Review Article

Sustainable Agriculture: Balancing Productivity and Environmental Stewardship for Future Generations

Abstract

All global development is based on the agricultural practice. If not managed responsibly, increasing its productivity and production might have an impact on the land's capacity in the future. Preserving potential land use might be achieved through sustainable agriculture. Enhancing and balancing productivity with environmental sustainability may be accomplished by concentrating on locally accessible organic resources, INM, IFS, etc. and proper management of soil health. Due to their high input usage efficiencies, decreased use of synthetic fertilizers and pesticides, and enhanced soil resilience and quality in a changing climate, they might increase agricultural output and ecosystem sustainability. This review briefly overviews sustainable agriculture, its components, and the potential to achieving overall sustainability by integrating innovative agronomic approaches and practices to meet the increasing demands for food while preserving the environment.

Keywords:*Agronomic practices, innovation, productivity and environmental sustainability*

1. Introduction

Agriculture is the world's largest industry and a major land use, providing 80% of the world's food and occupying most accessible land [1]. The agriculture industry plays a major role in the global economy's growth. Due to rising population and associated food security issues, developing nations still confront the most serious challenges. Increasing agricultural productivity using external inputs like pesticides and mineral fertilisers was the only way to increase food production in the 20th century [2,3]. At the price of diminishing natural resources, modern agricultural methods built upon the green revolution have resulted in a notable rise in grain production. Because of the externalisation of agriculture, soil fertility and environmental resilience deteriorated greatly [4]. It so demands alternative approaches that ought to educate farmers on how to apply their customary knowledge to yield greater grains while using less external inputs. Sustainable agriculture is the term for this approach, which is crucial right now.

Sustainable agriculture refers to farming practices that maximise the use of non-renewable resources, help the environment, and expand natural resources [5] without compromising the ability for current or future generations to meet their needs. Sustainable agriculture encompasses agricultural practices that are fair to the environment and enable the production of animals or crops without endangering human or natural systems. A viable way to allow agricultural systems to feed an expanding population while adjusting to changing environmental circumstances is through sustainable agriculture [6]. Sustainable agriculture helps the food production system become more resilient and stable by recognising and utilising ecological services. To ensure a safe and prosperous future for all, the current task is to keep creating and putting these sustainable methods into reality on a worldwide scale [7].

Integrated use of a range of soil, fertiliser, and pest management strategies, such as crop residue, manure, mixed cropping, and crop rotations methods have been promoted in sustainable agricultural [8, 9]. These methods improved soil quality, nutrient pools, climatic resilience, and ecosystem restoration while reducing soil degradation, which raised farmers' socioeconomic standing. The core tenet of sustainable agriculture is that productivity must increase while resource use must decrease. To accomplish the core objectives of sustainable agriculture, a variety of innovative alternative techniques have been put forth, including precision agriculture, water-saving agronomic techniques, IFS, INM, biofertilizers, conservation agriculture, and organic farming for soil management. With an emphasis on sustainable crop production, this review attempts to thoroughly investigate the developments in agronomic methods. The goal is to examine how these methods support achieving productivity balance while enhancing social welfare, economic viability, and environmental sustainability [10].

2. Advances in Agricultural Practices

The development of agronomic techniques from their historical foundations to contemporary advances illustrates how agriculture is a dynamic and adaptable industry. Obtaining an appreciation of this history is essential to understanding the current and future directions of farming techniques. Agronomy was originally entwined with the cycles of the natural world. The majority of these methods relied on rain feeding and emphasised regionally appropriate crop types [11]. Traditional practices ranged greatly, from terraced cultivation in hilly areas to the slash-and-burn approach in tropical woods [12]. These methods, which frequently used organic waste as fertiliser and were sustainable and well-suited to the local environment, however it is unable to support bigger population because of decreased productivity and the possibility of soil depletion [13].

These conventional practices saw a dramatic shift with the advent of modern agriculture. Beginning in the 1960s, the Green Revolution brought herbicides, synthetic fertilisers, and crop types with higher yields, significantly changing the agricultural landscape [14]. An important component of this revolution was mechanisation, which increased production and efficiency by substituting tractors and combine harvesters for most of the physical labour [15]. Governments all around the world started modifying their agricultural policies to accommodate these new technology, frequently offering subsidies for fertilisers and better seeds as well as encouraging monoculture methods that were motivated by consumer demand [16]. Agricultural techniques were revaluated when the effects of intensive farming practices on the environment and society became evident. This has led to the development of modern ideas and trends that aim to strike a balance between sustainability and productivity.

The desire for more effective and ecologically friendly farming methods gave rise to precision agriculture. Precision agriculture makes advantage of developments in big data analytics, IoT devices, and GPS technology to help farmers maximise the use of resources like pesticides, fertilisers, and water [17]. This strategy reduces farming's negative environmental effects while simultaneously increasing yield [18]. Another important development is organic farming, which substitutes natural solutions for artificial ones. Organic farming focuses on crop rotation, biodiversity preservation, eco-friendly seedinvigoration techniques [46] and the use of natural fertilisers and pest management to build a more sustainable agricultural environment [19]. Biological, cultural, and chemical methods are all included in integrated pest management (IPM), an all-encompassing approach to pest management. IPM tackles issues related to health and the environment by minimising the usage of hazardous chemicals. It has been shown to be successful in preserving agricultural yields while lowering the need for pesticides [20]. With the globe still facing issues like population increase, climate change, and environmental degradation, it is more important than ever for agronomic techniques to evolve such as INM, IFS, etc. Agriculture's adaptable character is shown by the shift from conventional to contemporary to creative, sustainable techniques, which reflects humanity's continuous effort to strike a balance between environmental stewardship and productivity.

3. Novel Agronomic Approaches for Sustainable Agriculture

Adopting cutting-edge strategies that seek to maximise environmental effect while maintaining production is essential to advancing sustainable agriculture [21]. These tactics are created with particular values and objectives in mind, frequently addressing the social, economic, and environmental facets of agriculture. While some strategies, like carbon farming, came into being with a strong focus on environmental policy, others, like agroecology and sustainable intensification, have evolved over time [22]. These strategies' flexibility enables them to accommodate a range of production circumstances and methods, frequently with well-established industry recognition and expert assistance, such organic farming [23,24].

3.1 Climate-Smart Agriculture (CSA): A key strategy for tackling the problems caused by climate change and how it affects agriculture is called "climate smart agriculture," or CSA. In order to increase productivity, adjust to a changing environment, and reduce greenhouse gas emissions, it strives to enhance agricultural methods. Due to the FAO's estimate that worldwide agricultural and livestock output must increase by 60% by 2050 compared to 2006 levels in order to fulfil demand, the need for CSA has grown as climate change poses a threat to food and nutrition security. With the aim of minimising environmental deterioration, CSA provides a thorough framework for accomplishing these objectives. The goal of CSA is to increase productivity while lowering greenhouse gas emissions by making improvements to soil and plant carbon sequestration [25].

A fundamental component of CSA is mitigation, which aims to cut or completely eradicate greenhouse gas emissions from agriculture. In order to do this, it promotes methods that allow plants and soils to function as carbon sinks, lowering the total carbon footprint of agricultural activity. By increasing agricultural yields, livestock output, and fisheries while reducing their negative environmental effects, CSA also seeks to increase food and nutritional security [26]. The strategy recognises that trade-offs may arise but can be controlled through efficient institutions, laws, and funding sources. It aims to strike a balance between the objectives of productivity, adaptation, and mitigation. The goal of CSA is to develop a more sustainable and resilient agriculture system that can both protect the environment and feed the world's expanding population.

3.2 Organic Farming: Millions of people across the globe are facing thepotential threat of heavy metal arsenic contamination throughgroundwater-soil-crop systems [51].Environmental preservation, animal care, food safety and quality, resource sustainability, and social justice are all prioritised in organic farming [27]. It makes use of market mechanisms to help achieve these goals and pay for internalised environmental externalities. The goal of organic farming is to establish humane, sustainable, and integrated production systems that manage biological and ecological processes, rely on renewable resources derived from farms, and ensure acceptable levels of crop, livestock, and human nutrition while offering a just reward for labour and other resources [22]. Numerous agricultural and ecological advantages come from organic farming. A component of organic farming is green manuring. The practice of ploughing under or incorporating any green manure crops into the soil while they are still green or shortly after they start flowering is known as "green manuring" [49].It encourages sustainable farming methods, biodiversity preservation, pollution reduction, and soil health. It uses less synthetic pesticides and emphasises biological pest management, natural fertilisers, and other environmentally beneficial techniques.

Additionally, organic farming is known to provide high-quality, chemical-free food [23], which is why people who are concerned about their health like it. Respect for the environment and animals, sustainable cropping practices, the use of non-chemical pesticides and fertilisers, the production of high-quality food, and the avoidance of genetically modified (GM) crops are some of the main characteristics of organic agriculture [28]. Food security is the goal of organic farming, which uses minimal external inputs and ecologically responsible methods [29]. It has become more widely accepted in society and provides farmers with chances to fulfil consumer demand for organic products while encouraging environmental stewardship.

3.3 Biodynamic Agriculture: An alternative to organic farming known as biodynamic agriculture blends organic methods with metaphysical ideas derived from Rudolf Steiner's teachings. It is among the first movements in organic agriculture, having been founded in 1924. Creating a harmonious interaction between the earth, plants, and animals is the main goal of biodynamic techniques, which frequently take cosmic rhythms like solar and lunar cycles into account to direct planting and harvesting. Organic farming and biodynamic farming both refrain from using synthetic chemicals and genetically modified organisms. Regenerating the soil, giving life back to plants and animals, and eventually healing the world are the goals of biodynamic methods. Both organic and biodynamic farming exclude synthetic inputs, while biodynamic farming emphasises sustainability and adaptation to different climates, promoting a broader ecological approach. By encouraging farmers to match their operations with natural cycles, this strategy strengthens agricultural resilience and fosters a closer relationship with the environment.Nowadays, researchers arefocusing more on eco-friendly seed invigorationtechniques to improve seed germination anduniform crop establishment.Vrikshayurveda, apart of Ayurvedic history is an ancient science ofplant life which deals with healthy growth ofplants and its productivity [48].

3.4 Integrated Farming Systems (IFS): A method to agriculture known as integrated farming systems (IFS) blends several forms of production, such fish and livestock or cattle and grains. This integration is akin to natural ecosystems, in which disparate components coexist together and "waste" from one becomes an input for another. Farmers may lower expenses, cut waste, and boost income and production by using IFS. The idea is founded on a circular economic paradigm, in which all elements of the system work together to support one another and nothing is really wasted. Combining crops with other aquatic plants and animals, fish, birds, and other wildlife is a common practice in integrated agricultural systems [30]. By lowering competition for resources like water and nutrients through crop rotation, intercropping, and mixed cropping, this strategy can increase biodiversity. Increased production and more effective agricultural management may result from this variety. Beyond efficiency, IFS can improve ecological sustainability by encouraging natural cycles in the agricultural system and lowering the demand for artificial inputs [31]. Farmers may increase yields and contribute to a more sustainable agricultural model by establishing linked subsystems. This all-encompassing method of farming is consistent with sustainability, offering a foundation for healthy and ecologically responsible farming operations.

3.5 Integrated Nutrient Management (INM): INM refers to the maintenance of soil fertility and of plant nutrient supply at an optimum level for sustaining the desired productivity through optimization of the benefits from all possible sources of organic, inorganic and biological components in an integrated manner. One of the most important agronomic management practices is integrated nutrient management (INM), which focuses on fertiliser nutrient supply to meet crop requirements while minimising input costs [32]. The INM also employs the use of certain microorganisms along with a minimum effective dose of adequate and balanced amounts of organic and inorganic fertilisers. Blending chemical fertilisers with organic manure is turning out to be a very good strategy for maintaining production, enhancing soil health, and guaranteeing environmental advantages in addition to a larger yield output. For the proliferation of soil microorganisms, the organic component of integrated nutrient management provides accessible nitrogen, organic carbon, and energy. A major goal of integrated nutrient management (INM) is achieving environmental benefits. This is accomplished by fusing the beneficial qualities of both organic and inorganic sources to create a blend that can be used to reduce the use of chemical fertilisers sparingly, maintain a balance between fertiliser inputs and crop nutrient requirements, improve soil fertility, maximise yield, maximise profitability, and minimise pollution [33].

3.6 Site-specific crop management (SSCM)/Precision Farming: Site-specific crop management (SSCM), sometimes referred to as satellite farming or precision agriculture (PA), is a farming technique that uses technology to enable farmers to monitor, assess, and control crop variability within and between fields [34]. The goal of this technique is to create a decision support system (DSS) that will optimise resource conservation and input utilisation for whole-farm management. In order to increase crop yields and facilitate wise management decisions, precision farming makes use of cutting-edge technology, data analysis, and sophisticated sensors [34]. An essential part of precision farming is site-specific management (SSM), which emphasises "doing the right thing at the right time and in the right place [36]. This method adjusts agronomic procedures to particular field circumstances by using yield monitors, remote sensing, and variable rate applications (VRA) [37]. With the development of GPS and GNSS technology, farmers are now able to produce intricate maps that illustrate the regional variability of important agricultural factors, facilitating the accurate application of inputs such as pesticides, fertiliser, and water [38]. Improved crop quality, decreased environmental impact, and more efficient use of resources are just a few advantages of precision farming. By maximising the use of essential inputs, it encourages sustainability by increasing yields, lowering the need for fertiliser and pesticides, conserving fuel, and improving water management [39].

3.7 Agroforestry: The deliberate blending of land-use systems based on forestry and agriculture, or agroforestry, has several advantages for long-term sustainability. This strategy may restore damaged areas, protect delicate ecosystems, and diversify agricultural production methods. Agroforestry techniques support environmental quality and the preservation of ecosystem variety when paired with ecologically focused land management. Agroforestry offers benefits to the environment and economy alike, particularly when it comes to mitigating the drawbacks of contemporary agriculture and advancing sustainable natural resource and agricultural systems. [13]. It does this by establishing integrated systems that serve economic and environmental objectives, so bridging the gap between forestry and agriculture. Agroforestry may defend against wind and water erosion, increase yearly plant yields, and assist agricultural systems in adapting to and mitigating the consequences of climate change [14]. Agroforestry also uses strips of land with trees and bushes to provide habitats and refuges for various plants and animals. All things considered, agroforestry is a sustainable method of using land that promotes better biodiversity, resource management, and environmental issue adaptation. Because it encourages environmental care and long-term productivity, it is consistent with the tenets of sustainable agriculture [25].

3.8 Natural farming

It is an environmentally friendly practice similar to organic farming, developedin Japan during 1935. Unlike conventional farming, natural farming improve soil health byaltering soil microbial diversity and also act as defence to plant pathogens. Soil can besupplemented with microbial inoculums like *Panchagavya, Beejamruth, Jeevamruth andKunapajala* to hasten the soil micro flora propagation and as soil enrichment. Theseindigenous concoctions are very significant to nurture the growth of soil microorganismswithout adding external inputs [50].

4. Advancement in Modern Agronomic Practices

With an emphasis on productivity, sustainability, and adaptability to environmental changes, agronomic techniques have developed to meet the demands of contemporary agriculture (Table 1).

Table 1. Advancement in modern agronomic practices

Particulars area	Description	Examples

Sustainable Practices	Approaches that promote environmental stewardship.	➢ Organic farming ➢ Conservation tillage ➢ Agroforestry
Climate Resilience	Strategies to adapt and mitigate the impacts of climate change.	➢ Drought-tolerant varieties ➢ Crop diversification ➢ Weather forecasting models
Soil Management	Techniques to maintain or improve soil health and fertility.	➢ Crop rotation ➢ Cover crops ➢ Organic amendments
Precision Agriculture	Use of technology to optimize field-level management.	➢ GPS-guided equipment ➢ Remote sensing ➢ Data analytics for decision making
Irrigation Technology	Improvement in methods to supply water to crops.	➢ Drip irrigation ➢ Sprinkler systems ➢ Computerized irrigation control
Crop Genetics	Development of crop varieties with enhanced traits.	➢ Genetically Modified Organisms (GMOs ➢ Hybrid crops ➢ Disease-resistant strains
Pest and Disease Control	Methods to protect crops from pests and diseases.	➢ Integrated Pest Management (IPM) ➢ Biological control agents ➢ Pesticides and herbicides
Farm Machinery and Automation	Advances in machinery and automation for farming efficiency.	➢ Autonomous tractors ➢ Drones for monitoring ➢ Robotic harvesters

With an emphasis on resilience, productivity, and sustainability in an ever-changing agricultural environment, these major areas of improvement reflect the continuous evolution of agronomic methods. Sustainable agriculture is supported by methods that improve soil health, such as crop rotation, cover crops, and the application of organic amendments. Crop irrigation efficiency has increased thanks to innovative techniques for delivering water; integrated pest management

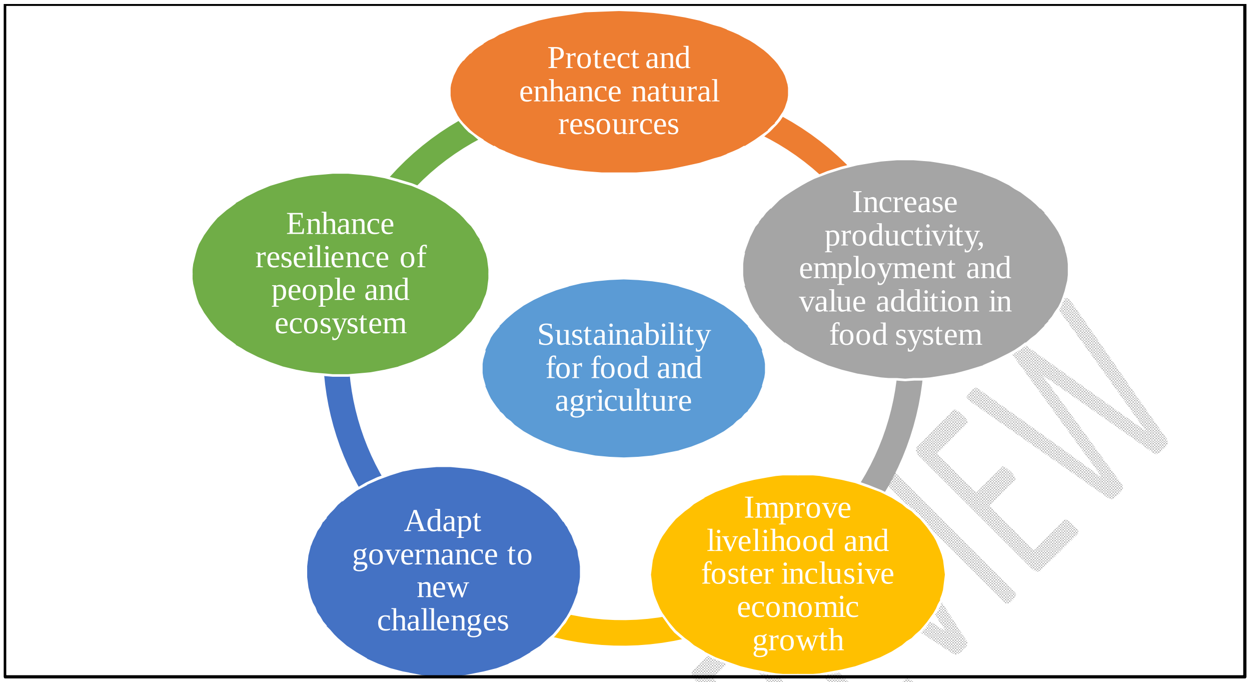
(IPM), which combines biological, chemical, and cultural controls to reduce the need for pesticides, is one such technique for safeguarding crops against pests and diseases [40]. Farmers can now apply inputs more precisely thanks to these technology, which lowers waste and boosts output. Environmental stewardship-focused strategies are becoming more popular. Sustainable farming strategies that boost agricultural production and ecological health include agroforestry, conservation tillage, and organic farming [41].

5. Balancing Productivity with Environmental Sustainability

Agricultural productivity aims to preserve the natural resource foundation that underpins future food production while also helping to feed the world's growing population. The importance of agriculture is growing, and it will continue to do so in light of the industry's projected continued expansion, the most recent developments in agricultural technology, and the shift to sustainable agricultural practices [42,43]. Farmers today mostly rely on outside inputs for their farming operations, which seriously harms theenvironment. Using locally available resources, this subject led the current inquiry to concentrate on old (ortraditional) methods that improve agricultural growth and development without harming the environment [47].As a result, an integrated approach to agricultural systems is not only appropriate but also required.

One of the biggest issues facing agriculture today is striking a balance between sustainability and production. The two objectives complement one another and are not mutually incompatible. A range of instruments and strategies known as Sustainable Food and Agriculture (SFA) are intended to guarantee the social, environmental, and financial sustainability of food production and consumption with 5 key principle (Fig. 1). In addition to reducing severe hunger and promoting food security, SFA also seeks to safeguard the environment, guarantee healthy lifestyles, and advance prosperity for all people, regardless of age. There are significant disparities in the philosophies, methods, and degrees of execution among the many nations that have previously made steps and endeavours to reform their food systems.

Fig. 1: Sustainability for food and agriculture key principles



(Source: FAO [44])

The primary challenge facing global agriculture is meeting the rising demand of an estimated 9 billion people by the year 2050, when there will be approximately 7 billion people on Earth. The expansion of productive agricultural land is limited, and climate change may further impede efforts to strike a balance between productivity and sustainability. The demand for food and other agricultural products is expected to increase by 50% between 2012 and 2050. To attain balance, additional development alternatives include: (i) advocating for conservation agriculture and good agricultural practices; (ii) encouraging mechanisation through robotics and ICT; (iii) growing value chains and agro-processing; (iv) enhancing food safety and quality compliance through institutional development and international collaboration for building capacity to handle Sanitary and Phytosanitary measures (SPS) standard and certification compliance; and (v) knowledge creation and technological advancement [45]. The development of climate-smart agriculture technologies must prioritise increases in output and resource efficiency.

6. Way forward

A holistic strategy that incorporates cutting-edge agronomic techniques, environmental physiology, and effective plant nutrition is essential for the future of sustainability. Climate change and population expansion are increasing the need for food, and sustainable agriculture has to adapt to meet these demands while reducing its negative effects on the environment. The application of technology to increase productivity and accuracy will be a crucial component of future agronomic techniques. Another crucial subject is sustainable soil management, which focuses on methods for restoring and preserving soil health. The use of organic amendments, decreased tillage, and cover crops—practices that enhance soil structure and biodiversity—are anticipated to proliferate. These methods not only improve soil fertility but also lessen erosion and sequester carbon. Agriculture that is robust to climate change is essential.

The development of cultivars that are more resilient to harsh weather, such heat- and drought-tolerant ones, will be a future strategy. Farmers may avoid climate-related risks and ensure steady crop production despite changing climates by using diverse cropping systems and utilising modern weather forecasting models. The study of plant reactions to stresses, or environmental physiology, will remain crucial to sustainable agriculture. Sustainable agriculture relies heavily on plant nutrition, and new strategies will try to maximise nutrient utilisation while reducing environmental effect. More effective fertiliser applications will be made possible by precision agriculture, and environmentally friendly substitutes like plant growth-promoting microorganisms (PGPMs) and biofertilizers will become more popular, improving soil health and lowering the demand for synthetic fertilisers.

In the approach for balancing productivity with sustainable agriculture, the incorporation of ecosystem-based practices like permaculture and agroforestry will be crucial [31]. These methods improve biodiversity, support a more balanced agroecosystem, and offer ecosystem services. To promote innovation in sustainable agriculture, cooperation between scientists, farmers, legislators, and industry stakeholders is crucial. Encouraging sustainable practices through supportive policies and regulations is essential to building a resilient and productive agriculture sector. To summarise, a comprehensive strategy that integrates cutting-edge technology, climate resilience, and environmentally friendly practises is necessary for the future of sustainable agriculture. By embracing these strategies, sustainable agriculture can meet global food demands while safeguarding the environment for future generations.

7. Conclusion

Achieving sustainable agriculture and production balance without endangering the environment for coming generations is possible and a must. Understanding and properly managing the components of sustainable development is possible. To meet the increasing needs of a world population that is growing at a rapid pace, advanced agronomic practices, environmental physiology, and effective plant nutrition must be integrated. The major objective is to preserve long-term ecological health and reduce environmental effect while producing an adequate amount of food. Organic additions and proper soil management strategies are becoming more popular because they enhance ecosystem services and preserve soil health. Another crucial area of research is climate resilience, which includes techniques like creating crops resistant to drought and utilising weather forecasting models to adjust to a changing environment. The issues of food security may be met while protecting the environment for future generations by combining sophisticated agronomic methods, environmental physiology, and effective plant nutrition. Maintaining an agricultural industry that is resilient and productive will need a continuous commitment to innovation and sustainability.

Disclaimer (Artificial intelligence)

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

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