1. SUSTAINABLE FOOD PRODUCTION AND PROCESSING—SUSTAINABLE AGRICULTURE AND BIOTECHNOLOGICAL APPROACHES IN FOOD CHAIN

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Abstract

The current trend of the increasing human population as well as the evolution of consumption patterns, increasing food demand and growing amounts of food waste influence changes along the entire food chain, from agricultural systems and natural resources to processing. It is worth underlining that the agri-food industry is considered one of the most important sectors of economic development in the world. However, the increased demand for food is depleting natural resources, causing soil erosion, landscape biodiversity loss and environmental pollution worldwide, creating new challenges for food security and sustainable food production. Therefore, sustainable agriculture and new technologies and approaches play an increasingly significant role in reducing negative environmental impacts while ensuring food safety. It stays in line with the model of food production development promoted by the Food and Agriculture Organization of the United Nations, according to which sustainable agriculture means the production of healthy, high-quality food in an environmentally friendly way, caring for animal welfare and protecting biodiversity, as well as ensuring income for farmers. This approach is also consistent with many concepts focused on the issue of sustainable, eco-friendly food production, such as development of sustainable agriculture, the One Health concept, Climate-Smart Agriculture, the European Green Deal and the Farm to Fork Strategy, strongly emphasising efforts to create a healthier and more sustainable food system.

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Introduction

As the literature data underline, the global human population is expected to reach 9.7 billion people by the year 2050 (United Nations Department of Economic and Social Affairs, 2015), which means that food production will need to increase. This puts a heavy burden on agriculture and its related sectors to meet the demand for food. Furthermore, the Food and Agriculture Organizations (FAO) report entitled *The future of food and agriculture: Trends and challenges* identifies some requirements ensuring adequate as well as affordable food supplies through sustainable agriculture in order to meet the increasing demand of the growing population. This report draws attention to the current and most urgent trends emphasising the complexity of agriculture and the food supply system as well as the opportunities and challenges necessary for its sustainability. In turn, the key challenges that food and agricultural systems will face in the nearest future can be divided into three groups: challenges for food stability and availability (including sustainable improvement of agricultural productivity with providing a sustainable natural resource base and taking into account climate change), challenges for food access and utilisation (including eradication of extreme poverty and reduction of inequalities, fight against hunger and malnutrition as well as drawing attention to the improvement of earning opportunities in rural areas, reasons for migration, crises, disasters and conflicts) and systemic challenges (with paying attention to food systems and effective governance at national and international levels (FAO, 2017). It is also worth quoting an important document indicating the goals facing today's societies entitled „Transforming our world: The 2030 Agenda for sustainable development", signed in 2015 by the leaders of the United Nations (UN) (UN, 2015). Among the 17 Sustainable Development Goals (SDGs) and the related 169 targets, which are to be achieved globally by 2030, SDG 2 underlines the necessity of more productive and less wasteful agriculture systems. In order to achieve this goal, a major transformation is needed in terms of what food is consumed and how it is produced, processed, transported and distributed. Therefore, the role of sustainable agriculture and new technologies and approaches will be of particular importance in reducing negative environmental impacts while ensuring food safety. It is consistent with the model of development of food production promoted by the FAO, according to which sustainable agriculture means the environmentally friendly production of healthy, high-quality food with care for animal welfare and biodiversity protection, as well as ensuring income for farmers.

Other concepts, such as the One Health approach, Climate-Smart Agriculture (CSA) or European Green Deal (EGD) and the Farm-to-Fork (F2F) Strategy, also stay in line with the above-mentioned FAO model. The idea of the One Health concept, established in 2004, assumes a strong connection between the health of people, animals and the environment. This approach involves multidisciplinary teams from different institutions working together to increase sustainable agriculture practice and improve health, society and conservation of natural resources while building social awareness. The One Health approach has been supported by organisations such as the World Health Organization (WHO), the FAO, the United States Centers for Disease Control (CDC) and the European Joint Program One Health (OHEJP) (FAO, 2010, 2013). In turn, CSA, according to the FAO, is a strategy that pays special attention to climate change, sustainably increases productivity, increases resilience through adaptation to climate change and reduces greenhouse gas emissions (FAO, 2010). As shown in Figure 1.1, sustainability is based on the link between the society (people), environment (planet) and economic value (profit), and an important challenge for public and private policy is to take them into account all together.

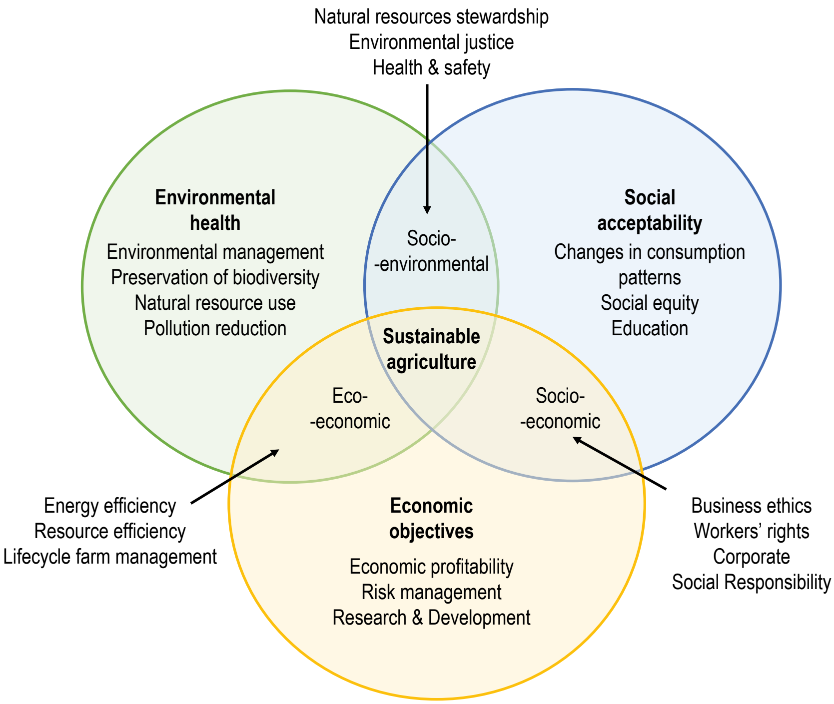

Figure 1.1. Venn diagram showing the relationship between three main objectives of sustainable agriculture

Source: based on (Abubakar & Attanda, 2013; Clark et al., 2021; Fenibo et al., 2022).

This direction of agricultural development and its transformation is to ensure food security and sustainable development of agriculture around the world, including poor countries. It should be emphasised that agriculture is the dominant economic direction in many countries and is crucial for meeting the basic needs and livelihoods of 70% of the world's poorest people (Global Commission on the Economy and Climate, 2014). Thus, adaptation, mitigation and food security as the three pillars of CSA will have significant implications for the world's poorest farmers. In Europe, the consequences of climate change and environmental degradation, already visible and possible in the future, have provided the basis for the development of an action plan called the EGD. Referring to the above-mentioned concepts and assumptions introduced in Europe and around the world, it may be said that all of them are perceived as caring for the environment and human well-being, with the common goal being sustainable development. In relation to sustainable food production and processing, it needs to be highlighted that sustainable food can only be obtained when the production process is environmentally and climate-friendly, economically justified and socially accepted. This concept is strongly related to the sustainable agriculture model, in which the negative impact of agricultural production on the environment is limited and available resources are used more efficiently. In this context, sustainable agriculture includes many elements, starting with the farmers' selection of practices, methods and tools for cultivation or breeding, usage of water, energy, machinery, plant protection products and fertilisers or seeds to caring for animal welfare, preservation of biodiversity around the farm, usage of methods which do not degrade soil, efficient water management and reduction of greenhouse gas emissions. Throughout the process, it is important that the choices made do not raise social objections.

1.1. European Union plan for sustainable agricultural production

The most important drivers of sustainable development, undoubtedly, include agricultural production. Unfortunately, as a key element in ensuring adequate food resources for a growing population, it can also be a significant obstacle to achieving the SDGs (Melchior & Newig, 2021). The intensification of production in the agricultural sector is often associated with the use of unsustainable agricultural practices, which in turn leads, among others, to the degradation of forest areas, increased greenhouse gas emissions, reduction of biodiversity or degradation of soil and water resources (Ramankutty et al., 2018). To reduce the negative impact of agriculture on the environment and natural resources, various models of agricultural production have been developed over the years, such as agri-environmental, integrated farming system (IFS), Low-Input Sustainable Agriculture Program

(LISA) as well as alternative agriculture involving systems such as organic, biodynamic, low external input or resource-conserving and regenerative (Bowler, 2002). Furthermore, it should be stated that in addition to counteracting negative environmental impacts, sustainable agriculture must simultaneously consider appropriate economic and social development. Accordingly, all over the world, various practices and regulations are being adopted to steer agricultural production along the path of sustainable development (FAO & UNEP, 2020).

European agricultural policy for obtaining sustainability has evolved progressively, adapting its assumptions to the economic socio-environmental situations in which it was operating at the time (Wrzaszcz, 2023). The first steps of agricultural improvement in the European Union (EU) date back to the 1960s, when the principles of the Common Agricultural Policy (CAP) were introduced. The CAP established economic and social objectives such as: (1) increasing agricultural productivity by promoting technical progress and optimal use of factors of production, especially labour; (2) ensuring a decent standard of living for farmers; (3) stabilising markets; (4) guaranteeing the security of supply and (5) ensuring reasonable prices for consumers, which, by their nature, were easily adaptable to subsequent reforms (Nègre, 2023). However, it should be noted that at the beginning the CAP was implemented through agricultural intensification (maximisation of production), the policy of guaranteed prices and unlimited purchase warrants leading to a lot of environmental damage or increasing surplus production (Nègre, 2023; Włodarczyk, 2022). Significant changes in the CAP took place in the 1990s due to the MacScharry reform,[1] which linked agricultural activities with environmental aspects, introducing, among others, measures to stimulate the use of environmentally friendly methods, including those aimed at intensifying agriculture and strengthening the importance of agricultural activity in environmental protection in rural areas (Wrzaszcz, 2023). The new look at agricultural production was reflected in later reforms, such as Agenda 2000 (protecting ecosystems and ensuring animal welfare), the 2003 Luxembourg reform (ensuring an appropriate level of agricultural income—1st pillar of the CAP, and supporting the development of rural areas and protection of the natural environment—2nd pillar of the CAP) and the 2013 reform (main issues of the reform: rural development; direct payments to farmers and market cooperation; management, financing and monitoring of the CAP), putting the CAP on a sustainable path by taking into account the productive, social and environmental aspects of agriculture (Adamowicz, 2021). Currently, all

[1] MacSharry reform, developed in 1992 by Ray MacSharry, European Commissioner for Agriculture and Rural Development (1989–1993), the first large-scale reform of the CAP, aiming at reducing the overall budget and quitting unlimited guaranteed prices. Finally, the policy contributed to direct income support for farmers, who were obliged to safeguard the environment, and incentives to improve food quality (European Council, n.d.; Historical Archives of the European Union, n.d.).

reforms and actions for sustainable agriculture are based on the EGD–a strategy that, as the European Commission (2019) stated, aims to:

> transform the EU into a fair and prosperous society, with a modern, resource-efficient and competitive economy where there are no net emissions of greenhouse gases in 2050 and where economic growth is decoupled from resource use (…), protect, conserve and enhance the EU's natural capital, and protect the health and well-being of citizens from environment-related risks and impacts.

The EGD puts agricultural production in a key position in the proper course of transformation and achievement of the assumed ambitious goals. The main objective of the EGD strategy is to put sustainable development and human well-being at the heart of economic policy, involving all stakeholders from various sectors, such as construction, biodiversity, energy, transport, agriculture and food. In the case of agriculture and food, the policy based on the F2F Strategy assumes:

- ensuring sustainable food production and promoting sustainable practices throughout the food industry,
- ensuring food security,
- promoting sustainable consumption and reducing food loss and waste,
- combating food fraud in the supply chain (EC, 2019).

The F2F Strategy is an important document aimed at building a sustainable food system; nevertheless, agriculture also plays a role in other economic assumptions, such as "climate neutrality" or the circular economy (Adamowicz, 2021). In the adopted strategy, agricultural production will play a significant role in sustainable production through activities including in particular:

- introducing agricultural practices that reduce emissions of CO_2 and other greenhouse gases (through changes in animal husbandry),
- increasing the use and development of energy production from renewable sources and investing in digesters,
- reducing the use of chemical plant protection products,
- reducing the use of antimicrobials in animal husbandry,
- improving animal welfare to ensure safe and high-quality food,
- reducing excess nutrients (especially nitrogen and phosphorus) in the environment,
- increasing the importance of an organic farm in agricultural production (strictly regulated and controlled under Regulation (EU) 2018/848 with subsequent amendments),
- increasing the financial support (eco-schemes) of sustainable agricultural practices such as precision farming or agroecology (including organic farming) (EC, 2020).

Furthermore, important support and, at the same time, a key tool for the implementation of the developed concepts of sustainable agriculture is the new CAP 2023-27. The new approach to the CAP allows for greater flexibility and takes into account local needs and conditions. The key document is Regulation (EU) 2021/2115, which defines the general objectives and 10 specific objectives, which are largely convergent with the assumptions of the EGD and the F2F Strategy or actions for biodiversity. The document also defines detailed rules for financial support for the agricultural sector, including in particular the European Agricultural Guarantee Fund (EAGF) and the European Agricultural Fund for Rural Development (EAFRD). Another important provision is related to strategic plans, which are developed individually by each member state and are assessed and monitored by the European Commission (Regulation (EU) 2021/2115, 2021). Thus, it can be seen that the implemented reform will, in fact, move away from its normative nature, focusing on results (in particular, the environmental ones) and increasing the role of Member States in the whole process (Leśkiewicz, 2020).

It is apparent that the plans introduced by the EU for sustainable development of agriculture are wide-ranging and very ambitious. Nonetheless, it should be noted that achieving appropriate economic results in agricultural production (economic aspect), ensuring the development of rural areas or adequate quantity, good quality and safe food (social aspect), while minimising interference with the environment and acting for its protection (environmental aspect) is a multi-dimensional, complicated process depending on many factors. In order to achieve the assumed goals and properly transition to a more sustainable model, further work is necessary on appropriate regulatory, financial and advisory support for the agricultural production sector, which is another major challenge for the EU.

1.2. Integrated agricultural systems

Meeting the growing demand for food in a sustainable way requires a shift from industrial agriculture, which is primarily focused on production, high productivity, self-sufficiency and affordability (Prost et al., 2017) to sustainable agriculture, which is environmentally friendly, socially acceptable and economically viable. Many alternative forms of agriculture have emerged in the meantime, such as permaculture, biodynamic agriculture, organic farming, natural farming, aquaponics, vertical farming, urban farming, precision farming, social and welfare farming, agroecology and "smart" or digital farming (Hassink et al., 2018; Ingram, 2018; Junge et al., 2017; Wezel et al., 2009; Wolfert et al., 2017); moreover, bioeconomy and circular economy have also developed (Borrello et al., 2016). However, it should be underlined that there are a number of threats present in agricultural production that negatively affect crops, such as plant diseases or droughts, which forces farmers to use solutions preventing losses and lowering the quality of crops. Various types of fertilisers, growth stimulants and pesticides are used on a large scale, which increases production on the one hand, but also affects the environment on the other hand. Therefore, methods based on biological systems, including the use of microorganisms, are of increasing interest since they may diminish adverse environmental consequences of modern agricultural production.

Beneficial microorganisms can increase yields by stimulating plant growth, removing pollutants and inhibiting the development of pathogens. Their properties are used in biofertilisers and biopesticides, designed based on different microorganisms. Biofertilisers are bio-based organic fertilisers that could come either from plant or animal sources, defined as preparations containing live microorganisms that help to increase soil fertility through various mechanisms, including fixing atmospheric nitrogen, dissolving phosphorus, decomposing organic waste, as well as enhancing plant growth through the production of growth hormones (Okur, 2018). Taking into account the origin and type of the raw material, we distinguish biofertilisers based on organic residues (green manure, crop residues, treated sewage sludge and manure) and biofertilisers based on microorganisms (containing beneficial microorganisms such as bacteria, fungi and algae) (Abbey et al., 2019; Lee et al., 2018). Stimulation of plant growth by microorganisms may result from different mechanisms, such as biological nitrogen fixation, phosphate solubilisation, micronutrient solubilisation, production of growth regulators, such as IAA (indole-3-acetic acid), gibberellic acids and cytokines, as well as increasing the bioavailability of minerals (Chaudhary et al., 2021). Moreover, some indirect mechanisms, such as releasing lytic enzymes, antibiotics, siderophores and cyanide production by microorganisms, may also be responsible for protecting the plant from pathogens (Mahmud et al., 2021). The advantages of biofertilisers, in addition to the basic properties, such as increased availability of nutrients and improvement of soil fertility, also include benefits such as low cost, protection of plants against soil-borne pathogens and increased tolerance to biotic and abiotic stress. It is also worth noting that the use of biofertilisers is associated with less environmental pollution while maintaining soil biodiversity, which contributes to sustainable agricultural production (Chaudhary et al., 2022).

The second group of products of significant importance for sustainable agriculture are biopesticides based on living organisms or natural products, demonstrating antimicrobial or insecticidal activity (Glare et al., 2012; Thakore, 2006). According to the United States Environmental Protection Agency (EPA, 2023), these compounds are "derived from natural materials such as animals, plants, bacteria and certain minerals". Biopesticides as an ecological alternative to traditional agricultural technology are a crucial component of integrated pest management programs. Depending on the type of compounds, different categories can be distinguished, such as microbial pesticides, biochemicals and plant-incorporated protectants.

Microbial pesticides are derived from different microorganisms including bacteria, fungi or viruses demonstrating activity towards pathogenic bacteria, fungi or insects. Their activity is often related to the production of different metabolites. The most frequently mentioned bacteria used as biopesticides are species of *Bacillus*, *Pseudomonas*, *Yersinia*, *Chromobacterium*, *Serratia*, and *Streptomyces*, while fungi include species of *Beauveria*, *Isaria*, *Metarhizium*, *Verticillium*, *Lecanicillium*, *Hirsutella* or *Paecilomyces* (Chang et al., 2003; Ranga Rao et al., 2007; Thakur et al., 2020). An important group of microbial pesticides are baculoviruses active against chewing and biting insects, such as *Lepidopteran caterpillars*. Insecticidal nematodes (EPNs) used as biocontrol agents are mainly species of the genera *Heterorhabditis* and *Steinernema* associated with the symbiotic bacteria of the genera *Photorhabdus* and *Xenorhabdus* (Chang et al., 2003).

Biochemical biopesticides are compounds of natural origin demonstrating activity towards pests by nontoxic mechanisms such as extracts or essential oils obtained from different plants, semiochemicals, plant growth-promoting regulators or insect pheromones (Kumar, 2012; Reddy & Chowdary, 2021; Singh et al., 2021). The compounds responsible for the insecticidal activity include phenolics, steroids, alkaloids, terpenoids, phenylpropanoids and nitrogenated compounds (Duan et al., 2016; Weber et al., 2019).

The third group of biopesticides are plant-incorporated protectants (PIPs), which are substances produced by genetically modified organisms (GMOs). The incorporation of genetic material into plants renders them unsuitable for pest attack. The best-known insecticidal molecules used in PIP technology are Cry proteins from the soil species of *Bacillus thuringiensis*, protease from Baculovirus, toxic complex (Tc) proteins from bacteria of the genera *Xenorhabdus* and *Photorhabdus*, as well as double-stranded ribonucleic acid (dsRNA) and Mir1-CP from maize (Fenibo et al., 2021; Parker & Sander, 2017; Shingote et al., 2013; Wei et al., 2018).

Biofertilisers and biopesticides play an important role in integrated agriculture systems as these solutions are environmentally friendly, may support the preservation of biodiversity and are less harmful to humans and animals.

1.3. Biotechnological applications for sustainable food production and processing

To ensure sustainable food production and processing, improving the effectiveness and efficiency of food systems is urgently required nowadays. In recent years, there has been a clear impact of biotechnology on industry and agriculture, e.g., by improving the quantity and quality of products. In the agricultural sector, biotechnological solutions play a significant role, ranging from increasing the efficiency of crops or animal husbandry to improving agricultural products, while ensuring that their environmental impact is reduced. Therefore, recent developments in agricultural biotechnology significantly support the food sector, ensuring its global security (Figure 1.2). The biotechnological achievements concern both the solutions introduced in the field as well as at further stages of the food chain. In addition to the above-mentioned solutions, which use biological systems, agriculture is increasingly reaching for solutions based on "omics" technologies and genetic modifications. For example, new plant breeding techniques (NPBTs) based on genome editing are promising technology employed in the food and agriculture industries for a variety of purposes, including genetic improvement of plant varieties and animal populations, characterisation and conservation of genetic resources and other uses (Tyczewska, Woźniak et al., 2018).

The genetic modifications of plants may improve their tolerance to environmental stress, such as drought, or introduce resistance to any diseases or pests. Moreover, some features crucial in food processing, such as increased purity or high yield efficiency, as well as features important from a nutritional point of view, may be improved by new biotechnological techniques. Interestingly, engineering plants can have a positive effect on the environment as they may efficiently absorb soil nutrients and reduce the use of agrochemicals, in turn reducing environmental pollution (Barrows et al., 2014; Ranjha et al., 2022; Tyczewska, Twardowski et al., 2023; Zhang et al., 2016).

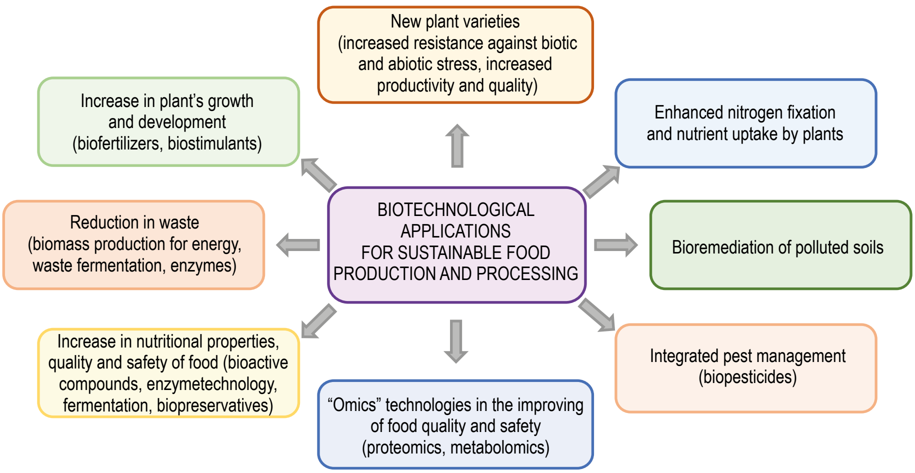

Figure 1.2. Biotechnological applications for sustainable food production and processing

Source: based on (Gosal et al., 2020; Lokko et al., 2018; Tyczewska, Twardowski et al., 2023).

Industrial biotechnology, in turn, plays a significant role in food production and processing, providing products that fit into new production and consumption patterns.

The solutions used in this field include fermentation, enzymatic biocatalysis, and even gene technology. Fermentation is one of the oldest known biotechnological processes and a key component of many industrial applications to obtain many different products, giving great opportunities for their modification and improvement. Similarly, enzyme biocatalysis has wide industrial applications including food and feed production (Lokko et al., 2018). Furthermore, the biotechnological use of microorganisms and their metabolites plays an important role at all stages of the food chain, being part of biopreparations used in agricultural production, taking part in the processes of degradation and biotransformation of waste and pollution, as well as in the processing of food or feed. It should also be emphasised that the "omics" technologies (genomics, transcriptomics, proteomics, metabolomics) used for the development of agricultural biotechnology, bioproducts and food biotechnology, are becoming increasingly important (Amer & Baidoo, 2021).

Conclusions

Agriculture is an important sector of the economy in many countries. However, conventional agriculture, which uses chemical fertilisers and pesticides to increase yields and production, negatively affects the ecological balance and food security, and is a major contributor to land and water pollution. Therefore, the idea of sustainable agriculture is becoming more and more important (Raman et al., 2022). Implementation of the assumptions for sustainable food production and processing requires multi-directional activities, in which biological systems and achievements of biotechnology have a significant share. Biotechnological innovations offer solutions to various civilisation challenges faced by today's world, including broadly understood sustainable agriculture, from improving crops through reducing waste from the agri-food industry to improving food. Biotechnological solutions can contribute to sustainable development by helping to achieve the SDGs, in particular, Goal 2—aiming to end hunger and achieve food security; Goal 9—emphasising the promotion of inclusive and sustainable industrialisation and supporting innovation, and Goal 12—indicating the need to ensure sustainable consumption and production patterns.

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