.

Improved crops developed using various genetic engineering techniques continue to reduce agriculture's environmental footprint and sustainably produce global food, feed, and fiber. Transgenesis is the extreme form of GM where one or more recombinant genetic elements taken from a sexually incompatible gene pool are inserted into a gene, promoter, and/or terminator. Cisgenesis involves inserting an identical copy of a complete genetic element, including gene, promoter, and terminator, within a sexually compatible gene pool. Intragenesis is when one or more components (gene, promoter, and terminator) of recombinant genetic elements isolated from different genes within a sexually compatible gene pool are inserted into the crop of interest. The most advanced and precise method is genome editing (often uses CRISPR/Cas technology), introducing a targeted mutation at a specific locus in the genome [193–195]. Gene-edited plants or their products have no foreign DNA or genes (transgenics) and are, therefore, not considered GMOs in the true sense. There is a quick rise in CRISPR technology to develop cultivars for food and feed quality, biotic and abiotic stress tolerance, and herbicide tolerance [196,197]. These biotechnological applications have overcome problems that have been difficult to achieve using traditional plant breeding approaches.

To date, 29 countries (24 developing and 5 industrialized) have commercialized biotech crops (Figure 6). Five crop species occupy 99% of the global biotech crop area comprising 190.4 million ha: soybeans (91.9 Mha), maize (60.9 Mha), cotton 25.7 Mha), canola (10.1 Mha), and alfalfa (1.2 Mha) [198–200]. Despite their advantages, many countries have not adopted GM technology, mainly for political and social reasons. In Europe, the adoption of GM crops has faced fierce resistance due to concerns over their perceived health and environmental impacts. Nevertheless, Europe imports over 30 million tons of GM corn and soy yearly for livestock feed, making Europe the world's largest regional consumer of GMOs [201,202].

In the 22 years of growing GM crops since 1996, the additional income to farmers is estimated at US $225 billion due to an additional 824 Mt of food, feed, and fiber produced worldwide. As a result of growing more environmentally friendly, GM crops, such as insect-resistant cotton, agricultural pesticide usage was reduced by 8.6% in that same period. This translated into a 19% reduction in associated environmental impacts [203]. Studies show that GM crops provide significant benefits to farmers. For example, a meta-analysis involving 147 research outputs found that GM crops have 22% higher yields than contemporary crops, resulting in a 68% increase in farmer profits [188].

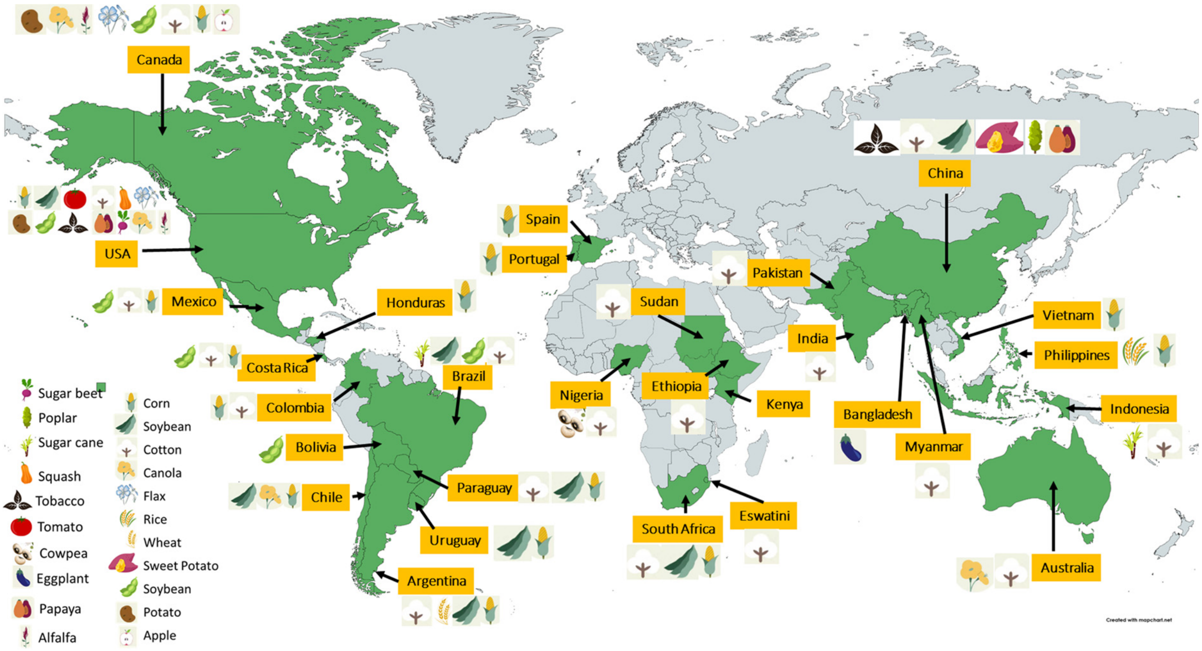


**Figure 6.** Countries that commercially grow genetically modified crops. This infographic was created based on the Genetic Literacy Project and other resources: International Service for the Acquisition of Agro-biotech Applications, Wikipedia, and Crop Life International websites [200–202,204,205].

However, it is difficult for the general public to come to clear conclusions on the safety of GM products because of the politicized nature of the GMO debate. For example, the decisions by regulators to allow the cultivation of Golden Rice and Bt eggplant in the Philippines has resulted in a fierce political debate [206,207]. Indian farmers are frustrated as the government continues to deny them access to Bt eggplant, while their neighbors in Bangladesh have been commercially growing it since 2013 [208,209]. Nevertheless, GM research continues in India in search of higher-yielding mustard and peanuts with low aflatoxin content that would benefit both consumers and farmers. However, the hostile political environment prevents these crops' adoption [210,211]. Despite no scientific basis for banning GM crops, as declared by many independent scientific organizations in every major country, approximately 60 countries still have significant restrictions on developing, testing, and growing them [201,202].

## 6. Conclusions

Sustainable agro-food systems provide food security and food independence for the planet. The agro-food sector spans many sectors of our economic activity, including farming, processing, and packaging of farm produce, distribution, marketing, consumption, handling of food waste, and many other related activities by providing livelihoods to nearly 3 billion people worldwide. It has transformed into an intertwined global network allowing the majority of the global population to engage in other activities, giving impetus for developing other sectors of society. While input-intensive agriculture, which arose with the Green Revolution, solved the problem of hunger for many, it also contributed heavily to climate change. With only four crop species providing 60% of the calories, our dietary diversity has declined over the years. Global warming and climate change-related phenomena are threatening the very foundations of agriculture. However, new scientific innovations are now available that can be deployed to mitigate the effects of climate change and to reduce the impact of food production on the environment. In this work, we provide evidence that fast-tracking the breeding and release of herbaceous perennial cereal, legume, and oilseed crops to replace annual crops, while promoting mixed cropping, reduces the use of synthetic fertilizer through breeding and deployment of fertilizer efficient cultivars; promotes organic, integrated, and regenerative farming systems; and enhances use of digital technologies to improve efficiency across the agro-food sector from farming systems to market access, which can reduce the impact of agro-food systems on the environment. We also show that all of these efforts will have a more significant impact when governments and regional bodies enact policies that promote sustainable farming, secure land tenure, and access to resources (including financial) for small-scale farmers, women, and indigenous communities and that ensure gender-sensitive social protection, including access to education and food for all. That a high proportion of GHG emissions from food production is from animal husbandry (meat and dairy) allows us to reduce the emissions and carbon footprint if we are willing to change our food choices. More environment-friendly food choices will also allow for equitable food distribution, improving food security for the many undernourished, estimated to constitute 10% of the global population, including 22% of all children under the age of 5 years affected by stunting. Hence, the future challenge is to: create sustainable agricultural food systems, minimize environmental pollution, increase yields, provide fair and equitable food distribution, and reduce malnutrition —leading to food security for all. With our willingness for change, combined with modern technological advancements, it would be possible to halt and reverse climate change and restore the planet's health.

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