Climate Smart Agriculture: The Role of Fertilizer Innovations and Efficient Plant Nutrient Management

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Abstract

Climate change has emerged as a significant threat to the global agro-economy, adversely affecting agricultural productivity, food security, and local and global agricultural development goals. To ensure sustainable crop productivity and meet future demands, it is essential to take prompt actions to address the current challenges of lower agricultural productivity due to climate change. Climate-smart agriculture (CSA) is a novel concept that offers a promising approach to tackle these challenges by introducing sustainable farming practices that minimize negative environmental impacts and enhance resilience to climate change. It involves realigning current agricultural practices and introducing smart techniques to reduce the adverse effects of agriculture that contribute to climate change and higher carbon footprints. The importance of climate-smart fertilizers in agricultural productivity cannot be overemphasized, as the soil is susceptible to structural changes and alterations in nutrient availability due to climatic impacts. Therefore, the implementation of proper nutrient management mechanisms and advanced fertilizer innovations has become a top priority in implementing the concepts of CSA. Consequently, there has been a greater focus on introducing more climate-adaptive and resilient plant nutrient delivery systems and technologies in recent times. For instance, nanofertilizer, bio-based controlled-release and slow-release fertilizers have provided a more sustainable and climate-friendly alternative to traditional synthetic fertilizers. Despite the innovations, challenges remain in implementing CSA practices and practices of climate-smart fertilizers at scale. This is largely attributed to the lack of proper knowledge and a streamlined policy framework on climate resilience in agriculture and fertilizers. This article seeks to review the role of fertilizer innovations and nutrient management in CSA, targeting the reduction of nutrient losses due to climate changes. It also examines the current status of climate-smart fertilizers with a particular emphasis on the current implementation challenges and future prospects in fertilizer production, leading to global food security by adapting to climatic changes. By highlighting specific examples of modern climate-smart agriculture and

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fertilizer management, this article aims to provide insights into the potential benefits and challenges of implementing CSA practices and encourage further research and development in this important field.

Keywords: Climate-smart agriculture, Climate-smart fertilizers, Climate change, Nutrient Management, Innovations in fertilizers

1.Climate change and sustainable agriculture

Sustainable agriculture is defined as "an integrated system of plant and animal production practices having a site-specific application that will over the long term satisfy human food and fiber needs" (Title 7. Agriculture, 2018). The main aim of sustainable agriculture is to get maximum benefits from the existing resources for the current inhabitants while maintaining the ecosystem's balance for future generations. In the recent past, as a consequence of exhausting the ecosystems, the globe has undergone irreversible climatic change, affecting all aspects of life on Earth. Climate change is a significant, anomalous variation of average weather conditions over a long period of time. The main causes of climatic changes have been identified as the gradual increase in the release of greenhouse gases after industrialization, changes in the sun's and earth's orbits, extensive agricultural practices, human activities, and changes in solar radiation intensity. Climate changes include changes in temperature, rainfall, snowfall, precipitation, and atmospheric gas levels (Mahato,2014). Its adverse effects on agriculture productivity and food security have already been demonstrated through the unexpected increase in global temperatures, variation in weather patterns, the shift in agroecosystem boundaries, the appearance of invasive crops and pests, and more frequent extreme weather events. Effects of climate change have generated serious consequences in agriculture including reduced crop yields, decreased nutritional quality of major cereals, and lowered livestock productivity. As a result, agricultural productivity and food security have been threatened more than ever. Substantial economic and scientific investments and adaptations are needed to maintain current yields, achieve higher production rates, and maintain food quality to meet increasing demand.

Realizing the future threats, the United Nations has already focused on introducing novel mechanisms called "climate-smart agriculture practices (CSA)" to manage the adverse effects on agriculture. CSA practices majorly focus on the adaptation of crops to climate change by introducing innovative mechanisms of fertilizer, weed control, pest management, water management, genetic rotation, and shifting in crop production. CSA practices have three main approaches known as the "Triple Win": increased productivity, enhanced resilience, and reduced emissions of greenhouse gases (Figure 1) (CLIMATE SMART AGRICULTURE, 2021; Gardezi et al., 2022).

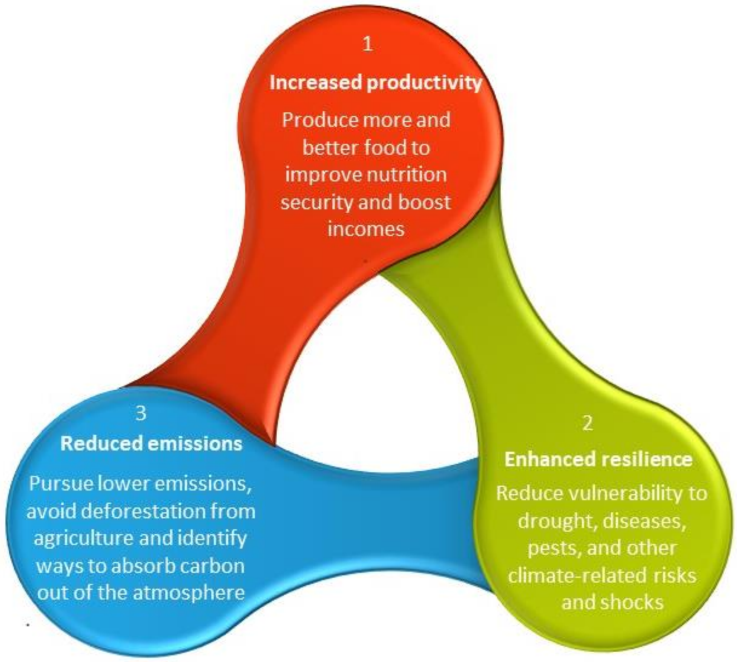

Figure 1: Triple win in Climate Smart Agriculture.

Smart fertilizers are one of the key factors that ensure the realization of the goals of CSA. The development of climate-smart fertilizers is still a challenge for scientists, and novel formulations and application methods are constantly being explored. This article reviews the role of fertilizer innovations and management in climate-smart agriculture, targeting the reduction of nutrient losses due to climate changes, the current status of climate-smart fertilizers with a particular focus on the current challenges in implementation, and the future prospectus in fertilizer production. The review will also emphasize a wider scope of the new practices and inventions toward enabling global food security by adapting to climatic changes. Finally, the effect of innovations on the environment as well as public health along with their future perspectives is analyzed.

2. The status quo

2.1 *Role of fertilizers in CSA*

Fertilizers play a central role in maintaining soil fertility and increasing crop growth and yield as indirect energy sources (Celikkol and Guven, 2017). Fertilizers are natural or synthetic chemical substances that contain essential plant nutrients to increase crop yield. Along with the increase in global population and high demand for food, an increase in crop productivity is required, and chemical fertilizers have provided the template for ensuring crop productivity. The choice of type, dosage, and method of application of fertilizers are the key to sustainable crop

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management (Hlisnikovsky et al., 2020). An ideal fertilizer should have at least three characteristics; minimum detrimental effects on the environment, the ability to provide the necessary amount of nutrients by a single application throughout the life cycle, and a high maximum percentage recovery(Trenkel, 1997).

Inorganic synthetic fertilizers are the most common forms of plant nutrients, where urea, triple superphosphate, and mutate of potash provide the key nutrients nitrogen, phosphorous, and potassium, respectively. While they are the most efficient mode of providing macronutrients, they have their inherent drawbacks. Most inorganic fertilizers, in particular nitrogen fertilizers, have resulted in a spectrum of environmental impacts, such as an increase in NO_x emissions, the aggravation of nitrate leaching, and the promotion of soil and water acidification due to their high solubility (Chen et al., 2021). For instance, an average of 14.5% of N in urea is lost due to volatilization. However, the percentage could be extended up to 64% in different instances (Schwenke, 2021). Groundwater contamination is a major and common problem for phosphate fertilizers. This leads to several issues such as eutrophication, scalability, and solubility (Arcand and Schneider, 2006). Potassium is the other major plant nutrient found in fertilizers and has issues with scalability and solubility. Therefore, reducing fertilizer input is of great importance in realizing the goals of CSA.

Furthermore, 4R nutrient stewardship shown in Figure 2 has provided the baseline to achieve CSA goals, increased production, increased farmer profitability, enhanced environmental protection, and improved sustainability with best management practices (BMP) (Khosla, 2014).

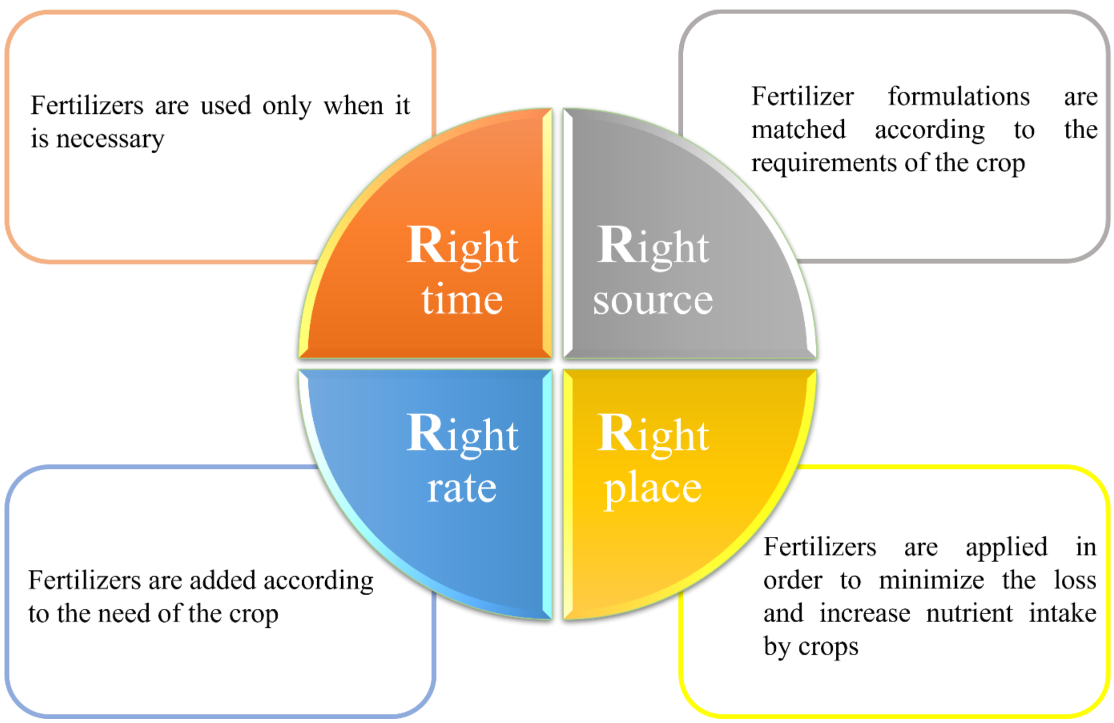

Figure 2: 4R Principles of Nutrient stewardship.

2.2 *Role of climate-smart fertilizers*

2.2.1 Reducing *greenhouse gas emissions*

One of CSA practices' main aims is to reduce greenhouse gas emissions (GHG) from agricultural practices. Anthropogenic greenhouse gases which are emitted during agricultural practices are shown in Figure 3 (Jantke et al., 2020). The total emission of greenhouse gases from agricultural fields has increased by 16% from the years 1990 to 2019 (The share of agri-food systems in total greenhouse gas emissions, 2021). The excessive application of chemical fertilizers causes the deterioration of atmospheric conditions due to the emission of greenhouse gases like N_2O, NO, CO_2 and CH_4. Gases such as N_2O and NO can be released directly from nitrogen fertilizers or indirectly via the volatilization of ammonia (Branca et al., 2021). Mainly, nitrogen fertilizers used in agriculture contribute to climate change through eutrophication, volatilization, and contamination of groundwater bodies (Shah et al., 2021). Although carbon dioxide is considered the major reason for unpredictable climatic changes, nitrous dioxide is more potent than carbon dioxide in trapping heat (Lazcano et al., 2021; Shah et al., 2021). CO_2 is produced mainly in the synthesis and transportation processes of fertilizers (Kakraliya et al., 2021). It can be emitted not only in crop applications but also in the synthesis processes of fertilizers (Branca et al., 2021). It is required to reform the fertilizer industry and make changes in fertilizer management practices to minimize excessive nitrogen use in agriculture. Better adaptation practices are required to reduce the consequences caused by climatic changes.

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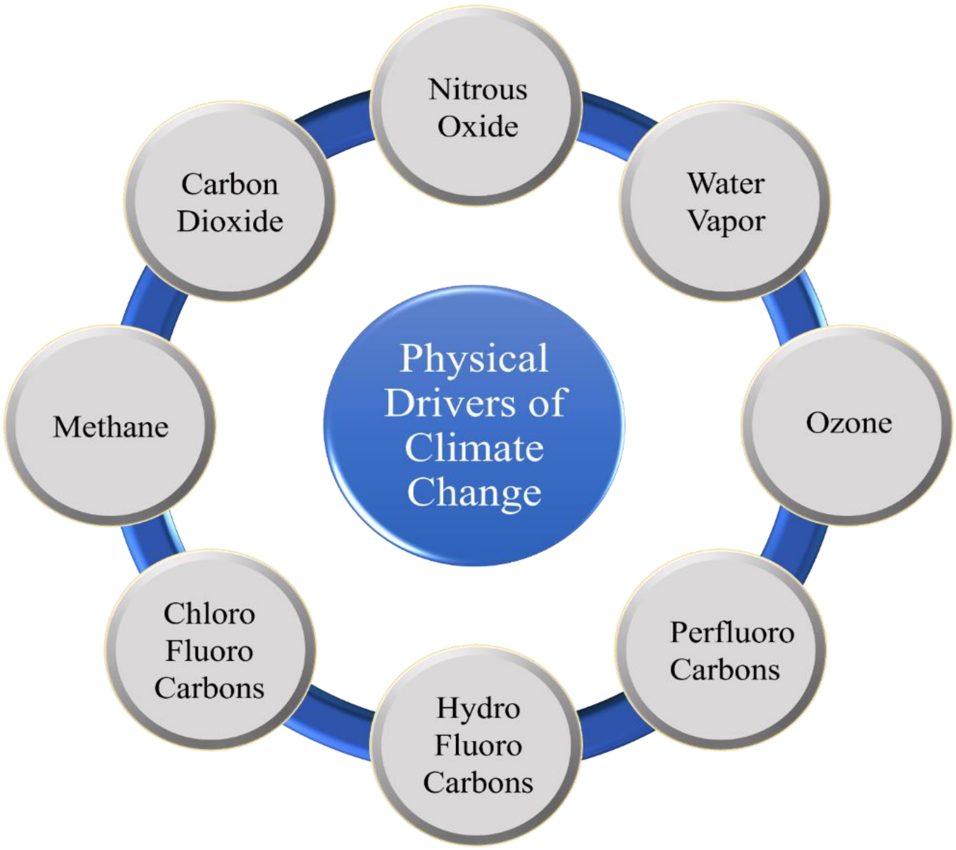

Figure 3: Physical Drivers of Climate Change (Green House Gases).

The reduction of GHG has been achieved not only by using new fertilizer variations but also by changing fertilizer application practices with existing fertilizers. China has been able to cut down the emissions related to nitrogen fertilizers by 20-63% by minimizing the overuse of N fertilizers and enhancing the energy efficiency in manufacturing fertilizers (Zhang et al., 2013). Operations that involve fuel consumption such as machinery and irrigation scheduling have been improved in the process of enhancing energy efficiency (Snyder et al., 2009) .

Slow and controlled fertilizers and stabilized nitrogen fertilizers with nitrification and urease inhibitors have been used to minimize the nutrient losses to the environment either as GHG or other methods (Trenkel, 1997). Controlled, or slow-release fertilizers can reduce the volatile N losses as NO_2 and NH_3 and leaching losses as NO_3^- (Shaviv, 2001). Fertilizers that contain inhibitors block the conversion of nutrients into volatile species by microorganisms. For instance, the urease enzyme inhibitor blocks the conversion of urea into ammonium, which will be ultimately converted into NO_2. Moreover, urea incorporated with dicyandiamide which is a nitrification inhibitor, and polyolefin have displayed the potential to be used as alternatives to reduce GHG emissions (Delgado and Mosier, 1996).

2.2.2 *Drought mitigation*

Drought is one of the climatic stresses that plants are experiencing during their growth and development due to the inhibition of nutrient flow mechanisms such as osmosis and diffusion (Sedghi et al., 2013). Droughts that arise due to current patterns and trends in the emission of greenhouse gases, can result in dry soils that are unsuitable for most plants' growth (Dai, 2011). For example, the drought resistance index of barley grown using organic fertilizers is statistically higher than that of barley grown using mineral fertilizers. This was because the trace elements and ingredients in organic fertilizers have caused more significant physiological and biochemical changes than those in mineral fertilizers. Increased water holding capacity, soil penetration resistance, decreased soil bulk density, reduced leaf injury, high water content, and membrane stability of leaves are physiological and biochemical aspects of organic fertilizers (Januskaitiene et al., 2021; Singh et al., 2019). Therefore, farmers residing in drought-prone areas like Ethiopia and Nigeria have been advised to use organic manures to enhance the soil-water -retention which controls the overall performance of plants during droughts (Amujoyegbe et al., 2007; Januskaitiene et al., 2021; Singh et al., 2019).

Micronutrients such as zinc, boron, and copper play a significant role in adapting plants for drought seasons (Dimpka et al., 2017). Zn which is required for plants in very minute concentrations assists to withstand extreme climatic conditions such as droughts by the regulation of water intake through the regulation of stomata, osmolyte accumulation, and stabilizing the cell membrane (Shah et al., 2021; Umair et al., 2020). Under drought conditions, ionic micronutrient formulations and nano formulations that are applied as fertilizers to the soil can help the plant withstand the harsh conditions (Dimpka et al., 2017).

Countries in Sub-Saharan Africa, Kenya, Uganda, and Indonesia experience more frequent droughts throughout the year (Gram et al., 2020; Kolot and Panen, 2021; Paul et al., 2020, Rware et al., 2020). Therefore, a combination of organic and mineral fertilizers has been used as a climate-smart integrated soil fertility management practice (Kolot and Panen,2021). The studies have shown that integrated usage of organic and inorganic fertilizers in Sub-Saharan Africa can result in greater agronomic effectiveness when compared to separate applications of each component (Gram et al., 2020). The higher agronomic effectiveness is explained by three major factors. The first factor is the increase in soil fertility through the application of fertilizers containing both major and macronutrients in desired amounts (Sanginga and Woomer, 2009). The second factor is the increase in the effectiveness of biological processes and the resilience in drought as a result of an increase in soil fertility and its organic matter. The third factor is the high effectiveness in nutrient uptake and mobility due to the integrated application of fertilizers (Gram et al., 2020).

The application of potassium and amino acid fertilizers to wheat as foliar fertilizers has also increased the plants' tolerance to drought stress by reducing the osmotic stress (Adhikari et al., 2020; Ahmad et al., 2019). In drought conditions, the application of potassium increases the yield, while the application of amino acids increases the growth index (Ahmad et al., 2019).

2.2.3 *Effect of High rain falls*

Phosphorous and nitrogen fertilizers are most susceptible to loss during heavy rainfalls due to solubilization and leaching. The most commonly used phosphate fertilizers such as single superphosphate (SSP), triple superphosphate (TSP), mono ammonium dihydrogen phosphate

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(MAP), and diammonium hydrogen phosphate (DAP) originate from rock phosphate and can be lost totally or partially during rainfalls (Everaert et al., 2018). When soil is saturated with water, rainfall increases the risk of surface P loss, which is applied as fertilizers such as TSP, SSP and this may cause another serious environmental risk known as tutrophication (Jian et al., 2016; Sharpley and Moyer, 2000).

It is reported that Struvite, which is a phosphate mineral, is a poorly soluble slow-release phosphorous fertilizer. However, the efficiency of struvite is similar to currently available phosphorous fertilizers (Everaert et al., 2018; Hao et al., 2013). P-exchanged layered double hydroxides (LDH) and clay minerals have gained attention as a phosphate fertilizer which could reduce the surface runoff of fertilizer (Everaert et al., 2018). Efficient slow-release formulations containing nitrogen and phosphorous-anchored hydroxyl apatite and silica nanoparticles have been reported by Kottegoda et al (de Silva et al., 2020; Kottegoda et al., 2017).

2.2.4 *Role of controlled/slow-release fertilizers in climate-resilient agriculture*

Fertilizers are developed by encapsulating plant nutrients into various carriers and coatings to increase efficiency and reduce premature loss by volatilization and leaching during climatic changes (Allen, 1984). Controlled-release fertilizers (CRFs) and slow-release fertilizers (SRFs) are types of fertilizers that release nutrients slowly over time, providing sustained feeding to crops. The release rate is usually determined by the fertilizer composition, soil temperature, and moisture (Figure 4). They typically provide nutrients to crops for several months to a year, depending on the product. These fertilizers can improve nutrient use efficiency and reduce fertilizer application frequency, resulting in economic and environmental benefits.

Coating materials play an important role in producing controlled-release climate smart fertilizers as they enable the controlled release of nutrients to plants to match the plant's uptake requirements. SRFs release nutrients over a longer period than conventional fertilizers and they either in a water-insoluble form or are bound to a slowly decomposing organic material. Some SRFs may have a coating or a membrane too. For example, sulfur-coated urea has demonstrated controlled release properties, and it has been commercially used (Sarkar et al., 2021; Wilson et al., 2008). The coating of the fertilizer is impermeable, and it can be degraded either physically, chemically, or by microorganisms (Dimkpa et al., 2017). However, the release of nitrogen from sulfur-coated fertilizers is unpredictable due to varying soil conditions such as soil temperature, moisture, and pH. Varying soil conditions cause a burst effect in which nutrients are released immediately in contact with water, and the remaining sulfur can cause acidification of the soil. Therefore, it has created problems in plants that require high amounts of nitrogen for their growth and development. Experimentally the nutrient release rates can be measured using water release studies and soil release studies. For example, the nitrogen release rate from urea- hydroxyapatite SRF has been investigated using a rapid water release study using FTIR spectroscopy (Kottegoda et al., 2017).

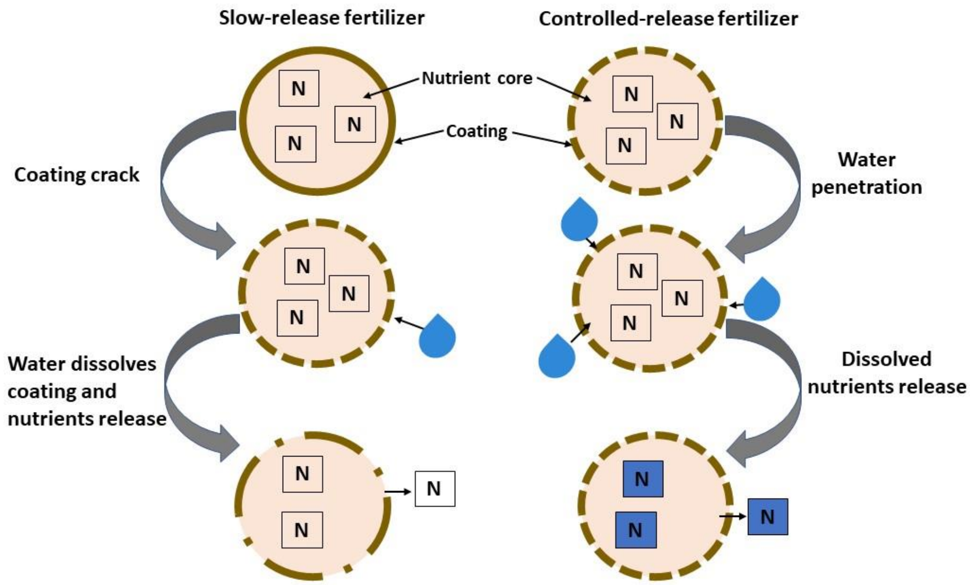

Figure 4: Slow-release fertilizers and controlled-release fertilizers

The modest technique of slow-release fertilizers is the development of polymer-coated fertilizers, especially polymer-coated nitrogen fertilizers (Jones et al., 2007; Landis et al., 2009). They are much more advantageous and efficient when compared to applying liquid fertilizers in rainy climates (Landis and Dumroese, 2009). The precise and controlled release of fertilizer or nutrients is controlled by the composition and thickness of the polymer coating which surrounds the inner nutrient core, the composition of the fertilizer, and the concentration of fertilizer (Shavit et al., 1997; Subbarao et al., 2013). Polymer coatings can be used for the efficient release of macronutrients such as nitrogen, potassium, and micronutrients like magnesium and calcium (Landis and Dumroese, 2009). The major problem with this technique is that most of the polymers are not easily biodegradable and may lead to various problems in soils (Lawrencia et al., 2021).

The most dependable and biodegradable coating materials in climate-smart agriculture practices are those that are derived from natural sources such as chitosan, lignin, and cellulose. These materials have the advantage of being renewable, biodegradable, and non-toxic making them more environmentally friendly than synthetic coatings (Zhou et al., 2015).

Table 1: Different Coating materials used in climate-smart agriculture

Coating Material	Applicability in Climate-Smart Agriculture	References

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Polymer coatings	Suitable for controlled release of nutrients and protection against leaching in acidic soils	(Du et al., 2006; Jarosiewicz et al., 2003; Morgan et al., 2009)
Calcium carbonate coating	Useful in alkaline soils to prevent nutrient loss and reduce soil acidity	(Abhiram et al., 2023)
Chitosan coatings	Can improve nutrient uptake by plants and reduce soil erosion, antimicrobial	(Gumelar et al., 2020; Li et al., 2019; Wu and Liu, 2008)
Lignin coatings	Can produce environment-friendly, and biodegradable fertilizer	(Lu et al., 2022)
Cellulose derivatives	Improve water absorbency and water-retention capacity of soil	(Zhang and Yang, 2021)
Attapulgite	Allow better synchronization between nutrient availability and plant needs in semi-arid climates	(Guan et al., 2014)

Struvite is a slow-release fertilizer that does not require frequent application, and the absorption rate is high before leaching out (Wang et al., 2005). It is an effective fertilizer as traditional ammonium-phosphorous fertilizer (Min et al., 2019; Wang et al., 2005). Struvite can be modified into slow-release fertilizers with both macro and micronutrients (magnesium and copper). The modification is done by combining ammonium struvite ($MgNH_4PO_4.6H_2O$) with metals of those elements of interest. It is reported that the agronomic efficiency of struvite is similar to some of the commercially available fertilizers (Arslanoglu, 2019; Arslanoglu and Tumen, 2021; Salutsky and Steiger, 1964). Therefore, farmers lack interest in using struvite as a phosphorous fertilizer. Moreover, the high production costs and the high selection of raw materials contribute to the lack of interest among farmers (Hao et al., 2013).

The production cost for slow and controlled-release fertilizers is relatively high and requires complex techniques. The production cost can vary depending on the specific type of fertilizer and the materials used in the coating. According to a study published in the journal 'Agriculture' in 2019 the production cost of slow-release fertilizers is generally higher than the traditional soluble fertilizers, with costs ranging from $500 to $1000 per ton for slow-release fertilizers compared to $200 to $400 per ton for traditional fertilizers (Wang et al., 2019). Further, most slow and controlled-release fertilizers do not possess water retention capacity which is the ability to hold water depending on the texture and composition of the fertilizer (Zhou et al., .[54] Therefore, high-performance fertilizers are required as a remedy for the above-mentioned issues. The development of new concepts for slow-release fertilizers should be more cost-effective with a better estimation of their effect on the economy and environment and with a better understanding of the performance of slow-release and controlled-release fertilizers.

Furthermore, some other slow-release fertilizers that can be used in harsh environmental conditions are listed according to Table 1.

Table 2: Slow and controlled-release fertilizers

Slow/ controlled release fertilizers	Synthesis	Nutrients	References
Apatite to phosphoric slow-release fertilizer	Mechanochemical reaction between Apatite, H_2SO_4, $(NH_4)_2SO_4$	P	(Chen et al., 2018)
Slow-release fertilizers by urea form	The condensation reaction between Urea, Formaldehyde	N	(Alexander and Helm, 1990)
Slow-release fertilizers by charcoal	Charcoal impregnated with a pellet-type fertilizer containing N, P, K, Mg, Fe, B, Mn, Zn, Cu, Mo	N, P, K	(Khan et al., 2008)
Slow-release fertilizers by zeolite	Zeolite nanocomposite impregnated by nutrients (N, P, K, Ca, Mg, S, Fe, Zn, Cu)	N, P, K, Fe, Mg	(Lateef et al., 2016)
	Surfactant-modified zeolite loaded with KH_2PO_4	P	(Bansiwal et al., 2006)
	Zeolite loaded with $NH_4H_2PO_4$ and K_2SO_4	N, K	(Li et al., 2013)
Slow-release fertilizers by graphene oxide films	Graphene oxide encapsulated with KNO_3	K	(Li et al., 2019)
	Chitosan-graphene oxide nanocomposite film coated KNO_3	K	(Andelkovic et al., 2018)
	Graphene oxide-Fe (III) composite containing phosphate	P	(Zhang et al., 2014)
Slow-release fertilizers with biochar	Mg-bio char composite with phosphate solutions	P	(Yao et al., 2013)
	Biochar impregnated with NH_4NO_3, KH_2PO_4, and SSP	N, P, K	(Gwenzi et al., 2018)
	NH_4^+ loaded biochar incorporated with a polymer matrix using microwave irradiation	N	(Wen et al., 2017)
Controlled release fertilizers by lignin	Lignin coated urea	N	(Mulder et al., 2011)

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	Trapping of urea/ hydroxymethyl urea/ urea-formaldehyde with lignin	N	(Jiao et al., 2018)
	Lignin and poly (vinyl acetate) (PVAc) as bio-coated urea	N	(Dos Santos et al., 2021)
	Lignin and ethyl cellulose-coated urea	N	(Fernandez-Perez et al., 2008)

2.2.5 *Climate-smart nano fertilizers*

Nano fertilizers have been identified as one of the most efficient methods for delivering plant nutrients owing to their aspect ratio and the unexpected properties of nanocarriers that are derived from quantum mechanics (Kumar et al., 2019). Nanotechnology has been used in numerous ways to improve the efficiency of fertilizer application in crops by improving the uptake, use efficiency, and minimum loss to the environment (Lal, 2008). Nanotechnology-based smart nutrient delivery systems are currently employed in agriculture to enhance crop yields along with the protection of food quality and nutrient value (Kashyap et al., 2015). Moreover, these are used to enhance abiotic stress tolerance along with resistance to climate change. In particular nano nitrogen formulations templates have been provided for minimizing the premature leaching of nutrients (Verma et al., 2022).

Encapsulation of active ingredients in agriculture such as fertilizers, herbicides, and micronutrients in controlled-release matrices is one of the recent advances in nanotechnology (Gunaratne et al., 2016; Kashyap et al., 2015). Furthermore, it has been reported that nanofertilizers can increase the ability to tolerate stress by increasing the nutrient uptake by three times compared to conventional methods (Manjunatha et al., 2019). With the broad range of advantages in nanotechnology such as broad perspective, high efficiency, functionalities, and convenient and easy applications enable its applications to deal with unpredictable climate changes such as drought, rainfall, and heat (Janmohammadi et al., 2016; Mittal et al., 2020). Smart delivery systems which use nanotechnology, have some positive impacts on climate-smart agriculture. These systems encompass advantages in a broad range such as self-regulating ability, the ability to regulate remotely, target-based action, and most importantly having multifunctional characteristics to resist climate stress (Yadav et al., 2023).

The most widely used application of nanotechnology in climate-smart fertilizers is the development of slow-release fertilizers (Wilson et al., 2008). When nutrients are applied with a combination of nano-dimensional adsorbents, the release of nutrients is very slow when compared to conventional methods, and this is a very convenient approach to climate-smart fertilizers (Zulfiqar et al., 2019). Not only macronutrients like nitrogen, potassium, and phosphorous but also some other micronutrients can be formulated as slow-release or controlled-release fertilizers using nanotechnology for the precision delivery of nutrients during climatic stresses.

Attapulgite, which is a natural nanoclay consisting of a network of nanorods, has been used in synthesizing a high-performance fertilizer with high water retention ability (Zhou et al., 2015). After treating with a high-energy electron beam, nanorods can be separated and modified into fertilizer with a slower releasing ability and lower leaching loss (Zhou et al., 2015). Further, modified attapulgite has a high surface area to act as an effective carrier of controlled- or slow-release fertilizers.

Hydroxyapatite nanoparticles (HANPs) have been modified using different nutrient sources for the effective delivery of both plant macronutrients and micronutrients (Abeywardana et al., 2021; Amarasinghe et al., 2022; de Silva et al., 2020; Fernando et al., 2021; Karunaratne et al., 2012; Kottegoda et al., 2011; Kottegoda et al., 2017; Madusanka et al., 2017; Samavini et al., 2018). Most of these plant nutrient formulations are slow and controlled-release fertilizers that release nutrients in a precise manner which is also more effective during vulnerable climate changes. Hydroxyapatite is a phosphorous source, and its unique nanomaterial properties give it advantages such as biocompatibility and bioactivity (Kottegoda et al., 2011; Sharma et al., 2022). Several studies have been conducted in developing controlled-release urea fertilizers by incorporating urea into hydroxyapatite. Moreover, studies have been carried out to monitor the urea release from morphologically different surfaces of hydroxyapatite. Furthermore, the doping of HANPs with cations and anions for the effective delivery of nutrients is reported and can be summarized according to Table 2.

Various micronutrients like Zn, Cu, Fe, Mn, and Mo have been incorporated into HANP for other applications rather than agricultural practices. Zinc-doped HA-urea nano seed coatings are an interesting option for field crops that allow a uniform distribution of fertilizers in a seed batch while enhancing germination The seed coating enables the protection of seeds during the early stages of growth from environmental conditions like climate change (Abeywardana et al., 2021).

Table 3: Hydroxyapatite Nanoparticle-based plant nutrient formulations

Plant nutrient formulations	Outcome	References
HANP	Positive effect on shoot dry mass, shoot and root elongation	(Fernando et al., 2021; Kottegoda et al., 2011)
Urea-HANP	Slow release of nitrogen (urea), High NUE in high temperatures, Enhanced seed germination	(Kottegoda et al., 2011)
Urea-modified HANPs encapsulated wood	Slow and sustained release of urea	(Kottegoda et al., 2011)
Urea-HA-montmorillonite	Slow release of nitrogen	(Madusanka et al., 2017)

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Mg-doped HA-urea	Slow release of nitrogen and efficient delivery of Mg	(Abeywardana et al., 2021)
Citric acid surface modified HANP	Increased availability of phosphorous	(Samavini et al., 2018)
Zn-doped hydroxy appetite-urea nano seed coating	Efficient plant macro (N and P) and micro(Zn) nutrient delivery agent, Increased growth and development of seedling	(Abeywardana et al., 2021)
Zn and Mg doped HANP modified with urea	Multi nutrient complex of Zn, Mg, N, Ca, P with efficient release of N	(Sharma et al., 2022)
Zeolite-HANP	Slow release of P, N and K	(Watanabe et al., 2014)
HANP incorporated with water soluble fertilizers (urea, $(NH_4)_2HPO_4$, K_2SO_4) into water hyacinth cellulose graft poly(acrylamide) polymer hydrogel	Availability of P with increased soluble P and decreased content of HANP	(Rop et al., 2018)
Urea- incorporated HA coated HA and K loaded wood chips	Controlled release of urea	(Elhassani et al., 2019)

2.2.6 Role of organic fertilizers in climate-smart agriculture

The integrated usage of organic fertilizer with inorganic fertilizer positively contributed to the CSA concept, mainly because it ensures reduced emissions of greenhouse gases due to less usage of fossil fuels (Khanal, 2009; Lazcano et al., 2021). Organic fertilizers can increase soil fertility with organic matter, and they have the potential to build up climate-resilient crop systems (Scialabba and Muller-Lindenlauf., 2010). According to a field trial experimented in Jilin province, China organic fertilizer amendments such as NPK (Nitrogen, Phosphorous, Potassium) plus corn straw and farmyard manure have shown a significant increase in corn yields when compared to conventional inorganic fertilizers mitigating the effects of climate change (Song et al., 2015). The long-term application of organic fertilizers has demonstrated improved soil fertility and nutrient use efficiency (Song et al., 2015). In particular, such practices increase the soil's resilience to elevations in temperature and changes in precipitation. Organic residues increase the water-holding capacity of soil and thereby enhance the retention of water in harsh climatic conditions (Datta et al., 2022).

The second most important factor of using organic fertilizers in CSA is that it causes the reduction of emissions of greenhouse gases including CO2, NO, and CH4 which are major contributors to positive radiative forcing. The demand for energy consumption from fossil fuel burning in organic agriculture is less than that of conventional inorganic fertilizers (Khanal et al., 2009). When organic fertilizers are applied, the soil structure increases resulting in reduced emissions of N_2O due to the lowering of denitrification (Goh, 2011). However, in some cases, it has been found that when organic fertilizers are applied on a similar scale to conventional mineral fertilizers, the emission of greenhouse gases is high due to the low yield (McGee, 2015).

2.2.7 Fertilizer Management in climate-smart Agriculture

According to a research program on climate change, agriculture, and food security in Northern Burkina Faso, farmers have aligned their cropping strategies according to climatic patterns (Ouedraogo et al., 2015). They have used more inorganic fertilizers in sesame cultivation by forecasting the weather and avoiding periods of high rainfall to reduce the washing out of fertilizers and increase nutrient uptake efficiency (Zougmore et al., 2021). Other than that, both nitrogen and potassium fertilizers can be applied in splits to reduce the loss during climatic changes (An et al., 2021; Mahato, 2014).

Micro dosing is one of the strategic applications used in climate-smart agriculture practices. In the micro dosing of fertilizers, small doses of fertilizer are applied rather than spreading them all over the field. This is important, especially to avoid end-season drought by helping the plant capture more native nutrients from the soil. The response of fertilizer depends on complementary practices like timely planting, weeding, fertilizing, and the incidence of diseases and pests; but even in drought years, farmers in Africa have gained a considerable yield by practicing micro dosing of fertilizers (Twomlow et al., 2011). This technology was developed by observing the decline of soil fertility and crop yields in the regions of sub-Saharan Africa which are affected by unfavorable weather conditions (Murendo and Wollni, 2015).

Furthermore, innovations in fertilizer applications have been suggested under the CSA program. Foliar application of fertilizers is one of the novel methods of application of fertilizer. This technology is not only developed to successfully face climate but also to reduce the emission of environmental pollution through chemical fertilizers which in turn affect unpredictable climate change. In particular, foliar fertilizer technology is combined with nanotechnology, where nanoparticles carry plant nutrients through the stomata of the leaves (Fageria et al., 2009). Small-sized nano fertilizers can be rapidly absorbed by plant tissues when applied as foliar, ensuring the rapid delivery of required elements and nutrients without any loss due to climatic changes. However, when the soil moisture content is lower the efficiency of foliar sprays could be reduced (Fageria et al., 2009). Hence, these can be used for the application of a few types of nutrients due to their differences in absorptivity. For instance, in high pH conditions plants experience a lack of Fe, and the foliar application of Fe as nanoparticles helps to withstand this condition (Mikula et al.). Another problem is that the application of foliar fertilizers such as potassium during the early stages of the plant does not have a significant contribution to withstanding salinity stress (Adhikari et al., 2020).

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The practice of growing a sequence of plant species on the same land in successive growth cycles is known as “crop rotation”, which can effectively enhance climate resilience, improve system robustness, and reduce the fragility of agricultural cropping systems (Yu et al., 2022). The effectiveness is performed through the enhancement of crops through the enhancement of water dynamics, soil health, and biological conditions (Bardhan et al., 2021). During drought conditions, crop rotation reduces the effects of increased drought intensity and heat waves by ensuring the yield of crops (Bardhan et al., 2021). It also reduces the emission of greenhouse gases and increases the ability of the soil to store carbon, and offsets the carbon emissions associated with agriculture.

Other than the conventional application of fertilizers onto the surface of the soil to ensure the number of nutrients near the surface is sufficient, the deep placement of fertilizers ensures better growth of the root system, and this can be used as a strategy for drought resistance (Li et al., 2021). Though the surface broadcasting of fertilizers is inexpensive, due to the volatilization and high solubility of fertilizers like nitrogen fertilizers, the deep placement method is more efficient. The deep placement of nitrogen fertilizers reduces the emission of greenhouse gases CH_4 and N_2O due to the extensive growth of root systems (Mingxing et al., 1993).

The reduction of greenhouse gas emissions is one other major step taken through the path of climate-smart fertilizers. Methane emissions in agriculture can be reduced by proper management of fertilizers including sulfate-containing fertilizers and fermented organic fertilizers (Sarauskis et al., 2021). Also, the application of both mineral and organic fertilizers in excess amounts can cause dispersing of fertilizers in the environment and it can impact negatively on the environment (Teklewold et al., 2017). Maintaining the proper ratio between organic and inorganic fertilizers can reduce negative impacts on the climate.

However, these practices are not used in isolation and mostly they are in combination with other management practices. For instance, under warmer climatic conditions, improved fertilizers are used in combination with improved seeds and water management (Arimi, 2020). In most cases, farmers have used a combination of adaptations of traditional practices and modern technology (Azadi et al., 2021).

3. Safety and impact on the human and environment

There is an interconnection between environmental or climatic indicators, social indicators, and economic indicators in climate-smart fertilizer practices in agriculture (Sarkar et al., 2021). Climate-smart agriculture and fertilizer management have more beneficial environmental effects. It enhances the reduction of greenhouse gas emissions, reduces soil erosion, and increases water and nutrient use efficiency. The effectiveness of smart fertilizers can increase and uplift the living standard of farmers. The livelihoods of both small and large-scale farmers can be expanded to a wider range in a more promising manner by increasing their capacity in agriculture by maintaining their resilience to agriculture (Abobatta, 2018).

The risk to both the environment and humans by using nanotechnology in climate-smart fertilizers has not yet been completely understood. In climate-smart agriculture, productivity and resilience should be increased while taking care of the environment (Azadi et al., 2021). The applications of nano fertilizers would not be safe in every application. Therefore, pre-detection of the risks and consequences of using nano fertilizer in conventional farms and fields is required.

Though nano-based climate-smart fertilizers help increase crop yield by resisting environmental stressors, they can cause contamination of water and soil. Nano-fertilizers used for edible plants can cause damage to human DNA through the generation of free radicals (Totin et al., 2018).

4. Current challenges and future prospects

The theoretical scopes of climate-smart agriculture are an adaptation to climate change, a sustainable increase in agricultural productivity, and a reduction of greenhouse gas emissions from agriculture. Though the theoretical consideration looks ideal, in the practical scenario all these objectives are not fulfilled (Kurgat et al., 2020). It is necessary to bridge the gap between theoretical and practical considerations in synthesizing and using climate-smart fertilizers. The main objectives of the CSA concept are not satisfied if a fertilizer, which resists climatic changes, could also react with soil or with the plant and emit greenhouse gases.

There is uncertainty about the location and timing of a certain climate change and the way that it will impact agriculture. The period of climate-smart fertilizer practices is limited to 2-5 years, and it needs to be embedded into long-term practices for better results (Barasa et al., 2021). As the rooting and nutrient transportation systems are different from one plant to another, mechanisms of fertilizer uptake vary in different plants grown in different soil depths. Further, the type of fertilizer can be site-specific depending on geographical and climatic conditions. During drought seasons, the soil is susceptible to drying, and most of the currently available fertilizers become inefficient due to a lack of water to dissolve them. Therefore, fertilizers that can release nutrients without the assistance of water should be synthesized to continue sustainability in agriculture.

Although there are many advantages and advances related to nanotechnology in climate-smart agriculture toward sustainable food production, their limitations should also be considered when formulating fertilizers. A major problem related to nanotechnology-based smart fertilizers is that their solubility is lower in an aqueous medium when taken in bulk.

As a result, their range of applications in agriculture is limited. As a remedy for this problem, using the chelating effect of some materials makes them well-suited for the synthesis of fertilizers by increasing their solubility. When nanomaterials are extensively released into the environment, there is a risk to public health as these nanomaterials could transfer through food chains (Zulfiqar et al., 2019).

Global climate changes may be projected toward unexpected extremes in the future, and more advanced techniques may be needed for climate-smart agriculture. In the future agriculture may be affected not only by changes in temperature but also by unexpected changes in rainfall. The frequency and magnitude of heat radiation are unpredictable in the future, but there is no doubt that in most parts of the world, these two can increase.

To face the current challenges in climate-smart agriculture, a lot of remedies have been proposed in the fertilizer field. One way to improve the acceptance of climate change in agriculture

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is to map its effects and incorporate them into fertilizer use. Some adaptation measures were chosen by farmers not because they were the best selection but because of their poor economic conditions, where high-yielding and efficient fertilizers cannot be afforded by them (Azadi et al., 2021). In this case, new methods of climate-smart fertilizers should be introduced at a low cost that is affordable to a considerable percentage of farmers. The facilities should be available for small-scale farmers according to requirements because most of the time small-scale farmers have adapted less to climate changes.

5. Conclusion

The global food security requires a significant transformation in agricultural practices, including the use of fertilizers. To develop climate-smart fertilizers, it is essential to evaluate past, current, and future climatic changes in specific geographic locations. The optimization of cropping systems through improved fertilizer management practices plays a significant role in climate-smart agriculture. Nanotechnology offers a promising alternative for synthesizing climate-resilient fertilizers. However, it is necessary to synthesize fertilizers that not only resist environmental changes but also do not emit greenhouse gases that contribute to climate change. In synthesizing and handling nanomaterials, it is important to understand their exposure effects. The knowledge and innovations about climate-smart fertilizers should be accessible to smallholder farmers and resource-dependent people in developing countries. Collaboration between policymakers, researchers, and industry stakeholders is necessary to ensure the accessibility and implementation of climate-smart fertilizers at scale. Ultimately, the development and dissemination of safe and effective climate-smart fertilizers are critical for achieving higher crop yields and building resilience against climate change.

Abbreviations used

CSA- Climate-Smart Agriculture, GDP - Gross Domestic Product, GHG- Green House Gases, LDH- Layered Double Hydroxides, NAE - Nitrogen Agronomic use Efficiency, NPK- Nitrogen, Phosphorous, Potassium, NUE -Nitrogen Uptake Efficiency

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