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RESEARCH PAPER

Systematic literature review on slow/ controlled release fertilizers (SCRF) material: fabrication methods, characteristics, nutrient release, and crop yield effects

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Abstract: Slow/controlled-release fertilizers (SCRF) are increasingly adopted to improve nutrient-use efficiency and reduce environmental losses amid fertilizer price volatility and sustainability demands. This systematic literature review synthesizes recent SCRF evidence by linking fabrication methods, material characteristics, nutrient release behavior, and agronomic outcomes. A structured search was conducted in ScienceDirect for open-access English research articles published between 2021–2025, focusing on urea-based SCRF that reported material composition/characterization, nutrient release profiles, soil indicators, and/or crop productivity. Thirty-eight studies met the inclusion criteria. The SCRFs were grouped into five material classes: synthetic polymers, natural/biobased polymers, biochar-based composites, inorganic minerals, and inhibitor/multifunctional systems. Fabrication was dominated by coating/encapsulation and blending to form core–shell granules (common in synthetic polymers), while polymerization, cross-linking, and casting frequently produced hydrogels or porous 3D networks (typical of biopolymers). Across studies, surface chemistry (hydrophobic versus hydrophilic functional groups) and coating integrity governed water ingress and release mechanisms (diffusion-barrier release versus swelling/degradation-assisted release), yet mechanical and swelling reporting remained inconsistent. Overall, SCRF improved crop yields relative to conventional fertilizers, with reported gains ranging from 1.47% to over 100% depending on material type, crop, and trial conditions. Key trade-offs persist between long-duration release precision, cost, and biodegradability, and cross-study comparison is limited by non-uniform biodegradation tests. Several papers assessed nitrogen-use efficiency and soil indicators (e.g., leaching or gaseous losses), but protocols and reporting units varied. Incorporating inhibitors or mineral fillers can further extend release, yet may increase persistence risks and complicate environmental fate assessment. Future work should standardize performance metrics and develop hybrid designs that balance release control, durability, and environmental fate.

Keywords: Slow/Controlled Release Fertilizers, Fabrication Methods, Material Characteristic, Nutrient Release, Crop Yield

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INTRODUCTION

Fertilizers are chemical or organic substances added to the soil to provide essential nutrients such as nitrogen, phosphorus, and potassium to support plant growth and productivity. In modern practice, synthetic fertilizers such as urea, DAP, and NPK are the most widely used due to their effectiveness in increasing crop yields [1][2]. However, in recent years, global fertilizer prices have surged due to rising energy costs, supply chain disruptions during the COVID-19 pandemic, and geopolitical conflicts that have hampered the supply of nitrogen-based fertilizers [2][3][4]. The increase in fertilizer prices has a direct impact on farmers, especially those who rely on nitrogen fertilizers. As input costs rise, many farmers are forced to reduce fertilizer applications or resort to other strategies, such as clearing new land, to maintain production levels. This pattern places additional pressure on the sustainability of agricultural systems by accelerating land degradation and encouraging agricultural expansion into non-productive areas [1][2].

As fertilizer costs rise and farmers adjust their input use, this challenge is further compounded by the low nitrogen use efficiency observed in many regions. Nitrogen use efficiency in many areas is only around 30–35%, so some fertilizer is not absorbed by plants and pollutes the soil and water [5]. This condition makes agriculture less profitable, encouraging the conversion of land to non-agricultural sectors, especially in areas with low soil fertility and declining economic value of land [6]. On the other hand, food crops like rice face high pest pressure, especially in intensive farming systems. To suppress pests, farmers implement crop rotation, for example, planting secondary crops (corn, soybeans, peanuts) after the rice harvest. However, reducing fertilization or crop rotation without proper nutrient management can reduce secondary crop productivity, complicating pest problems and increasing crop yields [7].

The high cost of fertilizer, the trend of land conversion, and pest pressure indicate that today's agricultural systems face increasingly complex challenges. In the field, low nitrogen fertilizer efficiency results in significant nutrient losses to the environment, increasing production costs while suboptimal crop productivity. This nutrient loss also weakens soil health and increases crop vulnerability to pest attacks due to unbalanced growth. This situation indicates a gap between agricultural needs, stable productivity, efficient input use, and minimal environmental impact and the still-widespread commercial fertilizer practices. Therefore, more effective nutrient management and reduced nitrogen loss are urgently needed to support sustainable production.

Various fertilizer innovations have been developed to address the limitations of commercial fertilizers and improve nutrient utilization efficiency. These innovations include the development of new material-based fertilizers, such as biofertilizers, biochar, organo-mineral fertilizers, and SCRF, which are designed to tailor nutrient release to plant needs. Biofertilizers and biochar can improve soil fertility and nutrient availability, while organo-mineral fertilizers combine the benefits of organic and chemical fertilizers. However, nutrient release in these innovations tends to be less controlled, so the physiological needs of plants, especially taller crops like corn that require more nitrogen, are not always met. As a result, nutrient losses to the environment remain high, plant productivity is less than optimal, and fertilizer use efficiency is lower than with SCRF [8], [9], [10].

The advantage of SCRF lies in its ability to fundamentally improve agricultural sustainability and efficiency compared to traditional fast-release nutrient sources [11][12]. This advanced formulation dramatically improves nitrogen use efficiency by synchronizing nutrient delivery rates with the actual physiological needs of plants throughout the growing season [13], [14][15][16][17]. By minimizing nutrient losses, SCRF helps protect water quality, lowers the risk of eutrophication, and mitigates the environmental impact of traditional fertilization practices [18][19][20][21][22]. This reduction contributes to a decrease in greenhouse gas emissions and water eutrophication [18][23].

Agronomically, the stable nutrients from SCRF support better root growth and plant morphology, enhance water and nutrient uptake capacity, and ultimately increase productivity, biomass accumulation, and crop yield [24][25]. Furthermore, SCRF addresses the over-fertilization problem common with commercial fertilizers, where tall crops like corn require more nitrogen than low-yielding crops like secondary crops, resulting in some traditional fertilizers not being absorbed and being lost to the environment [9][28]. SCRF overcomes this limitation by adjusting nutrient release to suit the physiological needs of the plant, thereby increasing fertilizer use efficiency, reducing environmental impacts, and supporting sustainable agricultural production. In the context of high fertilizer prices, increasing land conversion, and complex pest pressures, SCRF has emerged as the most superior and urgent fertilizer innovation to implement. The use of SCRF not only helps stabilize crop productivity but also optimizes input use, maintains soil health, reduces environmental pollution, and supports the sustainability of the agricultural system as a whole.

This Systematic Literature Review (SLR) on SCRF was conducted to systematically identify, analyze, and summarize existing research findings on SCRF. The purpose of this systematic review was to synthesize types of slow-release fertilizers from the perspective of composition, material properties, and nutrient release mechanisms, while assessing their effectiveness in increasing crop yields compared to conventional fertilizers. Specifically, this review aimed to: (1) identify the material compositions and fabrication methods of slow-release fertilizers used in recent studies on SCRF ; (2) evaluate the chemical, physical, and mechanical properties of materials that influence nutrient release behavior; (3) compare the release rates of nitrogen, phosphorus, and potassium, release duration, and biodegradability of various fertilizers; and (4) assess the differences in crop yields between conventional and slow-release fertilizers, including quantifying the percentage increase in yields across different crops. This paragraph provides a framework for understanding the relationship between fertilizer characteristics and their agronomic effectiveness.

MATERIALS AND METHODS

This study applies the Systematic Literature Review (SLR) method to comprehensively and unbiasedly examine research findings related to slow/controlled release fertilizers. The SLR procedure is carried out through several stages, namely (1) formulation of research questions, (2) systematic literature searches in scientific databases, (3) selection and inclusion-exclusion criteria for studies, (4) extraction and analysis of qualitative data, and (5) synthesis of findings. The purpose of this method is to identify, evaluate the quality, and analyze patterns from various empirical studies to answer the main research question, namely understanding the relationship between the chemical and physical composition of fertilizers, the properties of nutrient carrier materials, the underlying release mechanisms, and their effectiveness in increasing fertilizer efficiency and crop yields.

A systematic literature search was conducted in the ScienceDirect electronic database, covering publications from 2021 to 2025. The search strategy employed a combination of keywords, including “soil,” “fertilizer,” “soil quality,” “slow-release,” “urea,” and “nutrient leaching.” Articles resulting from the search were then screened through two stages based on inclusion criteria. The inclusion criteria focused on: (1) the type of article being a research paper; (2) being available in open access; (3) being written in English; and (4) specifically discussing the formulation, characterization, or application of urea-based slow-release/controlled-release fertilizers. Equally important, articles must include direct measurement data on at least one of the following parameters: chemical/physical composition of the fertilizer, properties of the carrier material, nutrient release profile, soil quality indicators, or crop productivity

RESULTS AND DISCUSSION

Formulation and Fabrication of SCRF Materials

The development of SCRF fertilizers involves a variety of materials and fabrication strategies. Based on the properties of their primary matrix or coating material, SCRF formulations can be broadly categorized into two major groups: polymer-based systems and non-polymer systems.

Table 1 presents a summary of various polymer-based SCRF formulations reported in the literature. The information in this table is structured to demonstrate the relationship between polymer material categories, material compositions, preparation methods, and the resulting product shape and structure, providing the reader with a general understanding of approaches used in SCRF design. Through this comparison, the table also helps identify design trends (e.g., core–shell structures or 3D hydrogel networks) and process choices relevant to the goal of controlling nutrient release rates. Therefore, Table 1 serves as a basis for discussing the most prevalent SCRF formulation strategies and their implications for their performance and potential application under field conditions.

Table 1. Polymer-Based SCRF Formulations

Material Type	Material & Composition	Method	Form	Structure	Ref
Synthetic Polymer	Urea 96% and polyurethane 4%	Physical polymer coating	Granular	Core-shell	[20]
	Urea; 33% SCU 33.3%; PCU 33.3%	Physical blending	Granular	Core-shell	[27]
	PCU-2; PCU-3; PCU-4; SCU; urea	Coating and blending	Granular	Core-shell	[28]
	Urea 93%; TMP/TM; DOODT; HDDA 7%	Coating with thiol-one click chemistry	Granular	Core-shell	[29]

Material Type	Material & Composition	Method	Form	Structure	Ref
	LCNF 8-9%; clinopptilolite 0.1%; urea -9%; AA-co-AAm 80-82%; MBA+APS 8.5%	Free radical polymerization	Hydrogel	3D network	[30]
	Coated urea 60%; common urea (uncoated) 40%	N/A	Granular	Core-shell	[31]
	Urea 80.6%; Stearic Acid 14.5%; Paraffin Wax 4.8%; Zn coating <0.1%	Sequential Coating	Granular	Multilayer Core-shell	[19]
	Urea 28%; ureaformaldehyde 62%	Condensation polymerization	Granular	Polymer matrix	[32]
	PFEHEMA 99.03%; AIBN 0.87%	Radical polymerization and Dip-Coating	Granular	Core-shell	[33]
	N 28%; P_2O_5 12%; K_2O 10%; bioactive double-membrane dual-control system 50%	Industrial coating/ encapsulation	Granular	Core-shell	[18]
Natural/Bio-based Polymer	MCC 14.12%; acrylic acid 50.18%; AOBA 13.12%; MBA 0.11%; APS 0.74%; urea 21.73%	Graft polymerization and cross-linking	Hydrogel	Porous 3D Network	[34]
	Tannin-based amine 87%; urea 13%	Physical Blending	Granular	Porous	[35]
	Urea 75%; LAO-g-GA 25%	Encapsulation	Pellet	Polymer matrix	[17]
	Urea core 95%; PU coat 4.965%; nano-copper laurate: 0.035%	Spray coating	Granular	Core-shell	[22]
	PVA 32.6%; sodium alginate 21.7%; humic acid 21.7%; citric acid 21.7%; urea 2.2%	Chemical Cross-linking & Casting	Hydrogel	Homogeneous	[36]
	Urea 92%; AESO 8%	UV-Curing Coating	Granular	Core-shell	[37]
	Chitosan 86.4%; TPP 8.6%; calcium oxide 0.9%; urea 4.1%	Membrane Casting and Ionic Cross-linking	Membrane	Porous 3D	[38]
	Gelatin 82%; glycerol 16.4%; n-SiO_2 1.6%; urea 100%	Dipping and Cross-linking	Hard Capsule	Core-shell	[12]
	Starch 10%; PVA 5%; cross-linker acid: 2%, 4%, or 6%, urea 83%, 81% or 79%	Fluidized Bed Coating	Granular	Core-shell	[39]
	Urea 61.8%; ECSL-100 38.1%	Solvent-Free Coating	Granular	Core-shell	[40]
	κ-Carrageenan 3.4%; guar gum 0.85%; epichlorohydrin & NaOH 94.35%; fertilizer (urea+DKP) 1.4%	Microwave-assisted Cross-linking	Hydrogel	Porous 3D Network	[41]
	MAP granular 90%; CO/LWS 4.95%; MDI 4.95%; DETA 0.1%	Layered coating	Granular	Core-shell	[42]
	Sodium Alginate 29.6%; LS 29.6%; SX 11.1%; GDL 11.6%; Urea 14.8%; KH_2PO_4 14.8%	Ionic & Physical Hydrogel Formation	Hydrogel	Porous 3D Network	[43]

Table 1 reveals two main material approaches: synthetic and natural/bio-based, with different fabrication method preferences and final structures. Synthetic polymers, such as polyurethanes and acrylic polymers, are often utilized through physical coating or blending methods to produce granular forms with a dominant core-shell structure [20][27][33]. This approach emphasizes controlling nutrient release through a physical barrier that envelops the urea core. On the other hand, formulations based on natural polymers such as chitosan, alginate, starch, and carrageenan, tend to utilize polymerization, grafting, or cross-linking techniques (chemical, ionic, or radical) to create hydrogels or polymer matrices with porous 3D networks [34][38][41][43]. These structures not only

serve as nutrient carriers, but can also enhance water retention and slow-release properties through diffusion and matrix degradation mechanisms.

These variations in shape and structure are closely correlated with the manufacturing method chosen. Techniques such as coating, encapsulation, and fluidized bed consistently produce granules with a core-shell structure [17][20][39], which generally aim for diffusionally controlled release. In contrast, methods such as radical polymerization, cross-linking, and casting more often produce hydrogels, membranes, or capsules with a homogeneous or porous 3D structure [30][36][38][12]. These structures offer dual release mechanisms: diffusion and swelling- or matrix-degradation-based release. Recent trends also point to innovations in hybrid materials and environmentally friendly coatings, such as the use of click chemistry [29] vegetable oil-based UV-curing coatings [37], and double-membrane systems and nanoadditives [18][22][12] to enhance performance and functionality.

Overall, the choice of polymer category significantly influences the formulation strategy and final product characteristics. Synthetic polymers offer reproducibility and tight control of the barrier layer, while natural polymers offer advantages in biocompatibility, sustainability, and the ability to form a 3D network that interacts with the soil environment. Recent developments in this field focus on optimizing material combinations, simplifying processes, and improving nutrient efficiency through advanced structural design and modified biobased materials.

Table 2. Non-Polymer Based SCRF Formulation

Material Type	Material & Composition	Method	Form	Structure	Ref
Biochar-based Composite	Biochar (corn straw) 32.5%; urea 50%; attapulgite 17.5%	Ionic Gelation	Granular	Porous	[44]
	Biochar (corn straw) 30%; Pyroligneous acid 10%; Bacillus spp 10%; conventional fertilizer 50%	Pyrolysis & adsorption	Granular	Porous	[45]
	Bentonite 38;5%; biochar (banana frond) 11.5%; urea 38.5%; sodium alginate 11.5%	Encapsulation	Bead/ pellet	Porous	[11]
	Urea 70%; biochar (rice husk) 30%	Coating	Granular	Core-shell	[46]
	Biochar (rice husk) 80%; attapulgite 10%; KH_2PO_4 5.71%; NH_4Cl 4.29%	Co-pyrolysis	Powder	Homogeneously Porous	[47][47]
	Biochar (corn stalk) 22.88%; NPK fertilizer 57.12%; PVA 8%; corn starch 12%; modified kaolinite 0.2%	Granulation & Coating	Granular	Core-shell	[48]
	Biochar (from quinoa straw; corn; rice husk; sugarcane bagasse) 2.5% and biogas slurry 97.5%	Impregnation	Granular	Porous	[49]
	Biochar (oat husk) 22.2%; urea 27.8%; Diammonium Phosphate (DAP) 27.8%; Water 22.2%	Impregnation	Granula	Porous	[50]
	Biochar (corn cob) 26%; $MgCl_2 \cdot 6H_2O$ 68.2%; NaOH 3.9%; NH_4Cl 0.31%; KH_2PO 0.16%	Precipitation/ Crystallization within Matrix	Powder	Porous	[51]
Inorganic Mineral	Digestate 81.5%; silicate components 18.5%	Sol-Gel Process	Solid	Porous	[52]
	Hydroxyapatite (HA) from crab shell 14.3%; urea or ammonium sulfate (AS) 85.7%	Simple Blending	Powder	Porous	[53]
Inhibitor/ Multifunctional	Urea 78.01%; water 15.60%; PVA 0.62%; Starch 0.42%; glycerol 0.20%; BOF[1] 10%	Coating	Granular	Double-layer Core-shell	[54]

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[1] BOF = Biochar-based Organic Fertilizer

Material Type	Material & Composition	Method	Form	Structure	Ref
System	PVA 25%; CMC 10%; urea 25%; naoh 35%; activated charcoal 5%	Chemical Crosslinking with ECH; Casting in Mold; and Drying	Hydrogel	Homogeneous Porous 3D	[23]
	Chitosan 6.25%; biochar 2.5%; glycerol 1.25%; NPK 90%	Coating/ Encapsulation	Granular	Core-shell	[55]
	Hyper CDU 100%	Air Condensation	Granular	Homogeneous	[56]

Based on **Table 2,** biochar-based SCRF dominates non-polymer formulations because biochar functions as a porous nutrient-host matrix that regulates release primarily through diffusion/desorption constraints. Accordingly, fabrication routes such as ionic gelation, adsorption-assisted processing, impregnation, encapsulation, and coating are leveraged to strengthen nutrient retention and slow dissolution, producing mostly porous granules/beads and, when additional layers are applied, more defined core–shell architectures [44][45][11][46][47][47][48][49][50]. A key development is the integration of minerals (e.g., attapulgite, bentonite, modified kaolinite), which improves mechanical integrity and adds ion-exchange/adsorptive sites, enhancing both durability and release control [44][11] [47][47][48].

Beyond biochar, inorganic matrices such as silicate-based solids and hydroxyapatite from crab-shell waste exploit mineral adsorption and low solubility to moderate nutrient release [52][53]. Meanwhile, inhibitor/multifunctional systems extend the design space via multilayer coatings and functional additives (e.g., BOF in coatings, activated carbon, chitosan), aiming for controlled release alongside added soil functions [54] [23] [55]. Overall, these non-polymer routes emphasize abundant waste-derived feedstocks and scalable processing, while increasingly adopting hybridized matrices to improve performance without relying on conventional synthetic polymer coatings as the primary platform [44] [48] [52] [54].

Characteristics of SCRF Materials

After discussing the formulation, synthesis methods, and structure of SCRF materials, the next discussion focuses on the surface chemical characteristics and physical properties of the materials. These characteristics include the type of functional group, hydrophilicity or hydrophobicity, and mechanical properties, which determine the material's interaction with water and the soil environment and play a role in maintaining the integrity of the fertilizer's structure during application. A summary of the chemical and physical characteristics of various SCRF materials based on material classification is presented in **Table 3.**

Table 3. Chemical and Physical Characteristics of SCRF

Material Type	Commonly Reported Functional Groups	Dominant Hydrophilic/ Hydrophobic Character	Reported Mechanical Properties	Ref
Synthetic Polymer	C=O, $-CH_2-$, $-CH_3$, -COOH, $-CONH_2$, C-O-C, C-F	Hydrophobic	Tensile strength, Elastomeric, Rigid	[27][29][30] [19][32][33]
Natural/ Bio-based Polymer	-OH, $-COOH/-COO^-$, C=O, $-NH_2/-NH$	Hydrophilic	Elastomeric, Young's Modulus, Tensile Strength, Crushing Strength, Elastic Modulus	[34][22][38] [12][39][43]
Biochar-based Composite	-OH, C=O, C-O/C-O-C, C=C	Hydrophilic	Compressive Strength, Tensile Strength, Dense Layer	[45][11][46] [48][49][14]

Inorganic Mineral	-OH/OH⁻, Si-OH, PO_4^{3-}, CO_3^{2-}	Hydrophilic	Gel Strength	[52][53]
Inhibitor / Multifunctional System	-OH, C=O, C-O-C, $-NH_2$	Hydrophilic	Tear Resistance, Mechanical Strength	[54][23][55][56]

Table 3 shows that differences in functional groups in SCRF are not simply chemical characteristics, but design levers that directly influence water entry pathways and nutrient release mechanisms. In synthetic polymers, the dominance of non-polar groups correlates with hydrophobic properties, allowing water to enter primarily through inhibited diffusion; this is advantageous for long-term release targets and high humidity conditions, as the coating acts as a stable barrier. In contrast, biopolymers and biochar composites rich in polar groups tend to be hydrophilic, allowing water to interact more readily with the matrix, allowing release through swelling and increased diffusion pathways, potentially beneficial for systems responsive to fluctuations in soil moisture content.

However, a key implication is that a design trade-off arises: increased hydrophilicity, while aiding water retention and moisture response, also potentially increases swelling, which can compromise structural integrity if mechanical parameters are inadequate. This is why, while functional group and hydrophilic/hydrophobic character data are relatively frequently reported, mechanical characterization remains a critical bottleneck, determining whether a coating will survive storage, transportation, application, and wet-dry cycling in soil. Future SCRF research needs to explicitly link these three elements: surface chemistry, water entry mechanisms, and mechanical metrics, so that material selection is based not only on release profiles but also on operational durability in the field.

There is no universally “better” property between hydrophilic and hydrophobic; the choice depends on the intended release mechanism and field conditions. Hydrophobic coatings (typical of synthetic polymers) primarily act as diffusion barriers and are therefore suitable for long-duration release and for mitigating nutrient losses under high-moisture or leaching-prone conditions [27][29][30]. In contrast, hydrophilic matrices (common in bio-based polymers, biochar composites, and some inorganic systems) facilitate water uptake and swelling-assisted transport, enabling moisture-responsive release and improved nutrient availability near the root zone under variable rainfall or high-demand cropping systems [34][45][46][52]. Hybrid or multifunctional designs can combine these behaviors, using a hydrophilic phase to retain water while a hydrophobic phase moderates diffusion, offering more adaptive release control ([54]; [55][56]. Therefore, optimal SCRF design should be selected based on crop demand, soil texture, climate, and target release duration, with substantial potential in layered or composite architectures that integrate both properties.

Nutrient Release Performance of SCRF

Based on the chemical and physical characteristics of SCRF materials discussed previously, nutrient release performance is the next important aspect that determines the effectiveness of fertilizers in providing nutrients in a controlled manner. This subsection analyzes the percentage of nitrogen release, release duration, swelling ratio, and biodegradability of various types of fertilizer materials, as summarized in **Table 4**. This evaluation not only shows the differences in release capabilities between materials but also links the surface and mechanical properties of each material with the nutrient release mechanisms that occur in the field.

Table 4. Nutrient Release Performance of Slow/Controlled Release Fertilizers

Material Type	% Nitrogen Release	Release Duration (day)	Swelling Ratio (%)	Biodegradability	Biodegradability Test	Ref
Synthetic Polymer	2 – 5,7	40	0.45 - 1.51	30.77% - 60.78% in 240 days	Soil burial test	[29]
	52.75	30	2404 - 7244	N/A	N/A	[30]
	75	28	N/A	N/A	N/A	[19]
	80	70	N/A	N/A	N/A	[43]
Natural/ Bio-based	61.46	42	30134	43,73% in 60 days	N/A	[34]

Material Type	% Nitrogen Release	Release Duration (day)	Swelling Ratio (%)	Biodegradability	Biodegradability Test	Ref
Polymer	68.14	49	N/A	N/A	N/A	[35]
	72	30	N/A	N/A	N/A	[17]
	>80	105	3.31	N/A	Thermogravimetric Analysis (TGA)	[23]
	80.77	30	945.16	45% in 28 days	Soil Burial Test	[48]
	78	28	N/A	100 % in 90 days	Soil Burial Test	[37]
	13.80	10	109.52 - 132.62	N/A	N/A	[38]
	75–79	28	70.9- 117.4	N/A	N/A	[12]
	86.90	44	N/A	N/A	N/A	[40]
	22.50	1	10610	100% in 56 days	Soil Burial Test	[22]
	77.08	28	9190	38.87% in 60 days	Soil Burial Test	[36]
Biochar-based Composite	62 - 70	30	89	N/A	N/A	[41]
	71.10	14	N/A	N/A	N/A	[46]
	43.54	30	N/A	40% in 30 days	Soil Degradation Test	[52]
	19.10	29	86.11	34.41% in 30 days	Soil Burial Test	[55]
	64	7	N/A	0%	Analisis rasio H/C dan O/C	[49]
	19.20	30	N/A	N/A	N/A	[51]
Inhibitor/ Multifunctional System	18.30	28	87.12 - 101.29	89.5% in 90 days	Biodegradation properties	[54]
	50	16	5691	48% in 3 months	Soil Burial Test	[42]
	8.93	33 days	58-85	30-40% in 30 days	Soil Burial Test	[14]

Based on the synthesis of various studies in **Table 4**, the performance of slow/controlled-release fertilizers (SCRF) shows a consistent trade-off pattern between long-term release precision and environmental sustainability. Materials with the most stable release control tend to have low biodegradability, while more environmentally friendly materials often exhibit greater performance variability.

Synthetic polymers generally exhibit the most stable and extreme controllability of release duration. Synthetic polymer-based formulations can be engineered to produce very slow nitrogen release[43]. This performance is primarily attributed to the material's hydrophobic properties and the stability of the polymer layer structure, which limits the diffusion of water and nutrients. However, these advantages are offset by limitations in sustainability, with relatively low biodegradability [29] potentially leaving material residues in the soil.

In contrast, natural biopolymer-based materials demonstrate superior biodegradability. Some formulations have been reported to undergo near-complete degradation in less than 90 days [22][37]. However, their nutrient release performance varies widely, ranging from a rapid release [22] to a slow release rates [23]. The extreme variation in swelling ratio values [23][34][36], indicates the material's high sensitivity to water. This condition has implications for the potential instability of nutrient release in the field, especially in soils with significant moisture fluctuations.

Biochar-based composites generally act as medium-term nutrient carriers while providing additional benefits as soil amelioratives. Nitrogen release from these systems is relatively rapid to moderate[14][46]. However, their biodegradability has been reported to be low to very limited [49]. These findings limit the environmental sustainability claims of biochar-based SCRF systems if they are not combined with more readily biodegradable materials.

Inhibitor and multifunctional systems represent different approaches to controlling nutrient release, namely by modifying chemical and biological reactions in the soil. The performance of these systems is highly contextual, as reflected in the wide variation in nitrogen release rates[14][42]. Their effectiveness is strongly influenced by specific environmental conditions, such as moisture, microbial activity, and soil characteristics, thus limiting the generalizability of performance across application locations.

Furthermore, the high proportion of parameters reported as not available (N/A), particularly swelling ratio and biodegradability, indicates methodological gaps in the literature. This reporting inconsistency complicates quantitative comparisons between studies and hinders integrated evaluations that simultaneously link nutrient release performance, material physicochemical properties, and environmental impacts.

It should be noted that biodegradability testing in the various studies in Table 4 was conducted using diverse methodological approaches, such as soil burial tests, soil degradation tests, thermogravimetric analysis (TGA), and indirect analysis using H/C and O/C ratios. This diversity of methods reflects the lack of a uniform biodegradability evaluation standard in SCRF fertilizer research. Therefore, the reported biodegradability values are best understood as an indication of the material's degradation tendency, rather than as a basis for fully equivalent quantitative comparisons between studies.

The implications of these findings suggest that the design of SCRF fertilizer carrier materials cannot focus solely on a single performance parameter. Nutrient release stability, swelling behavior, and biodegradability must be considered simultaneously in material design. An imbalance in any one parameter, such as excessive swelling or excessively low biodegradability, has the potential to reduce agronomic effectiveness and increase the risk of material residues in the soil. Therefore, the design approach for SCRF materials needs to be directed at controlling the material's physicochemical properties in an integrated manner, rather than simply optimizing nutrient release rates.

Overall, the results of this synthesis confirm that to date, there is no single carrier material capable of simultaneously meeting the criteria of stable nutrient release, controlled physicochemical properties, and adequate biodegradability. Most studies still focus on optimizing one or two performance parameters, while the interrelationships between these parameters and their implications for environmental sustainability have not been comprehensively evaluated. Furthermore, the lack of standardization in reporting performance parameters and test methods further limits comparisons across studies. This situation opens up opportunities for further research focused on the development of SCRF systems based on integrated material design and more uniform and comprehensive performance evaluation.

Effectiveness of Slow/Controlled Release Fertilizer on Crop Yields

After discussing nutrient release performance, the next step is to evaluate how the characteristics and release mechanisms of SCRF fertilizers impact crop growth and yield. This subsection presents data on the effectiveness of slow/controlled-release fertilizers compared to conventional fertilizers, including yield increases measured on various test crops, as summarized in **Table 5**. This analysis helps link material properties and nutrient release performance to real-world agronomic benefits.

Table 5. Effectiveness of Slow/Controlled Release Fertilizer on Crop Yield

Material Type	Tested Plant	Conventional Fertilizer Yield (kg/ha)	Slow-Release Fertilizer Yield (kg/ha)	Yield Increase (%)	Ref
Synthetic Polymer	Wheat	7013	7479	6.70	[28]
	Rice	8865	8995	1.47	[31]
	Wheat	11180	13760	38,4	[19]
	Sunflower	3084	3870.94	25,5	[43]
Natural/ Bio-based Polymer	Pakchoi	3100	4426	42.77	[35]
	Wheat	2448	4896.91	100.04	[48]
	Spinach	1168	2428	108	[39]

	Wheat	3325	4199	26.30	[36]
Inhibitor/ Multifunctional System	Wheat	3100	4426	40 - 44	[54]

Based on yield data from various studies summarized in **Table 5**, SCRF consistently demonstrates the ability to increase crop productivity compared to conventional fertilizers. However, the magnitude of yield increases varies significantly, depending on the type of material and the characteristics of the plants tested.

Natural biopolymer-based SCRFs show the highest potential for yield increases among other material groups. Several studies report very significant yield increases [39] and a 100.04% increase in wheat [48]. These findings indicate that nature-based materials not only contribute to environmental sustainability but also significantly increase the efficiency of nutrient utilization by plants. These significant yield increases are thought to be related to the ability of natural materials to create a more conducive rooting environment, although the magnitude of the plant response remains strongly influenced by the material formulation and growing conditions.

Meanwhile, inhibitor or multifunctional systems have also shown promising agronomic performance, with yield increases ranging from 40–44% in wheat [54]. This approach works by controlling soil biochemical processes, such as inhibiting nitrification, thereby reducing nitrogen loss and increasing nutrient availability to plants. Although data are still limited, these results suggest that non-coating approaches can be an effective alternative for increasing fertilizer efficiency, particularly in certain cropping systems.

In contrast to these two groups, synthetic polymer-based SCRFs showed the widest range of yield increases, ranging from relatively low increases of around 1.47% in rice [31] and 6.70% in field wheat [28] to quite significant increases under certain conditions, such as 38.4% in potted wheat [19] and 25.5% in sunflower [43]. This variation indicates that although synthetic polymers have good nutrient release control capabilities, their agronomic effectiveness is highly dependent on the suitability of the formulation to the crop type and the environmental conditions of the application site.

When compared to the synthetic results in **Table 4**, it appears that yield increases do not always correlate directly with the longest nutrient release duration. As shown by He et al. (2025), materials that provide long-term release control, such as synthetic polymers, do not always produce the highest yield increases. Conversely, studies by X. Zhao et al. (2025) dan Zafar et al. (2021) revealed that materials with more variable release performance, such as natural biopolymers, can actually elicit greater plant responses. Similar findings were reported by Etminani-Esfahani et al. (2025) for inhibitor systems. This confirms that the effectiveness of SCRF is determined not only by material parameters but also by the suitability of nutrient release patterns to the physiological needs of the plant at a particular growth stage. Furthermore, the data also show differences in response between pot trials and field trials, particularly in wheat. A comparison between the results of the pot-scale study by Umar et al. (2023) and Wang, Sun, et al. (2025) in the field indicated that the results from a controlled scale do not necessarily fully represent more complex field conditions, so that multi-location tests and real cultivation conditions are important aspects in evaluating SCRF performance.

These findings demonstrate that crop yield improvement depends not only on the ability to control nutrient release but also on the material's interaction with specific crop and environmental conditions. Therefore, SCRF design needs to consider the integration of several aspects: nutrient release patterns, the material's physicochemical properties, and the plant's response to growing conditions. Overly generic formulations can result in variable agronomic effectiveness, so design strategies should be geared toward materials specific to crop types and agroclimatic conditions.

Overall, this synthesis confirms that SCRF is not only a nutrient control technology but also an agronomic strategy for increasing crop productivity. Natural biopolymers and inhibitor systems emerge as the most promising candidates, combining yield enhancement with potential environmental sustainability. However, the current literature is still limited to the evaluation of single materials, limited crop species, and a variety of non-standardized cultivation conditions. This gap opens up opportunities for further research, including the development of SCRF formulations tailored to specific crops and agroclimates, as well as the standardization of performance evaluation methods across the board.

CONCLUSION

Based on a systematic literature review of 38 recent studies (2021–2025), it can be concluded that slow/controlled-release fertilizers (SCRF) are a promising innovation for improving fertilizer efficiency, crop productivity, and agricultural sustainability. SCRFs can be grouped into five main material categories, each with unique release mechanisms and characteristics. Synthetic polymers such as polyurethane and urea-formaldehyde are generally hydrophobic core-shell, providing precise and long-lasting nutrient release through diffusion, but have poor biodegradability. In contrast, natural biopolymers such as chitosan and sodium alginate are hydrophilic and often form porous hydrogels, releasing nutrients through swelling while improving water retention and soil properties, although their release performance is more variable. Biochar-based composites utilize their porous structure to adsorb and gradually release nutrients, acting as soil amendments, although their long-term release control is less predictable than synthetic polymers. Inorganic mineral materials such as silica and hydroxyapatite offer a simple and stable approach, but their engineering flexibility is limited. Meanwhile, inhibitor and multifunctional systems integrate physical, chemical, and biological controls to manage nutrient dynamics in the soil more holistically.

In general, the characteristics of SCRF are determined by the surface chemistry and physical strength of the material. Differences in functional groups influence hydrophobic/hydrophilic properties, thus determining water entry pathways and nutrient release mechanisms: synthetic polymers tend to be more hydrophobic and act as diffusion barriers with minimal swelling, while biopolymers and biochar composites are more hydrophilic, readily absorbing water and supporting swelling-based release and increased water retention around roots. Inorganic mineral materials are also generally hydrophilic with relatively simple and stable surface groups. Furthermore, mechanical properties (e.g., tensile/compressive strength, gel strength, tear resistance, rigid/elastomeric behavior) are important for maintaining coating/matrix integrity during storage, application, and in the soil, but are often not consistently reported, representing a significant gap in SCRF durability evaluation.In terms of performance, SCRF consistently demonstrates the ability to increase crop yields compared to conventional fertilizers, with increases ranging from 1.47% to over 100%, depending on the material and crop type. Natural biopolymers and inhibitor systems often show very high yield increase potential, while synthetic polymers provide more stable increases. This agronomic advantage is supported by SCRF's ability to align nutrient release with crop needs, thereby reducing nutrient loss to the environment, suppressing greenhouse gas emissions, and minimizing the risk of eutrophication. Furthermore, the use of agricultural waste-based feedstocks, such as biochar and biopolymers, strengthens the sustainability dimension by supporting a circular economy.

However, the development and implementation of SCRF still face several challenges. Consistent performance in the field is strongly influenced by soil and climate conditions, requiring specific formulations for each agroecosystem. Relatively high production costs and fabrication complexity can also be barriers to adoption, especially for small-scale farmers. On the other hand, there are still gaps in the uniform reporting of performance parameters, such as swelling ratio and biodegradability, which hinders direct comparisons between studies. Therefore, future research should focus on developing hybrid systems that combine the advantages of different materials, for example, by coating a porous biochar matrix with a thin layer of biodegradable polymer to achieve precise release control while remaining environmentally friendly. Furthermore, standardization of evaluation methods and more comprehensive long-term field testing are needed to validate SCRF performance under real-world conditions. By addressing these challenges, SCRF has the potential to become a crucial pillar in the transformation towards more productive, efficient, and sustainable agricultural systems.

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