PLANT SCIENCE TODAY
Vol 12(sp1): 1-18
https://doi.org/10.14719/pst.8148

eISSN 2348-1900

REVIEW ARTICLE

Sustained release fertilizers: A pathway to increased crop yield and efficient nutrient utilization - A review

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Received: 09 March 2025; Accepted: 20 August 2025; Available online: Version 1.0: 17 October 2025

Cite this article: Kathirvel L, Raviraj A, Arunadevi K, Kannan P, Gomathi V, Anandhi V. Sustained release fertilizers: A pathway to increased crop yield and efficient nutrient utilization - A review. Plant Science Today. 2025; 12(sp1): 1-18. https://doi.org/10.14719/pst.8148

Abstract

Food scarcity has emerged as a critical global challenge due to the rapid increase in population, necessitating innovative agricultural solutions to enhance crop productivity. The Green Revolution introduced synthetic fertilizers to increase yields; however, their excessive and inefficient use has led to nutrient leaching, soil degradation and adverse environmental impacts. Sustained Release Fertlizers (SRFs) provide a sustainable alternative by ensuring a gradual and controlled release of nutrients in the rhizosphere, thereby optimizing nutrient uptake and improving plant growth. SRFs, including slow and controlled-release fertilizers, enhance nutrient use efficiency (NUE) by synchronizing nutrient availability with crop growth stages, reducing nutrient losses and minimizing environmental pollution. These fertilizers not only mitigate the negative effects of conventional fertilizers but also contribute to long-term soil fertility and water conservation. This review explores the mechanisms of SRFs, their types, external factors influencing nutrient release and their impact on crop yield and soil health. Furthermore, the integration of SRFs with precision agriculture and sustainable farming practices offers an effective strategy to improve agricultural productivity while reducing excessive fertilizer application. By addressing nutrient management challenges, SRFs represent a promising approach to ensuring future food security and promoting environmentally responsible agricultural practices.

Keywords: crop yield; nutrient release mechanisms; nutrient use efficiency; sustainable agriculture; sustained release fertilizers

Introduction

By 2050, it is predicted that there will be an increase in the global population of approximately 2.3 billion people compared with the previous 40 years (1). Food demand is predicted to increase if the population tends to grow. As a result, fertilizers supply plants with nutrients and are frequently believed to increase crop yields and their use has increased on a global scale (2).

Fertilizers are therefore the top priority in the search for innovative sustainable agricultural techniques to meet world food requirements and challenge food security issues. Over 3 billion tons of crops are produced each worldwide, with a demand of 187 million tons of fertilizer, which is vast (3). By 2022, it is estimated that demand will exceed 200 million tons (4). Globally, the USA is the largest producer of fertilizers followed by India and Ukraine is the smallest producer (5). Among all fertilizers, urea has the highest nitrogen concentration (approximately 46 %) and is inexpensive and is most frequently utilized in agricultural practices. The most inevitable macronutrients are nitrogen, phosphorus and potassium (N, P and K). Among the three macronutrients nitrogen (N) plays a primary role in foliage development in plants (6). Hence, they supply more nutrients to rhizosphere soil and increase crop output; therefore conventional fertilizers are widely used around the world and have a substantial impact on plant growth and root development (7).

Plants absorb only a portion of the nutrients provided, with the remainder lost to the environment through processes such as rain, irrigation, fixation and volatilization. These losses lead to environmental, economic and health issues and negatively impact plant physiology, growth and nutritional quality (8). SRFs are designed to release nutrients progressively over time, ensuring that plants have consistent access to vital nutrients throughout their growth cycle. This technique lowers the risk of nutrient leaching while increasing nutrient absorption efficiency. Thus, they deliver improved nutrient use efficiency (NUE) and higher yields without suffering from nutrient loss (9). Currently, the traditional fertilizer fates in soil are shown in Fig. 1.

NUE can be described as the yield achieved per unit of

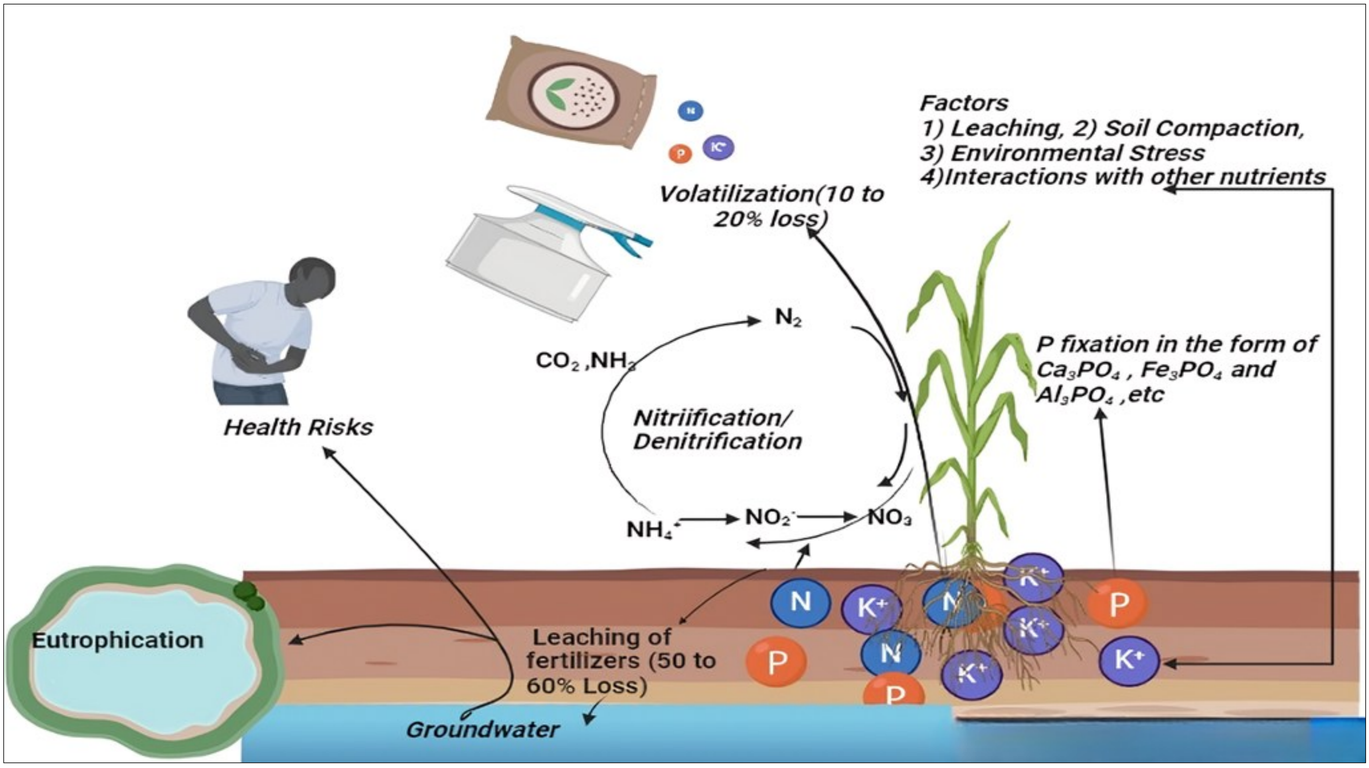

Fig. 1. Fate of traditional fertilizers in soil.

fertilizer input, or it can be understood in relation to the recovery of applied fertilizer. NUE is a crucial concept in assessing crop production systems (10). The nutrient use efficiencies of different macro and micronutrients are shown in Table 1.

The importance of NUE can be highlighted through the following points: inefficient nutrient use can lead to nutrient losses through leaching, runoff, or volatilization, contributing to water pollution, soil degradation and greenhouse gas emissions. Improving NUE helps reduce these negative environmental impacts and promotes a more sustainable agricultural system (11). Fertilizers and other nutrient sources represent a significant cost for farmers and growers. By optimizing NUE, farmers can achieve higher yields with lower input costs, improving their profitability and economic sustainability (12). With a growing global population and limited arable land, increasing NUE is crucial for meeting the increasing demand for food, feed and fibre. Efficient nutrient utilization ensures increased crop productivity and yield stability, contributing to food security (13). Nutrients, such as nitrogen, phosphorus and potassium, are finite resources that require energy and resources for their extraction and production. Improving NUE helps conserve these valuable resources and reduces the dependency on external inputs (14).

Table 1. Nutrient use efficiency of several nutrients (11)

Nutrients	Nutrient use efficiency (NUE%)
Nitrogen (N)	30-50
Phosphorus (P)	10-20
Potassium (K)	>80
Sulphur (S)	8-12
Zinc (Zn)	2-5
Iron (Fe)	1-2
Copper (Cu)	1-2
Manganese (Mn)	1-2

Traditional fertilizers, while instrumental in enhancing crop yields, often exhibit low NUE due to rapid nutrient solubilization and leaching, leading to significant environmental losses and poor synchronization with plant nutrient demands (15, 16). Over-application of these fertilizers can result in greenhouse gas emissions (e.g., N_2O), nutrient runoff, soil degradation and contamination of surface and groundwater (17). Moreover, the abrupt nutrient availability frequently exceeds plant uptake capacity or shifts into chemical forms inaccessible to roots, further decreasing NUE under environmental stress conditions (18). In contrast, SRFs which include both slow-release fertilizers and controlled-release fertilizers represent a significant innovation in nutrient management. These formulations are designed to align nutrient release with plant uptake dynamics, improving efficiency and reducing losses (19). By encapsulating nutrients in coatings (e.g., polymers, biochar, or clays), SRFs allow a gradual, time-dependent release, supplying nutrients in optimal amounts at critical growth stages (20). This not only enhances NUE but also contributes to climate change mitigation and soil health by lowering emissions and improving microbial activity (21). While literature has often treated slow- and controlled-release fertilizers separately, a unified understanding of SRFs is still lacking. Therefore, this review aims to integrate both concepts, clarifying their distinctions and overlaps to provide a comprehensive perspective. A temporal trend in publications on SRFs from 2000 to 2024 is illustrated in Fig. 2. Hence, this paper summarizes the types of SRFs and the environmental impact of the use of SRFs, mechanisms of nutrient release, factors influencing the performance of sustained-release fertilizers, improved NUE and crop yield and application and management strategies, challenges and identifies the future directions linked with the improvement and use of SRFs through recent studies.

Sustained-release fertilizer (SRF)

Sustained release fertilizers which release its nutrients based on

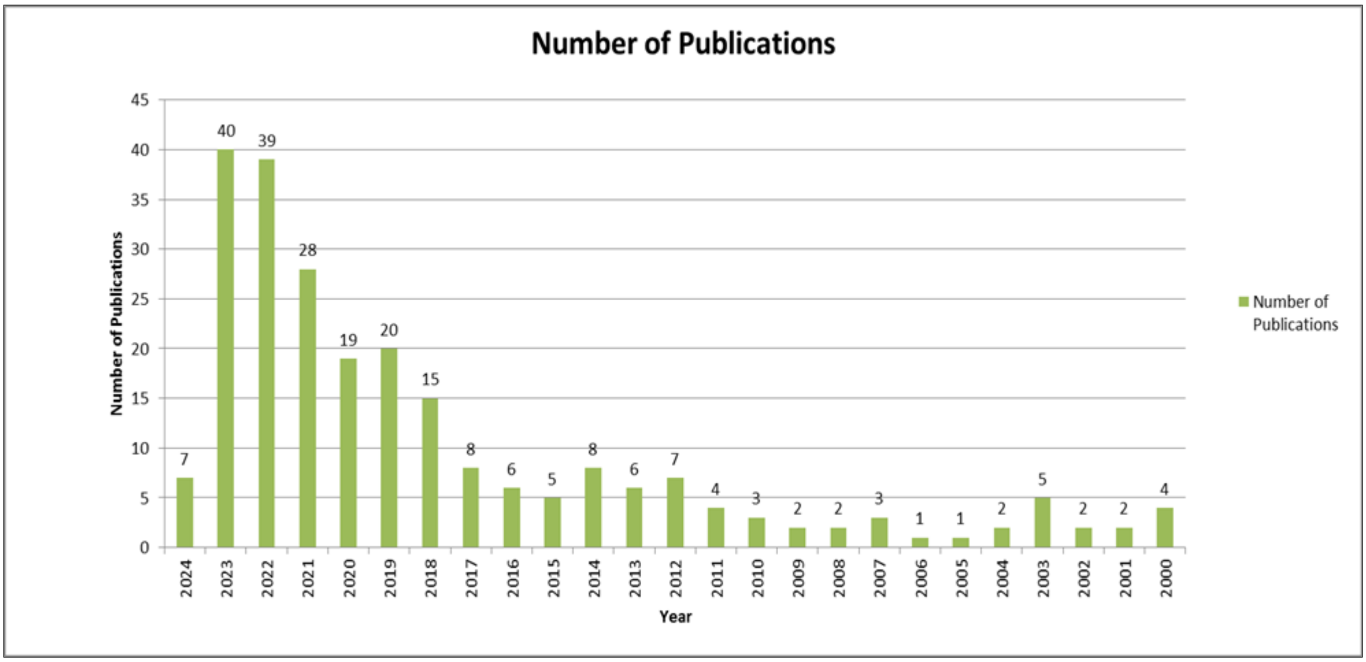

Fig. 2. Number of publications on sustained release fertilizers during 2000 to 2024 years. Source: Scopus database, Access date: 15 December 2024, Time: 10:30 PM.

the soil condition and plant uptake ability. These fertilizers usually attain maximum efficiency in nutrient deficit crops. SRFs contain outer layer and inner layer composed of carrier nutrients as well as encapsulation (22, 23). Water use efficiency and NUE are the two major deciding factors for its release. The carrier material act as protective transporter of packed nutrients and surface coating enhances the excess nutrient loss. This type of mechanism facilitates the nutrients uptake ability of plant at faster rate thereby increase the crop yield.

Types of SRFs

Slow-release fertilizers (SRFs) are generally classified into two main categories: coated and *matrix-based* types. Each of these can further be categorized as either slow-release or *controlled-release* fertilizers, depending on their nutrient release mechanisms and rates. However, it is important to note that the distinction between "slow-release" and "controlled-release" fertilizers is not always standardized across the literature, which can make direct comparisons between different SRFs challenging. Fig. 3 illustrates the hierarchical classification of SRFs, highlighting these subdivisions.

Slow-release fertilizers usually dissolve nutrients in the soil by absorbing moisture or water as a result the granules enlarge where, the osmotic pressure increases. The nutrient release mechanism involves two viz. diffusion and breakdown.

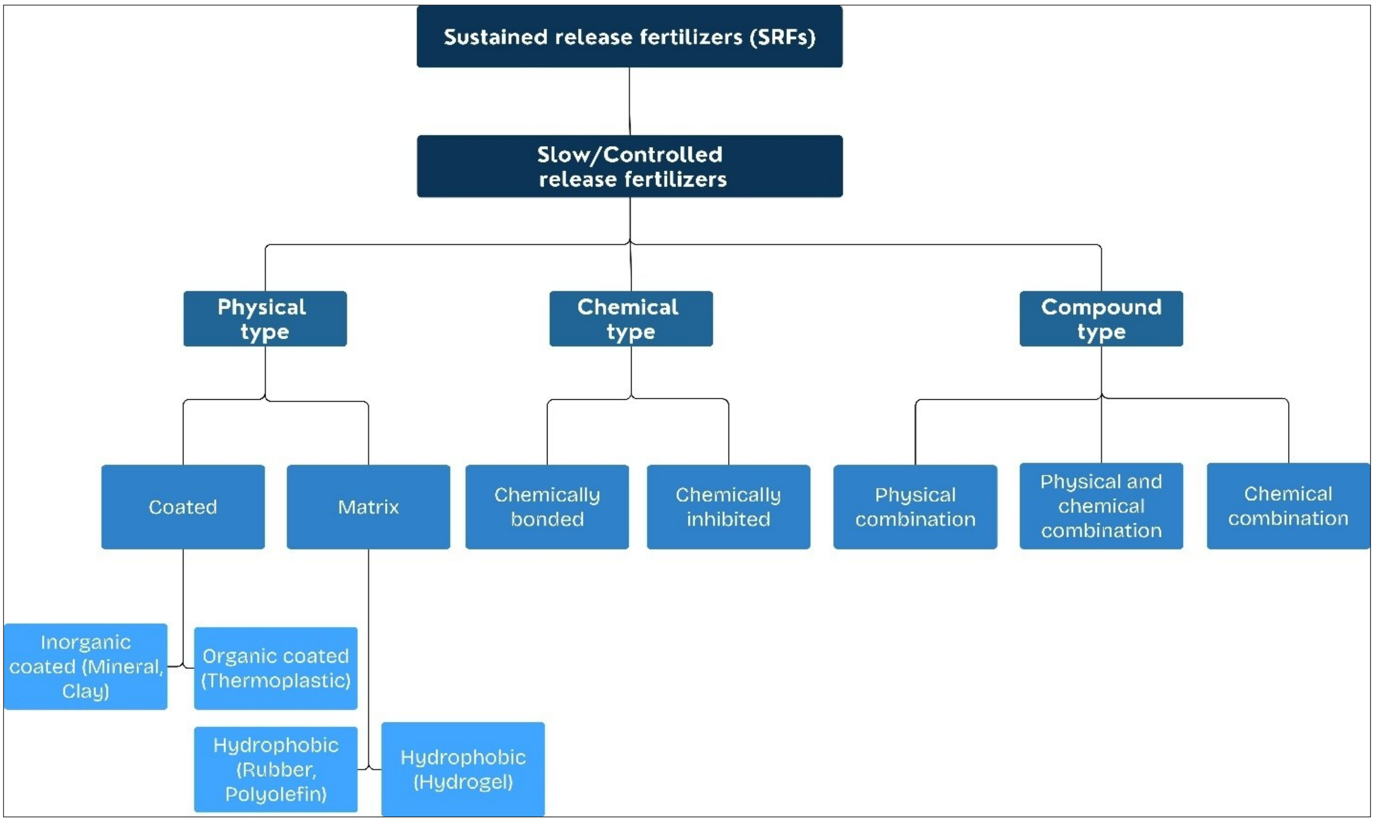

Fig. 3. Different classification of SRFs.

This type of fertilizer exhibits additional features excludes the type of soil, moisture content, pH of the surrounding environment and microbial activity which influences the plant uptake ability. This could be achieved by using special covering materials like temperature-sensitive hydrogel. The pace at which fertilizer is released is also affected by the eroding process of the dissolving media, which is regulated by the compactness of the lattice structure (24). Another way to improve fertilizer efficiency is to increase the coating material's adherence to the fertilizer core (25). The fertilizer release rate profile is influenced by fertilizer solubility. When nutrient release patterns are analyzed, there is a high correlation between laboratory studies and field circumstances (26). There are two categories of fertilizer release rates: chemical and physical releases (27).

Physical release mechanism: The types of penetration and absorption can be used to categorize physical release formulations. Several substrates coat or encapsulate agricultural compounds, which are then released by a process known as permeation. This method enables the creation of a cellulose-based membrane in water, where agricultural chemicals dissolve into a saturated solution. The solvent then permeates the surrounding environment through a concentration gradient. In the adsorption type, the chemical is absorbed into the matrix and released either through diffusion or by shrinkage (28).

Coated fertilizers: Fertilizers are coated or encapsulated with inert, slightly soluble, or water-insoluble materials and are made by condensing urea with various aldehydes, resulting in a slow dissolution rate (29). Inorganic compounds and biopolymers are the two main groups of coating materials. Sulphur, bentonite and phosphogypsum are examples of biopolymer materials, whereas biopolymers can be either naturally occurring or synthetically produced and include starch, chitosan, cellulose and polyurethane, among other polymers (19). Furthermore, current research shows the use of organic material compounds such as polyphenols, rosin and charcoal (30). Numerous combinations of these materials were examined to study their impact on the amount of released fertilizer and to ascertain whether these materials may be used as coating materials for SRFs. This section classifies the materials into four groups: inorganic materials, synthetic polymers, natural polymers and other organic substances. The discussion of synthetic and natural polymer coatings is included in the section on polymer-coated fertilizers.

Organic and inorganic coating materials: Coating materials play a pivotal role in regulating the release profile of nutrients in sustained-release fertilizers (SRFs) and they are broadly categorized into organic and inorganic types. Organic coatings such as starch, lignin, chitosan, humic acid and biodegradable polymers are increasingly favored due to their biodegradability, environmental compatibility and renewable origin (20, 26). These materials often provide a moderate release rate and improve soil microbial activity, but their water resistance and mechanical strength are sometimes limited, especially under high-temperature and high-moisture field conditions (31).

In contrast, inorganic coatings such as sulfur, bentonite clay, zeolites and mineral-based layers exhibit excellent water impermeability and structural integrity, ensuring a more precise and extended nutrient release pattern (16, 19). However, inorganic coatings may pose environmental concerns due to slower degradation and potential accumulation in soil. Some studies suggest that inorganic materials like bentonite can swell and self-seal, improving nutrient retention, whereas organic coatings such as starch or chitosan are more eco-friendly and improve carbon input to the soil (18).

Recent comparative studies indicate that composite coatings combining organic and inorganic materials can optimize the release characteristics while maintaining environmental safety (32). For example, starch-bentonite composites have shown promising results by leveraging the binding ability of starch with the structural reinforcement of bentonite to achieve both sustained release and soil improvement.

Most inorganic coating materials primarily consist of minerals and sulphur. The Tennessee Valley Authority (TVA) founded the Sulphur Coated Urea (SCU) in 1961. However, incomplete coating often leads to a "burst effect", where nutrients are released instantly upon contact with water, mismatching plant needs (19). In recent research, low-cost sulphur-based compounds, including phosphogypsum and gypsum, have also been reported. They have an advantage over sulphur since they can easily supply plants with sulphate ions, are mildly soluble in water and do not change the pH of the soil (33). Gypsum is used in SRFs to alter their nutrient release patterns and increase their effectiveness in certain soils. It regulates nutrient availability, is beneficial for soils with high pH or alkalinity and improves soil structure and water infiltration, which enhances nutrient uptake by plants (34).

Several nonpolymeric organic compounds have been considered, with the potential to improve the biological, chemical and ion exchange properties of soil (35). Biochar is a solid by product of this process, which occurs when biomass is broken down at high temperatures and fuels devoid of the addition of external oxygen (36). Although biochar can function as a stand-alone SRF in soil applications, its storage, transportation and incorporation into the soil present significant challenges. Furthermore, biochar alone lacks the nutrients necessary for plant growth; therefore, it must be combined with other fertilizers to increase nutrient levels and increase crop yield and soil fertility (37). They made inexpensive, renewable SRFs by pulverizing biochar through ammonium sulphate impregnation. After that, they coated the biochar with three dissimilar concentrations (3 %, 6 % and 10 %) of PLA solutions; the 10 % PLA-coated SRF held water for a maximum of five days and remained stable at 230 °C for a maximum of 25 days, during which time the urea was released for a maximum of 25 days. As a result, the PLA and biochar combination has a low rate of nitrogen release and excellent thermal stability. This technique also offers suggestions for the creation of future low-cost, renewable SRFs (38). Polylactic acid (PLA) is a biodegradable polymer made from renewable resources like corn starch. It is widely used as an eco-friendly coating material in controlled-release fertilizers due to its biodegradability and good film-forming ability (39). Biochar has excellent thermal stability preserves its porous structure and surface functionality over time, allowing it to adsorb and slowly release nutrients, thereby enhancing nutrient availability and reducing leaching. Its resistance to microbial degradation ensures long-term nutrient retention, making it effective in improving NUE in slow-release fertilizer systems (40, 41).

Other porous inorganic minerals, such as zeolite and metal nanoparticles, may also be utilized as coatings for SRF materials. When added to SRFs, zeolite, a porous substance with strong mechanical and thermal strengths, has a distinct effect (42). By using 4A zeolite-modified polyurethane, the addition of polyurethane and zeolite achieves excellent interoperability, extending the nitrogen release duration of the urea envelopes to 70 days. The impact of zeolite fertilizer on sugarcane yields along the northern coast by combining it with organic fertilizers. The sugarcane production of the experimental field was double that of the control group when fertilizer and fertilizer were applied, indicating a significant increase in crop yield from the use of zeolite (43). Metal nanoparticles exhibit excellent dispersion and antibacterial and hydrophobic properties. By adding Fe_3O_4 nanoparticles to castor oil as a coating material (21), created a biobased SRF. This change increased the membrane cross-linkage and thermal stability, significantly extending the number of SRF release cycles to 70 days.

Bentonite, a type of clay, is employed as a binder or matrix in the production of SRFs. Due to its superior swelling properties, it can absorb and retain water, enabling controlled nutrient release. Bentonite forms a gel-like coating around fertilizer granules, which helps manage nutrient release and reduces leaching, runoff and volatilization, thus enhancing NUE in plants (44). Due to their hydrophilic properties, SRFs using a hydroxypropyl methylcellulose (HPMC) binder release nutrients more quickly than those with a starch component, which release 25 % of urea within 8 hr. This study shows that physical interactions between mineral and binder molecules, including van der Waals forces, hydrogen bonding and electrostatic attraction, play a role in slowing nutrient release. The use of attapulgite modified with ethyl cellulose (EC), carboxymethyl cellulose and hydroxypropyl methylcellulose (CMC/HMC) hydrogel (20) similarly delayed nutrient release, comparable to bentonite. Although the release rate was slower than in previous experiments (15 % over 3 days), this was attributed to the optimal proportions of crosslinker content, EC and the CMC/HMC hydrogel. SRFs provide several advantages over conventional fertilizers, including reduced nutrient losses, enhanced NUE and beneficial environmental effects. SRFs provide a steady and extended nutrient supply, reducing the need for labor and resources. These stable, eco-friendly inorganic materials, like sulfur, gypsum and bentonite, are well-suited for sustainable agriculture. SRFs improve nutrient management by allowing farmers to tailor nutrient release to match specific crop growth stages, optimizing plant nutrition (29).

Materials made of laminated silicates, such as clay and montmorillonite, have the advantages of being both affordable and eco-friendly (45). Fertilizers with these modified polymer coatings can be made with better water and chemical absorption. Using a coagulation technique, chitosan-montmorillonite microsphere SRFs with varying amounts of montmorillonite were created. This resulted in a multi porous surface that improved the release time by increasing the adsorption of KNO_3 (46).

Polymer-coated fertilizers: The newest technology in fertilizer creation is the use of polymer-coated nutritional fertilizers. They have soluble nutrients as a core encircled by a polymer and are intended for use in crop production. Superabsorbent polymers are a subset of cross-linked hydrophilic polymers that are essential to PCFs because they can expand and hold enormous amounts of water when swelled. Diffusion via a semipermeable membrane facilitates release (16). Polymer-coated fertilizers are one of the contemporary uses that have increased NUE and may soon spark a revolution in the agricultural sector. The primary issues with producing fertilizers coated with polymers are the types of polymers and the ways in which they are applied. The soil temperature and moisture that penetrate the polymer covering, rather than the soil texture, salinity, pH, or microbial activity, have a greater impact on nutrient release via a semipermeable or impermeable polymer barrier. Thus, the time needed for fertilizers coated with polymers to release nutrients may be predicted (47).

Hydrophobic or hydrophilic (gel-forming) polymer-coated granules or tablets are one-way SRFs that are produced. These polymers are derived from thermoplastic or resinous ingredients. Regarding hydrophobic coatings, nutrients are released as a result of partial coating degradation. This occurs when the coating becomes porous and starts to compress, which eventually releases nutrients (48). Superabsorbent polymers provide more regulated nutrient release since the nutrients are removed from the pores created in a coated polymer and subsequently swell. The development of this kind of gel-based polymer is still ongoing (49).

Biodegradable polymers derived from renewable resources are increasingly utilized in sustained-release fertilizers (SRFs) because of their affordability, improved marketability, capacity to increase crop growth and yields, nontoxic nature, ability to maintain soil fertility, biodegradability and resilience to climate variations (50). Biodegradable composites containing urea were created from starch-g-poly(vinyl acetate) (51) and starch-g-poly(L-lactide) (15). The rate at which urea was released was controlled by varying the graft efficiency.

Chitosan, a widely abundant natural polysaccharide, has antiviral and antifungal properties, serves as a nitrogen source for agricultural nutrition and it enhances stress tolerance in various horticultural applications, making it a promising candidate for agricultural fertilization to promote plant growth (52).

Despite being lightweight but consuming much space, agricultural waste (such as rice straw, grape vines, wheat straw, tree pruning, fruit-bearing trees, cane bagasse, etc.) is becoming a major problem that harms the environment. Waste is usually disposed of via environmentally harmful methods such as landfilling or incineration (53). New regulations necessitate reducing carbon emissions and managing carbon stocks to transform waste into a cost-effective, eco-friendly raw material applicable across various sectors (54).

Matrix-based fertilizer: Matrix-based fertilizer (MF) is a novel, affordable slow-release option. It encompasses matrix-based urea and matrix-based compound fertilizer, both made using similar processes and materials. The release of nutrients in these fertilizers occurs through nutrient desorption from functional materials and the breakdown or dissolution of the matrix materials. MFs can be divided into two types: nutrient adsorption and diffusion control. While their nutrient release period is shorter compared to coated fertilizers, MFs provide advantages such as balanced nutrition, cost efficiency and eco-friendliness. They are highly suitable for field production and pollution-free agriculture, holding great promise for agricultural applications (24). Three treatments using a randomized block design were carried out (35): a control test (CK, no urea applied), a common urea treatment (CU, 195 kg N/ha) and a matrix-based urea treatment (MU, 195 kg N/ha). In addition, two laboratory experiments were conducted to assess nitrogen leaching and ammonia emissions from matrix-based urea. The findings showed that the MU group, composed of bentonite, organic polymers and urea, outperformed the standard urea treatment group. Grain yields in the MU group were 6.3 % and 14.7 % higher than in the CU group and both agronomic efficiency and apparent recovery efficiency were superior with MUs compared to CUs.

Glass matrix-based fertilizer (GMF), a by-product of the ceramic industry, was used on "Tarocco" orange trees. The GMF blend provided a long-term supply of micronutrients, especially iron, effectively reducing chlorosis symptoms, increasing the leaf SPAD index and lowering the Fe index. GMF not only cuts down the need for chemical additives like Fe chelators but also reutilizes industrial waste and organic residues, enhancing the value of these innovative organomineral formulations. Although research on this nanotechnology-based method for crop nutrient delivery is limited, the initial results are promising (55). The creation of eco-friendly nanoparticles that carry urea as a crop nutrient enables controlled release, making them ideal for use as nanofertilizers. This study showed that the incorporation of urea molecules into a hydroxyapatite nanoparticle matrix reduces their high solubility (56).

Chemical release mechanism: This type involves reversible chemical linkages between the fertilizer's constituents and the cellulose matrix. To release fertilizers into the environment, they must break chemical connections that bind amino, carboxylic, or hydroxyl groups together. The environment acts as a catalyst to release chemical fertilizer that are chemically bonded (57).

Chemically bonded fertilizers: Chemically bonded fertilizers are created by linking fertilizers with one or more chemical substances via covalent or ionic bonds to form a compound that is either slightly soluble or insoluble in water. These fertilizers provide a slow release of nutrients due to the direct influence of crop roots and microbial breakdown. The rate at which nutrients are released is mainly affected by factors such as particle size, soil moisture, temperature and pH levels (58). Furthermore, the nutrient release is influenced by the material chemical structure, the strength of the covalent or ionic bonds, the level of polymerization and the extent of environmental degradation. Typical chemical materials used in these fertilizers include urea formaldehyde, isobutylidene diurea, polyphosphate and long-lasting silicate potassium fertilizers.

The effects of five controlled-release nitrogen fertilizers: isobutyl diurea (IBDU), sulfur-coated urea (SCU), urea formaldehyde (UF), methylene urea (MU) and polyolefin-coated urea (ESN) were examined. These slow/controlled-release fertilizers enhanced leaf chlorophyll content, net photosynthesis rate, transpiration rate, nitrogen levels and root activity to varying degrees. The fertilizers effectiveness, ranked from most to least effective, was MU > IBDU > UF > ESN > SCU. In general, chemical slow/controlled-release fertilizers outperform physical fertilizers (59). The experiment was conducted on 16S rRNA gene clone library and found that urea-formaldehyde fertilizer significantly boosted bacterial diversity in onion bulbs and sugar beet roots. Principal coordinate analysis revealed that UF fertilizer altered the bacterial community structures in both plants, suggesting its potential to influence plant associated bacterial communities (60).

Chemically inhibited fertilizers: Incorporating inhibitors into chemically inhibited fertilizers allows for the gradual release of nitrogen. Common inhibitors include urease inhibitors, which slow down urea hydrolysis and nitrification inhibitors, which delay the nitrification of ammonium. Typical inhibitors include hydroquinone, acetohydroxamic acid, pyridine and dicyandiamide. A field experiment with lettuce in the Savanna of Bogota showed that 3,4-dimethylpyrazole phosphate (DMPP) does not affect greenhouse gas emissions during lettuce cultivation. Moreover, reducing nitrogen application by 20 kg N/ha with DMPP preserved yields and enhanced crop quality (61). The impact of nitrification inhibitors (NIs) on maize yields was investigated in loamy-sand soil in Thailand. The findings showed that using NIs boosted maize grain yields by 13-20 % and whole plant yields by 17 -24 % (62).

Compound type

The compound type of SRF is a fertilizer made through a combination of physical and/or chemical methods. This type of fertilizer includes two or more types of slow-release fertilizers and is classified into three categories:

1) A combination of physical and chemical fertilizer (utilizing both physical and chemical methods),

2) The physical combination of fertilizer (via a coating method) and

3) Chemical combination fertilizer (inhibitors).

The combination of physical (e.g., coating, encapsulation) and chemical (e.g., inhibitors, stabilizers) methods in compound-type fertilizers enhances nutrient efficiency through synergistic action. Physical barriers control nutrient release timing, while chemical additives prevent premature losses by inhibiting nutrient transformations. Together, they ensure a more synchronized nutrient supply with plant demand, reduce leaching and emissions and improve overall NUE (19).

These fertilizers can effectively control the release and transformation of nutrients in the soil, offering significant development potential and broad prospects. While there are few reports on physical combination fertilizers, they are still considered due to the fast pace of fertilizer innovation. Chemical combination fertilizers are often found in patent form. Research has explored the synergistic effects of physical and chemical combination fertilizers.

The experiment was conducted a feasibility study on newly developed coated urea containing biological inhibitors. The study assessed four types of fertilizers: coated urea (CU), coated urea with dicyandiamide (CU + DCD), coated urea with hydroquinone (CU + HQ) and coated urea containing both dicyandiamide and hydroquinone (CU + HQ + DCD). The findings showed that the CU + HQ + DCD treatment significantly outperformed standard urea, increasing pod yield by 27.3 %, total yield by 6.7 % and protein content by 9.17 %, while decreasing NO_3-N content by 46.56 % (63).

Mechanisms of nutrient release on SRFs

Three distinct phases often accompany the release of nutrients from SRF: the lag period, the steady release period and the decay period (64). During the initial phase, a small amount of fertilizer dissolves in the soil core, as moisture from the soil, mostly in the form of vapour, wets the coating gaps. No fertilizer is discharged; the driving force is the vapour pressure differential. Hydrogel SRFs, however, swell after they absorb water. The delay could result from the time required to reach a steady state between the flow of solute outgoing and water entering the internal voids or from filling them with the necessary amount of water (65). In the second phase, as water penetrates the core, more solid fertilizer dissolves, raising the osmotic pressure and the critical water volume of the saturated solution. This enables the fertilizer to be slowly released through the expanded hydrogel network or the cracks in the polymer coating. Diffusion to the soil is constant since the granules solution content remains saturated (66). The coating material ruptures and the fertilizer content bursts out instantly if the pressure increases above a specified threshold. Most of the fertilizer has dissolved and released during the decay stage, which decreases the driving force, concentration gradient and release rate. The mechanism of the SRF is discussed in Fig. 4 below. A comparison of traditional fertilizer and sustained-release fertilizers is presented in Table 2.

Factors affecting SRF performance

The size, coating thickness and homogeneity, as well as the choice of materials and filler and binder for the formulation, all impact the release rate of SRFs, as we previously covered in the section on SRFs technology. The step at which nutrients are released is also influenced by the environment's microbial activity, temperature, moisture content and pH. Soil conditions greatly influence both the rate and pattern of nutrient release. The final mechanism of nutrient release in soil is governed by a combination of physical factors (like pH, temperature, moisture levels and wetting and drying cycles), chemical factors (such as soil composition) and biological factors (including microbial activity) (50, 63).

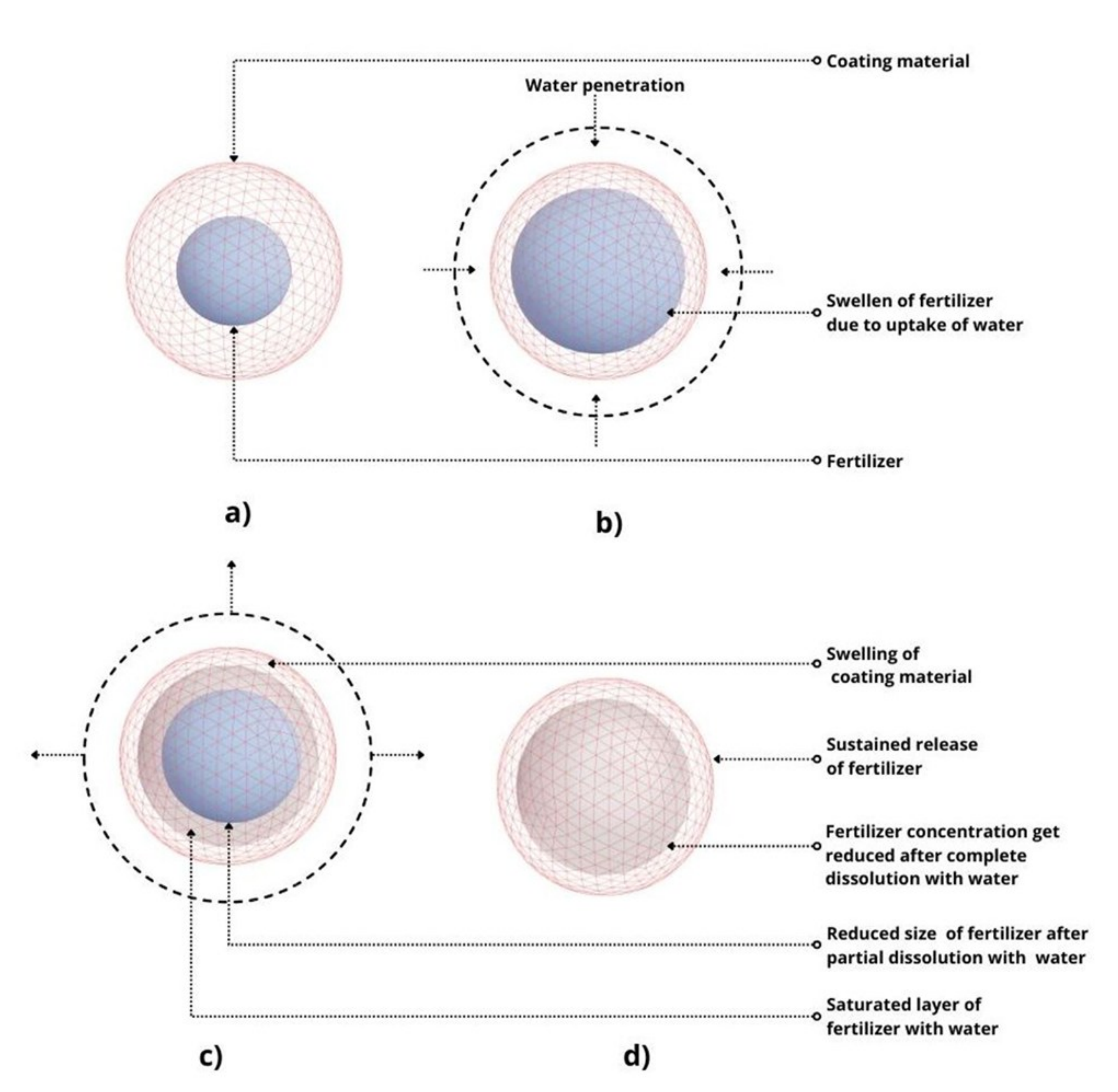

Fig. 4. Mechanism of sustained release fertilizer. (a) Sustained release fertilizer granule. (b) A lag period during which water seeps into the fertilizer through the coating. (c) Internal pressure builds up and releases itself continuously into the surroundings. (d) Decay stage, during which the release rate and concentration gradient decrease.

Table 2. Comparison of traditional fertilizer and sustained-release fertilizer

Fertilizer particular field	Traditional fertilizer	Sustained release fertilizer
Cost	Less	Expensive
Environmental impact	Pollution	Green
Nutrient use efficiency	Low	Better
Public use	Wider	Encourage to use
Invention technology	Easy	Little complicated
Release duration	Short time	Much more in traditional fertilizer
Nutrient loss	More	Less
Market available	Frequently	Moderate
Pattern of release	Non sustainable manner	Controlled manner
Factors affect for release	Soil and water	Soil pH, texture, temperature, microorganisms, moisture

Environmental factors affecting the release rates of SRF

Soil pH : The interactions between chemical species within the granule and the ion diffusion coefficient are strongly influenced by the acidic or alkaline properties of the release medium (67) and a large concentration of H+ ions in an acidic environment (pH 2-5) has been reported. This reduces the swelling capacity by protonating most of the carboxylate anions (COO^-) and inhibiting anion-anion electrostatic repulsion in the network. Similarly, in an alkaline environment (pH > 9), the presence of Na^+ ions in the solution shields the COO^- anion from electrostatic repulsion between anions. As the conversion of COOH groups to COO^- ions increases electrostatic repulsion, the swelling capacity is expected to peak between pH 5 and 9, when the solution is in a more neutral state. Hydrogels are intelligent materials that react well to pH since their research has demonstrated on-off swelling behavior between pH 8 and 2, with slower release and reduced swelling at lower pH values as mentioned in the previous studies (68).

Moisture: The diffusion rate of fertilizers is impacted mainly by the effect of moisture on the release of resin-coated fertilizer. Insufficient moisture can quickly increase nutrient concentrations and slow the release rate. When the root system comes into direct contact with the resin-coated fertilizer in the later stage, moisture has little impact.

Temperature: A rise in temperature shortens the lag period and accelerates the release linear rate (69). The solubility of nutrients within the polymer and the diffusion rate increase with temperature in the environment (soil), since the diffusion coefficient is temperature dependent (70). Additionally, higher temperatures cause greater swelling, which enlarges the pore size and results in faster release rates. It was also noted that the release rate doubles with every 15 °C increase in temperature. Diffusion occurs more rapidly at 37 °C compared to 25 °C. The study highlighted how temperature changes affect degradation behavior in enzymatic environments (71).

Microbial activity: Because of the concentration gradient difference across the polymer coatings, approximately 15 % to 30 % of the fertilizer that was not released from polymer-coated SRFs must disintegrate for the remaining fertilizer to be released. SRF biodegradation is a complicated process that is regulated by biotic and abiotic environmental stresses (50). The breakdown of biodegradable polymer coatings proceeds as follows: As the microorganisms settle on the polymer surface, they release enzymes that break down the polymeric bonds into oligomers, which are dimers that break down into monomers. Under aerobic biodegradation, these monomers are subsequently transformed into carbon dioxide, water, minerals and biomass; under anaerobic biodegradation, they are transformed into carbon dioxide, methane and humic material; and no potentially hazardous materials are left behind (72).

The biological and microbiological activities of soil are contingent upon various environmental factors, including temperature, moisture content, pH and soil type (73). The impact of soil type on the SRF release profile has been the subject of numerous investigations. Although many kinds of soils exist, silt, clay, sandy and loamy soils are the most prevalent varieties. The silt is a smooth soil with particles larger than 2 mm. Because the soil contains minerals and water, it is rich and fruitful. Clay soil has particles smaller than 2 mm, making it an extremely compact type of soil. Because tiny particles prefer to clump together, they can hold onto water and nutrients. These soils are extremely dense and rich. Less than 18 % clay and more than 68 % sand are characteristic of sandy soils in the top 100 cm of the soil (74). Sand (particle size >63 mm), silt and less clay make up loam soil. Sand, silt and clay constitute approximately 40 %, 40 % and 20 % of the mineral makeup by weight, respectively (75). Compared with sandy soils, loam soils usually offer superior drainage, air and water infiltration and higher humus, moisture and nutrient contents. Conversely, sandy soils have a low or non-existent structure, limited capacity to retain water, high permeability and high susceptibility to compaction (76).

Larger holes in sandy soils result in increased oxygen circulation, which in turn increases the activities of microorganisms that break down the polymer coating (50). Generally, higher temperatures and moisture contents in soils stimulate microbial activity, which favours communities with easier access to and metabolism of substrates (63). Additionally, the nitrification rate of ammonia is higher in loamy soil compared to sandy soil, leading to reduced NH_4 availability and consequently lower NH_3 volatilization in loamy soil than in sandy soil (77).

Crop yield enhancement

Increased nutrient availability and uptake

SRFs play a crucial role in enhancing nutrient availability and uptake in agricultural practices. Because nutrient retention and dissolution must be balanced, an SRF with good nutrient loading capacity may not always translate into increased NUE for the crop being studied. The relatively long time it takes for nutrients to be retained and the rapid or unstable nature of SRF nitrogen dissolution would be extremely harmful to the ability of crops to absorb nutrients efficiently. The application of SRFs has been shown to improve crop growth by facilitating higher and more consistent nutrient uptake throughout the growing season. In previous studies, controlled release nitrogen fertilizers were shown to increase nitrogen availability to plants as they grow, allowing for improved biomass production (78). This balanced nutrient delivery system supports healthy plant development and increased resilience to environmental stresses.

Improved growth and development

The goal of SRFs is to provide nutrients that meet the needs of plant growth. The abrupt changes in nutrient availability that frequently occur with traditional fertilizers are avoided by this regulated release technique. Therefore, plants are able to absorb nutrients more effectively, which promotes improved growth and development (52). The increased nutrient availability from SRFs directly contributes to improved plant health. By supplying essential nutrients at optimal rates, these fertilizers help improve physiological functions within plants, such as photosynthesis and respiration. Consequently, plants exhibit stronger growth characteristics, including larger leaf areas, deeper root systems and increased biomass (79). A recent study indicated that the use of SRFs can stimulate plant growth significantly. For example, maintaining an adequate nutrient supply promotes cell division and elongation, crucial processes for overall growth. This stimulation is particularly evident in crops that require a consistent nutrient input throughout their life cycle (80).

Enhanced grain quality and yield

In addition, a notable increase in NUE resulting from the use of SRF could increase crop quality and output. Crop quality is related to the nutritional content, phytochemical makeup, health advantages, sensory qualities and safety of a food crop (81). However, as a result of SRF treatments, agricultural productivity is frequently linked to crop biomass and grain yield (82).

Numerous studies have demonstrated that applying SRF increases crop quality and increases productivity even further. For example, over a 4-year field study, SRUF treatments applied to a cotton-garlic intercropping system increased garlic bulb production by up to 7.4 % and lint cotton yield by up to 17.3 % compared to urea treatments alone (83). Despite receiving one-third less nitrogen than the standard urea treatment (300 kg N ha^{-1}), the SRUF treatment at 200 kg N ha^{-1} equal or higher yields of cotton and garlic. The SRUF used consisted of epoxy resin-coated sulfur-coated urea and epoxy resin-coated urea, engineered with different coating thicknesses and extended-release times to gradually supply nitrogen in line with the crops' needs over a prolonged period. The effects of SRUF on crop quality and productivity have also been assessed in other cropping systems, including rice-oilseed rotation (84), direct seeded rice (31), winter oilseed rape, greenhouse tomato production (85) and wheat-maize crop rotation.

A long-term field experiment in a rice-oilseed rotation system showed that the SRUF treatment increased rice yields by up to 8.2 % and oilseed rape yields by up to 15.5 %. In a two-year field experiment conducted on a direct-seeded rice system, compared with UF, the SRUF treatment increased the rice grain yield by 27.8 % at the same rate of 360 kg N ha^{-1}. Additionally, in a larger regional field experiment across nine experimental sites, compared with UF alone, SRUF increased the seed yield to 11.7 % and the oil yield to 12.4 %. Regional field studies are important because they include weather variability while assessing the effects of the SRUF on crops. A related greenhouse production system study further revealed that with SRUF treatment, tomato yield significantly increased by up to 20.1 % (85). Compared with conventional urea fertilizer, a recently developed polymer-coated SRUF increased maize yield by 20 % (86).

Nutrient use efficiency (NUE)

Reduced nutrient loss and waste

The application of SRFs significantly minimizes nutrient loss, particularly nitrogen loss. These fertilizers are designed to release nutrients steadily, aligning nutrient availability with crop growth stages, which reduces the risk of leaching and runoff during heavy rainfall (87). This controlled release mechanism is essential for maintaining optimal nutrient levels in the soil. SRFs contribute to waste minimization by maximizing crop nutrient uptake. Excessive fertilizer applications often lead to surplus nutrients that are not utilized by plants, resulting in wasted resources and potential environmental harm. By delivering nutrients in a controlled manner, SRFs help ensure that the majority of the applied nutrients are effectively absorbed by crops rather than being lost to the environment (30). SRFs are instrumental in reducing nutrient loss and minimizing waste in agricultural practices. By efficiently synchronizing nutrient release with plant uptake, these fertilizers support improved NUE and contribute to sustainable farming practices. This controlled release is typically achieved through advanced formulations that minimize nutrient leaching and volatilization. By ensuring that nutrients are available to plants over an extended period, SRFs effectively reduce the amount of fertilizer that is lost to the environment (88).

Improved soil fertility and health

SRFs play a significant role in improving soil fertility and health by providing a steady supply of nutrients over a lengthy period. The application of SRFs supports the development of a healthy soil microbial community. Healthy soil micro biotas are essential for nutrient mineralization, which in turn increases the availability of nutrients to plants. By promoting beneficial microbial activity, these fertilizers contribute to the overall fertility of the soil, making it more productive for agricultural use (89). The use of SRFs can help mitigate issues related to soil acidity, which often arises from the overapplication of chemical fertilizers. By supplying nutrients in a balanced manner, these fertilizers can maintain a more stable pH level in the soil, promoting better nutrient availability and plant health. This aspect is crucial for crops that are sensitive to soil acidity and require specific pH conditions for optimal growth (90). SRFs contribute to long-term soil health by improving soil structure and fertility. Over time, the consistent supply of nutrients encourages the development of organic matter and enhances the physical properties of the soil, such as aeration and water retention. This improvement leads to healthier growing conditions for crops and promotes sustainable agricultural practices that benefit the environment (91). This fertilizer enhances the biological, chemical and physical properties of the soil, thereby contributing to sustainable agricultural practices. By effectively managing nutrient availability, SRFs not only support crop productivity but also promote long-term soil health.

Increased nutrient uptake and utilization

The implementation of SRFs has been associated with increased nutrient uptake in various studies. For example, research has demonstrated that the combination application of sustained release fertilizers with organic manures results in better nutrient absorption in crops such as chickpeas (92). Improved uptake not only supports robust plant growth but also contributes to higher crop yields and improved quality of produce. SRFs increase nutrient utilization efficiency, which refers to the proportion of applied nutrients that are taken up by plants and used for growth. By providing a more constant nutrient supply, these fertilizers help improve the uptake efficiency of key nutrients such as nitrogen and phosphorus. This efficiency is vital for increasing agricultural productivity while simultaneously reducing the amount of fertilizer needed per hectare (52).

A single application of SRF can provide mineral nutrition to plants for a lengthy period, ranging from 3 to 18 months. The slow release of SRF ensures a consistent and continuous supply of nutrients such that it remains in phase with the requirements of plants, prevents leach losses of nutrients, damages plants and enhances the fertilizer efficiency of the products (93). In this long-term study, nitrogen use efficiency (NUE) was significantly higher in the SRF treatments, which achieved a nitrogen delivery rate of 60.6-87.7 % through bleeding sap, compared to the UF treatments at the same nitrogen application rate. While long-term field studies on specific crops offer a more complete understanding of NUE via SRF, the high costs and significant manpower needed for these studies are clear limiting factors. Moreover, comparative reports have shown that the application of SRF, when applied approximately 5-7 cm from the roots, results in better fertilizer use efficiency than broadcast fertilization doses (94). Some recent studies have indicated that crop yield and NUE increase with the application of SRFs, as shown in Table 3. Furthermore, incorporating SRF into seedling pots within the root plug zone, or through an in-hole or adjacent planting-hole method, promotes early seedling growth (95).

Environmental impact

Traditional fertilizers are lost in many ways and the loss of fertilizers can lead to environmental impacts. Due to the use of SRFs several environmental impacts are shown in Fig. 5.

Reduced soil pollution and contamination

In some ways, fertilizers are spread into the soil, quickly releasing many nutrients, which leads to problems in the soil hardens the soil and reduces the infiltration of water into the soil. Moreover, when it rains or water is applied, a significant amount of fertilizer can leach into lakes and groundwater, leading to contamination. The use of SRFs can help mitigate the risks associated with soil degradation caused by excessive application of chemical fertilizers. Conventional fertilizers often lead to imbalances in soil nutrient profiles and deterioration of soil health due to their rapid

Table 3. Enhancement of crop yield and nutrient use efficiency (NUE) due to the application of sustained release fertilizers (SRFs)

Crop	SRF	Crop yield	Nutrient Use Efficiency (NUE)	Reduced Nutrient loss	References
Oil seed rape	Bio char coated urea	Increases	20	20	(120)
Rice	Resin and polyurethane coated urea	More	Higher	-	(121)
Brinjal	Humic acid coated di-ammonium phosphate	Increases	43.8 % higher uncoated DAP	-	(122)
Rice	Starch coated urea	8.8 %	43.96 % more compared to conventional fertilizer	-	(123)
Maize	Slow-release fertilizer	2.2 %	32.2 %	-	(124)
Rice	Chemical fertilizer with straw	6.8-18.2 %	42-150.5 %	-	(125)
Wheat	Bioactive sulphur coated urea	4457 kg/ha	22.17 %	-	(126)
Tomato	Polymer coated urea, carbon coated urea	4600 kg/ha	25 %	-	(42)
Wheat, maize rotation system	Polymer coated urea SRF	Increases	26.6 %	20 %	(127)
Wheat	Polymer (mixing polyacrylamide and polyacrylnitrite coated di-ammonium Phosphate	Increases	-	27 %	(128)

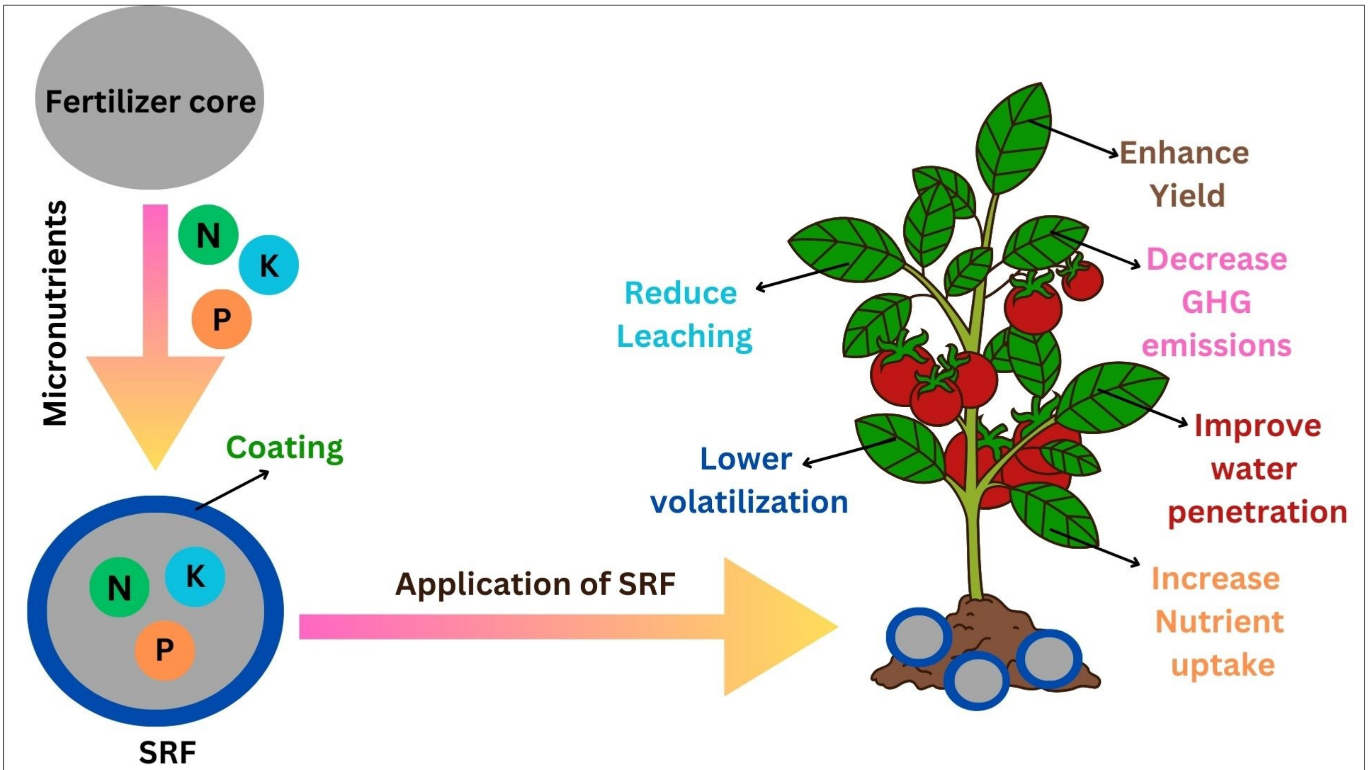

Fig. 5. Environmental impact due to the use of SRFs.

release and potential for overapplication. By providing a sustained nutrient supply, SRFs help maintain soil structure and fertility over time, decreasing the likelihood of soil degradation (96).

Chemical fertilizers can lead to negative changes in soil microbial profiles and degrade the physicochemical properties of the soil (97). SRFs, by reducing the frequency and intensity of fertilizer applications, contribute to better outcomes for soil biodiversity. Healthier soil microbial communities, which are critical components of soil health, are essential for maintaining ecological balance and promoting nutrient (22).

Improved water quality and conservation

The widespread use of fertilizers to maintain crop health has resulted in significant benefits and unintended harm. Chemical treatments pose risks to both direct and indirect exposure and to the environment (98). While beneficial for crops, the chemicals and nutrients in fertilizers can be lethal to fish, birds and other wildlife at high doses. Excessive amounts of fertilizer chemicals in water systems can create "dead zones" by reducing oxygen levels and causing chemical poisoning, harming various life forms. Additionally, beneficial organisms such as honeybees and soil microbes can be inadvertently eliminated along with pests, disrupting the ecosystem crucial for crop health and sustainability (99). In addition, the excessive use of traditional fertilizer remains a critical concern because of its potential to degrade water quality. Uncontrolled nutrient leaching has been noted to cause unwanted increases in pollution levels, affecting both groundwater and surface water ecosystems (100).

SRFs contribute to improved water quality by minimizing nutrient leaching into waterways. Nutrient conservation is vital for preventing pollution in inland and coastal waters, as nutrients are often lost into the ocean when they are used inefficiently. This conservation results in less contamination of groundwater and surface water bodies, promoting healthier ecosystems (101). When SRFs are coated with eco-friendly polymers like humic acid, ethyl-cellulose and starch, they not only release nutrients gradually but also prevent nutrient loss to the soil and environment.

Application and management strategies

The application methods for SRFs differ greatly among crop types, soil types and environmental conditions. Techniques in precision agriculture may improve SRFs efficiency by matching the timing of nutrient release with the critical growth stages of a crop. Finally, incorporating SRF into a system that includes methods of soil amendment and moisture management may even further increase nutrient availability and uptake (102).

Rates and timing

The application rates of SRFs are related to an understanding of crop nutrient requirements in relation to soil fertility levels. Therefore, application rates should, be imposed upon such knowledge of nutrient availability to meet crop demands with less overapplication of fertilizers. These regularly changing rates of application, according to the stages of growth of crops, maximize nutrient uptake and minimize waste. For example, higher rates are needed in the critical growth phase, whereas lower rates can be used when nutrient demand is reduced (103). This approach aligns nutrient availability with plant needs, optimizing growth and development.

The timing of application is critical since it is necessary to synchronize nutrient release with several key phases of crop growth. Therefore, applications should be made either at the beginning of a growing season or during maximum nutrient uptake periods. This can lead to the progressive release of nutrients that reduce the risk of leaching or runoff during rainfall events. It is also beneficial to consider climatic aspects and soil moisture conditions when determining application timing. For example, the application of SRFs before expected rainfall improves nutrient uptake by ensuring that moisture aids in the breakdown and release of nutrients from fertilizers in a progressive manner (104). Timing refers only to the season of the year, which is the spring and fall of the active growth phases. This is because single applications made in spring after winter dormancy result in effective new growth (105, 106).

Soil preparation and fertilization methods

Effective land preparation is essential for ensuring that the highest level of efficiency of SRFs is achieved. Several methods of preparation commonly undertaken for changing favourable structural changes in the soil include tilling and conditioning the soil. These factors can help improve aeration and increase the water-holding capacity of the soil. This approach facilitates the optimum incorporation of SRFs, thereby ensuring their gradual nutrient release. The effectiveness of the proper incorporation of SRFs within the soil can be strongly influential. In this regard, it is recommended that SRFs be incorporated into the topsoil during planting. This maximizes contact with the soil and allows for more efficient nutrient uptake by plants in view of ensuring that nutrient release occurs in tandem with the plant's growth stages.

Nutrient management largely pertains to the type of fertilizer, rate of application, timing and placement. While blueberry plants prefer ammoniacal nitrogen to nitrate nitrogen, most crops can utilize both forms of nitrogen. Effective nutrient management should adhere to the "Four R's" of fertilizer application: using the right nutrient, in the right amount, at the right time and in the right location for the specific crop (16). Under ideal conditions, conventional fertilizers become accessible to plants at a reliable rate (19). They release all readily available nutrients shortly after being correctly applied to soil with adequate moisture. This means that their release is immediate and not in step with the changing nutrient needs of crops throughout their growth cycle; thus, there is a need for timely side dressings. The snap bean can be described as following a growth pattern of slow-fast-slow. Plants require fewer nutrients during the early stage, more nutrients during the middle stage and fewer nutrients towards the end stage. Conventionally, several side dressings match the demands of nutrient, reduce nutrient losses and improve fertilizer efficiency. The overuse of fertilizers in one application without regard to plant growth stages perpetuates nutrient loss through leaching or runoff. Moreover, it may burn plants. This often leads to nutrients not being available when the plants need them most (107).

Integration with other nutrient management practices

Sustainable nutrient management practices are essential for improving long-term agricultural productivity. The integration of organic amendments with inorganic fertilizer applications is a part of long-term integrated nutrient management (INM) (108). This approach addresses the need to maintain soil health while maximizing the efficiency of nutrient use. The use of organic inputs in nutrient management can significantly improve nitrogen availability, which is crucial for meeting the critical growth stages of crops (109). By leveraging organic materials, overall soil fertility can be enhanced, resulting in better nutrient retention and availability for plants. SRFs have emerged as effective tools to improve NUE in various cropping systems. Their slow nutrient release mechanisms help synchronize nutrient availability with plant demand, leading to reduced nitrogen losses and enhanced crop responses (110). This interaction is vital for sustainable farming practices, particularly in systems reliant on both rice and wheat cultivation. Combining SRFs with practices that increase soil biological activity can further increase nutrient release. For example, biochar has been recognized not only as a carrier for nutrients but also as a substance that promotes beneficial microbial activity in the soil (111). This enhanced activity is critical for the effective mineralization and utilization of nutrients. The integration of SRFs with other management strategies contributes to long-term soil fertility and productivity. Continuous reliance on solely inorganic fertilizers has been detrimental to soil productivity, highlighting the need for a more balanced approach that includes organic practices (112). This balanced integration supports both crop yield and environmental sustainability. The integration of SRFs with other nutrient management practices offers significant advantages in enhancing nitrogen use efficiency (NUE), improving soil health and optimizing crop yields. By combining these fertilizers with organic inputs and advanced management techniques, farmers can achieve sustainable agricultural practices that not only benefit productivity but also promote environmental health.

Economic and environmental sustainability

SRFs offer several economic advantages, including reduced fertilizer application frequency and reduced input costs over time. The gradual release of nutrients decreases the chances of nutrient leaching and volatilization, helping to increased crop yields and reduced environmental pollution (113, 114). This translates to cost savings for farmers who would otherwise need to apply fertilizers more frequently. Some of the advantages of SRFs are shown in Fig. 6.

The initial investment for SRFs often exceeds that of conventional fertilizers because of their advanced formulation and production processes. However, long-term economic benefits, such as improved crop productivity and lower environmental remediation costs, can offset these initial expenses (52). Economies of scale may further reduce costs as production technologies improve and market demand increases.

Several factors influence the economic feasibility of adopting SRFs, including market prices, local agricultural practices and specific crop requirements. The effectiveness of SRFs in different soil types and climatic conditions also plays a crucial role in determining their economic viability in specific contexts (115). Farmers must assess local conditions and potential returns on investment before adopting these fertilizers.

Cost-benefit analyses illustrate that while SRFs generally have higher production costs than conventional fertilizers do, their long-term benefits make them economically attractive. The overall improvement in NUE can reduce the quantity of fertilizers needed, thus lowering overall costs when applied systematically. Additionally, SRFs mitigate the risks associated with nutrient leaching and environmental pollution, which could lead to potential regulatory penalties or costs associated with environmental remediation.

In terms of environmental impact, SRFs effectively reduce nutrient leaching and runoff, contributing to improved water quality and ecosystem health. By minimizing excess nutrients entering waterways, these fertilizers help fight against eutrophication, thus positioning themselves as suitable for sustainable agricultural practices. Additionally, the controlled release of nutrients aligns more closely with plant uptake needs, further supporting agricultural sustainability.

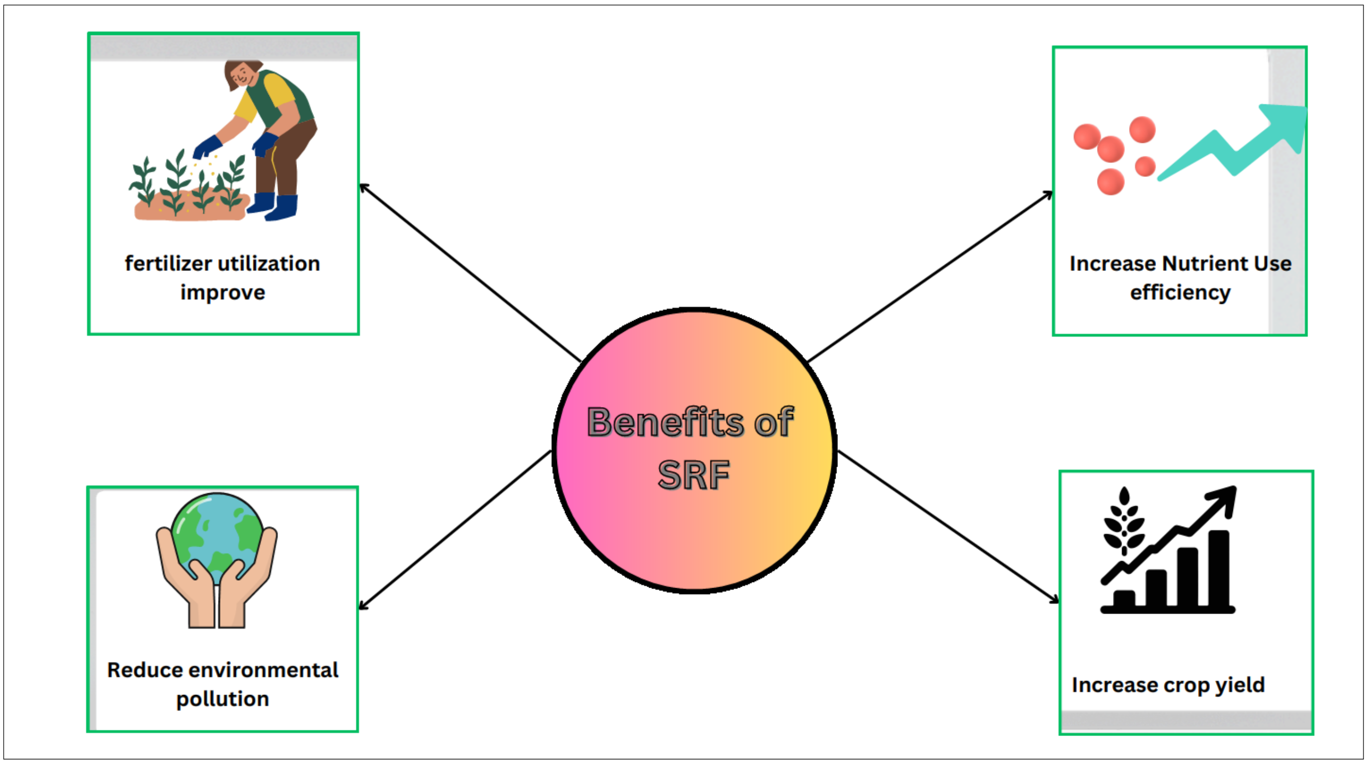

Fig. 6. Some of the benefits of the SRF.

Future directions

The future development of SRF is poised to leverage innovative materials and techniques that enhance their efficacy while minimizing their environmental impact. Certain approaches involve the use of biodegradable components, advanced controlled release mechanisms and eco-friendly raw materials. The future of SRF lies in developing cost-effective, biodegradable options that are environmentally friendly. These fertilizers should preserve soil structure and support the health of microbial communities within the soil. Additionally, their design must consider scalability and feasibility for industrial production, necessitating a relatively straightforward manufacturing process. While SRFs show promise for improving nutrient efficiency, scalability and industrial feasibility present notable challenges. The manufacturing of SRFs often involves complex coating technologies, high production costs and energy-intensive processes, which can limit large-scale adoption, especially in developing countries (9). For instance, synthetic polymer coatings, though effective, may not be cost-effective or biodegradable, raising concerns about both environmental and economic sustainability (16).

To overcome these practical limitations, recent research has focused on simplified, low-cost processes using natural and biodegradable materials such as starch, lignin and biochar, which are more scalable and environmentally friendly (116). Additionally, equipment and processes must be adapted to ensure uniform coating, mechanical stability of granules and compatibility with existing fertilizer production lines (19). Therefore, for widespread implementation, SRF design must balance efficacy, cost, material availability and process simplicity to ensure practical industrial application. Biodegradable polymers, particularly cellulosic materials, are poised to play a pivotal role in the preparation of these advanced fertilizers (23).

Research into new materials for SRFs is critical for achieving better performance and reducing environmental impacts. Innovations may include the development of biodegradable coatings and the use of slow-release technologies that ensure that nutrients are available to plants for extended periods. This supports the precision agriculture goal of minimizing resource input while maximizing output (92). The utilization of biodegradable materials in SRFs is an encouraging direction. Materials such as chitosan derived from shrimp exoskeletons have been synthesized into micro or nanoparticles, highlighting their potential in fertilizer applications. These biodegradable options not only reduce the environmental footprint but also promote prolonged nutrient release without adverse effects.

Most SRFs research focuses on individual nutrients due to the advanced development of single-nutrient slow-release technology and its practical applications. However, crops need a variety of nutrients for healthy growth. Multi-element SRFs provide major nutrients (N, P and K) and trace elements like calcium, magnesium, sulfur, iron and zinc. These fertilizers simplify management by meeting crop nutrient needs with a single application (117). Therefore, research should expand beyond single-nutrient SRFs to include the development of multi-element SRFs.

Researchers have utilized mathematical modeling to study the nutrient release process from SRFs, aiming to improve the precision of fertilization strategies. However, existing models often oversimplify the dynamics of nutrient release. They inadequately account for various environmental factors, such as soil type, climatic conditions and microbial activity, which significantly influence nutrient release. As a result, these models fall short in capturing the complexity of nutrient release across diverse crops, environments and soil conditions. Additionally, many models are primarily designed for single-element fertilizers, like N-SRFs, P-SRFs, or K-SRFs, highlighting the pressing need for a more comprehensive nutrient release model capable of addressing the intricacies of multi-element SRFs (118).

The fusion of digital farming technologies with precision agriculture has created a more informed decision-making framework for farmers. This approach enables real-time monitoring and data collection of soil health, moisture levels and crop health, which is crucial for the effective application of SRFs (92). The adoption of data analytics in combination with precision agriculture has assisted in optimizing fertilizer application rates and timings. By analysing factors such as weather patterns and soil conditions, farmers can tailor fertilizer usage to meet the specific needs of crops, enhancing efficiency and reducing waste (92). The role of Internet of Things (IoT) devices in data gathering is particularly significant, as they provide continuous feedback for farmers (119). The future of agriculture heavily emphasizes the need for automation through smart equipment that can handle the precise application of sustained release fertilizers. Drones, automated tractors and sensor technology can contribute to more precise fertilizer application, thereby minimizing the environmental impact while maximizing crop productivity (92). These technologies enable farmers to apply fertilizers only when necessary, contributing to sustainable farming. By focusing on these future directions, the combination of digital farming and precision agriculture is expected to create more sustainable, efficient and productive agriculture.

Conclusion

In summary, SRFs represent an important development in modern agriculture, providing improved NUE and making a substantial contribution to environmentally friendly farming practices. SRFs controlled release techniques minimize environmental pollution, minimize nutrient leaching and promote long-term soil fertility. Since they may release nutrients gradually in accordance with the stages of crop growth, farmers input expenditures can be reduced while productivity is maximized and fertilizer treatments can be performed less frequently. SRFs contribute to sustainability by preserving limited nutritional resources such as potassium, phosphorus and nitrogen. Additionally, they minimize the harmful effects traditional fertilizers have on the environment, such as greenhouse gas emissions, soil deterioration and water contamination.

Farmers can further customize nutrient application by incorporating SRFs into precision agriculture. This allows them to apply fertilizers at the appropriate times and in the appropriate amounts to maximize crop output and minimize waste. SRFs contribute to food security by increasing crop productivity and yield stability, particularly considering the limited amount of arable land available. This helps to meet the rising worldwide demand for food. SRFs present a viable answer to the problem of feeding more people while consuming fewer resources as the world's population increases. Future advancements in SRF technology, such as environmentally friendly materials and biodegradable coatings, could strengthen the sustainability of these fertilizers and reinforce their role in safeguarding the world food supply while preserving the environment.

However, despite their potential, several limitations must be acknowledged. High production costs and limited availability of coating materials, particularly biodegradable or bio-based ones, can hinder widespread adoption especially in low-income or resource-constrained regions. Regional variability in soil types, climate and cropping systems may also affect the performance of SRFs, requiring localized calibration and research. Additionally, some synthetic coatings may persist in the soil, raising concerns about long-term environmental accumulation if not properly managed.

Scaling up SRF technologies poses engineering and economic challenges, including the need for adaptable, cost-effective manufacturing processes and integration into existing fertilizer supply chains. Finally, while field-level emissions are reduced, life-cycle assessments reveal that energy-intensive manufacturing of SRFs may offset some of the climate benefits if sustainability is not considered holistically. Future innovations should focus on lower-cost, biodegradable materials, region-specific formulations and energy-efficient manufacturing, which will be essential to realize the full sustainability potential of SRFs. Continued research and policy support are crucial to making SRFs a cornerstone of global sustainable agriculture.

Acknowledgements

I would like to express my sincere gratitude to all those who contributed to the successful completion of this study. I also extend my appreciation to AEC&RI, Tamil Nadu Agricultural University at Coimbatore for providing the resources and facilities necessary for this work. Special thanks to my colleagues and friends for their encouragement and constructive discussions. Finally, I am deeply grateful to my family for their patience, understanding and constant encouragement.

Authors' contributions

KL, RA, AK and KP performed the study and were involved in gathering and analyzing relevant literature on sustained release fertilizers. KL wrote the first draft of the manuscript. RA and GV conceived of the study, formulated its objectives and participated in its design and coordination. AV contributed to editing, formatting and finalizing the manuscript for submission. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: The authors report there are no competing interests to declare.

Ethical issues: None

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Additional information

Peer review: Publisher thanks Sectional Editor and the other anonymous reviewers for their contribution to the peer review of this work.

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