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Advancements in Precision Fertilization Technologies and Controlled-Dispersion Fertilizers for Sustainable Rice Cultivation

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World hunger remains a persistent challenge, necessitating sustainable agricultural strategies to address food demands. Efficient fertilizer use in rice cultivation is identified as a key contributor to sustainable agricultural development. The study introduces precision side-depth fertilization application technology for direct-seeded rice, optimizing fertilization processes and enhancing efficiency. The research explores various side-depth fertilizer application devices, focusing on their ability to seamlessly combine precision and depth. The proposed intermittent fixed-point precision method and device aim to meet side-depth fertilization requirements, addressing these challenges. In the context of increasing demand for food production, driven by population growth, the paper discusses the limitations of conventional fertilizers. Excessive use of chemical fertilizers results in challenges such as high production costs, resource depletion, and environmental pollution. To break this cycle, the study emphasizes deep fertilization technology, strategically applying fertilizers at specific depths during crop growth. The impact of fertilizer discharge devices on uniformity is crucial in mechanized farming. To enhance crop yields, the application of fertilizers is essential. Traditional manual fertilization methods in paddy rice cultivation are labor-intensive and inefficient. The study advocates for the mechanization of fertilizer application, considering the mechanical and physical properties of fertilizers. The research investigates the effects of particle size distribution and fertilizer concentration on flow parameters, contributing to the design of effective fertilizer application machines. The paper addresses the limitations of conventional fertilizers, emphasizing the environmental concerns associated with nitrogen-based fertilizers. Controlled-Dispersion Fertilizers (CDFs), particularly those with hydrogel coatings, emerge as a promising solution. The study categorizes coating materials into inorganic, synthetic polymer-based, natural polymer-based, and other organic materials, providing insights into their effectiveness. In conclusion, the paper underscores the significance of precision fertilization technologies, deep fertilization methods, and Controlled-Dispersion Fertilizers in promoting sustainable agricultural practices and addressing global food security

Keywords: Sustainable Agricultural Development, Chemical Fertilizers, Coating Materials, Fertilization Technologies.

Introduction:

World hunger remains a pervasive issue and will continue to be a significant concern throughout the 21st century. Rice, a crucial staple crop feeding over half of the global population, stands out in addressing this challenge. Efficient fertilizer use in rice cultivation can enhance yield, suppress weed growth, maintain soil fertility, reduce workload, and lower production costs, contributing to sustainable agricultural development [1]. Precision side-depth fertilization application technology integrates precise fertilization with side-depth application. During rice sowing, a specified amount of fertilizer is applied at a particular depth (50 mm depth) alongside the rice seed row (30-50 mm from the seed side), covered by a mulching device. This method synchronizes seed sowing with base, greening, and tiller fertilization, streamlining operations and cutting labor costs. Concentrating fertilization at a specific lateral depth from rice seedling roots prevents damage, facilitates nutrient uptake, and minimizes nutrient loss, thereby improving efficiency [2].

Research on precise side-deep fertilizer application devices for direct-seeded rice in water can enhance chemical fertilizer utilization, boost rice crop income, and reduce environmental pollution. This research is crucial for realizing fully mechanized rice production and sustainable agricultural development. For instance, a disc ejector-type side-depth fertilizer application device was designed, optimizing key components and analyzing factors affecting performance. An air-blower side-depth precision rice fertilizer application device demonstrated superior side-depth fertilizer application. A side-deep fertilizer application device was developed, optimizing discharge performance through parameter adjustments [3]. An intermittent fixed-point precision rice side-depth fertilization method and device were proposed, meeting side-depth fertilization requirements. An inter-row roller-type cavity application and fertilizer discharge device were designed, showing promising cavity-tying performance and stability. However, existing devices excel in either precision fertilization or side-deep fertilization, struggling to seamlessly combine both, leading to issues like uneven spatial distribution of particle fertilizer in the fertilizer ditch and unstable depths in side-deep fertilization [4].

In contemporary society, addressing the continuous demand for food resulting from population growth, agricultural producers strive for high crop yields by extensively employing chemical fertilizers. However, the increase in crop yields does not align proportionally with the rise in fertilizer use. Excessive fertilizer application poses challenges, including elevated production costs, resource depletion, soil compaction, acidification, and diminished land productivity, leading to a detrimental cycle of dependency on fertilizers. To break this cycle, deep fertilization technology is utilized, involving the strategic application of fertilizer at specific depths and positions during the crop growth period. This method enhances fertilizer utilization and is considered pivotal for promoting crop growth and productivity [5]. In modern mechanized farming, deep fertilization is primarily executed through deep placement devices, with the effectiveness of fertilizer application dependent on the discharge devices within these devices. Studying the impact of fertilizer discharge devices on fertilizer uniformity is crucial for improving efficiency and reducing environmental pollution [6].

Fertilizer spreaders typically employ a grooved-wheel design for precise fertilizer application. This design, featuring grooved or raised surfaces, facilitates even dispensing into the soil. Despite its advantages, such as a simple structure and precise flow control, it faces challenges of pulsation and stability during fertilization. Researchers have extensively studied structural parameters to enhance grooved-wheel fertilizer discharge effectiveness. Previous studies have analyzed parameters like wheel radius, number of teeth, working length, and groove profile. Optimal parameters for uniform fertilizer discharge were found, highlighting the significance of the number of concave grooves and wheel radius [7]. In earlier research phases, the Discrete Element Method was used to qualitatively and numerically analyze the effects of primary wheel structural parameters on fertilizer filling status, forces, and kinetic properties. Through orthogonal experimental analysis, structural parameter optimization was conducted, indicating that the best uniformity was achieved with specific groove depth, tooth ridge thickness, and helix angle [8].

However, the real-world operation of fertilizer application machinery is not in a steady-state environment; it is influenced by various working parameters, such as the forward speed of the equipment. Previous studies have investigated the impacts of working factors on fertilizer discharge quantity, providing insights into fertilization performance. Yet, a deeper understanding of the relationships among forces, displacements, kinetic energies, and physical parameter variations of fertilizer particles under different working parameters is necessary for a comprehensive grasp of their impact on fertilization uniformity [5]. One highly effective method to enhance crop yield is the application of fertilizers. In the cultivation of paddy rice, manual labor has traditionally been the primary technique for fertilizing fields. Unfortunately, this approach is associated with significant physical strain, high costs, and inefficiency. The utilization of fertilizers can be substantially improved, and agricultural sustainability can be advanced through the precise application of fertilizers using mechanization [9]. The movement characteristics of fertilizer application equipment are influenced by the mechanical and physical properties of the fertilizer, thereby affecting the selection of component materials and the configuration of structural parameters [10].

Several key factors, including density, size, elastic modulus, suspension speed, coefficients of restitution, and collision recovery coefficient, characterize fertilizers. Researchers have further explored the properties of interactions among fertilizer particles. [11]conducted a study to examine the impact of particle size distribution and fertilizer concentration on flow parameters. In their investigation, Song et al. utilized EDEM simulation to modify parameters such as restitution coefficient, rolling friction coefficient, static friction coefficient, and others that influence the contact characteristics of fertilizer particles. These experiments played a crucial role in shaping the design of fertilizer application machines [12]. During the fertilization process, fertilizer particles inevitably come into contact with the moving parts of the application device. This interaction is particularly evident in fertilizer spreaders utilizing pneumatic and disc centrifugation, where grains may come into contact with the interior surface of the apparatus [13].

A rapid and efficient tool for immediate use, the fertilizer granules may fracture at elevated contact speeds, leading to broader dispersion and smaller particle sizes. Consequently, the kinetic energy of the granules decreases, resulting in increased energy disparities among the fertilizer particles. This, in turn, alters their trajectories. Previous research indicates a potential decline in the precision and uniformity of fertilizer application in the field. The degree of breakage in fertilizer granules is predominantly influenced by their mechanical and physical properties. To ascertain the optimal structural design for the distribution device and investigate the factors affecting fertilizer particle fragmentation, [14] delved into elastic collisions. Presently, there is no established correlation between the mechanical properties of a fertilizer particle and the impact velocity required for fragmentation. To validate advancements in fertilizer application methods and equipment, our study scrutinized the mechanical properties of four commonly used fertilizers in agricultural production. Specifically, we assessed their behavior in both static compression and dynamic impact scenarios.

Impact of Nano-Nitrogen Fertilizers on Crop Growth and Sustainability:

The presence and application of nitrogen (N) and nano-nitrogen (nN) play pivotal roles in the growth and development of plants. Nitrogen, an essential component for plant life, participates in crucial photosynthetic processes and forms the building blocks of amino acids, enzymes, and proteins within plants. Proteins and enzymes, integral to biochemical processes regulating plant life, influence crop yield optimization. Furthermore, nitrogen present in plant roots, as proteins and enzymes, aids in water and nutrient absorption. Various proteins within plant cells serve structural roles, while others act as enzymes, facilitating essential biochemical processes. Nitrogen is also involved in the synthesis of genetic components, such as DNA [15].

Nano-fertilizers containing nitrogen exhibit a significant influence on rapid plant growth, impacting both shoot and root systems by increasing chlorophyll content in plant leaves. This accelerates agricultural cycles and enhances crop productivity through the application of nitrogen, phosphorus, and potassium. The nanoscale particles of nitrogen, constituting a small percentage of nano-urea compared to normal urea, demonstrate unique properties attributed to their smaller size, larger surface area, and higher particle density. These particles can efficiently penetrate cell walls or stomatal pores, facilitating their transfer to various plant organs through mechanisms such as plasmodesmata, aquaporin, ion channels, and endocytosis. The active chemicals in nano-fertilizers can be released in response to biological needs during environmental stresses [16]. Plants generally absorb nitrogen in the form of NO_3^- and NH_4^+. Nano-fertilizers with nitrogen can be employed to ensure a continuous uptake of nitrogen at controlled release rates, reducing losses. Studies on various crops, such as Zea mays L., Borago officinalis L., Glycine max L., Brassica napus L., Solanum tuberosum L., and Coffea arabica, have demonstrated the positive impact of nano-fertilizers on nutrient uptake, plant development, and productivity. These studies have reported benefits such as higher nutrient uptake, improved food grain quality, enhanced essential oil production, increased seed productivity, and improved chlorophyll content and photosynthetic efficiency [17].

In contrast to conventional fertilizers with rapid and spontaneous nutrient release, nano-fertilizers provide nutrients progressively. The controlled release of nutrients by nano-fertilizers leads to higher nutrient uptake due to root exudates and efficient movement from nanoscale pores via molecular transporters. This progressive nutrient supply reduces environmental contamination, eutrophication, groundwater pollution, and diseases associated with the overuse of conventional fertilizers. Notably, the IFFCO nano-urea in India has shown promising results, contributing to increased production, lower agri-input costs, improved nutritional quality of crops, and enhanced agricultural sustainability and environmental safety [18]. The use of nano-urea, with its small size and favorable surface area-to-volume ratio, ensures higher root biomass and more productive tillers, branches, chlorophyll, and leaf photosynthesis, ultimately leading to higher agricultural crop production. Field trials conducted in India have shown an 8% increase in production using nano-urea, accompanied by lower agri-input costs. The application of nano-urea not only proves beneficial for crop yields but also contributes to agricultural sustainability and environmental safety, minimizing the negative impacts associated with the overuse of traditional fertilizers.

Table 1: Crop-Specific Impacts Resulting from Nano-Nitrogen Fertilizer Applications [19] [20].

Crop	Concentration Range	Impact
Oryza sativa L.	25–100% n-NF	Enhanced plant length, biomass, and tiller number. Highest yield (2.8 t ha−1) at 100% n-NF, minimizing nitrogen environmental impact [21] [22]
Zea Mays L.	0.32% and 0.76% n-NF	Increased nutrient uptake, improved N-use efficiency, better plant performance, and superior fruit/grain quality compared to conventional urea [23]
Borago officinalis L.	0.002% and 5% n-NF	Improved essential oil production and growth responses, including plant biomass and length [24] [25]
Glycine max L. and Zea mays L.	25–75% n-NF	Significant impact on agronomic traits, yield, and quality. Partial replacement of conventional urea with nano-urea reduced nitrogen losses [26]
Pennisetum glaucum L.	0.3–0.5% n-NF	Influenced productive tillers, nutrient uptake, and crop productivity through foliar application [27]
Glycine max L.	90 kg N/ha	Affected shoot, root, nodulation traits, seed yield, and protein positively. Nano-nitrogen is

		considered a better alternative to standard N fertilizer [28]
Saccharum officinarum L.	80–161 kg N/ha	Increased cane length and fresh weight. Nano-nitrogen reduced nitrate leaching and increased sugar production [29]
Solanum tuberosum L.	25% n-NF and 46% N	Enhanced agronomic traits, photosynthetic pigments, and tuber yield. Nano-fertilizers positively impacted potato quality [30]
Triticum aestivum L.	14–41 kg/ha (17% n-NF) and 37–110 kg/ha (46% N)	Improved agronomic and biochemical activities, suggesting nano-chelated nitrogen as an environmentally friendly alternative [31]
Zea Mays L.	69–161 kg N/ha	Increased N2O emissions and growth traits. Biomass showed an incremental trend with rising N concentration [32]
Triticum aestivum L. et al.	2.5 mL/L n-NF	Enhanced crop yield in wheat, sesame, pearl millet, and mustard. Optimum yield observed with combined application of organic manure, bio-fertilizer, and nano-fertilizers [33]
Brassica napus L.	30–90 kg N/ha	Effective improvement in growth and physiological activities. Nano-fertilizer application minimized soil flooding [34]
Punica granatum cv. Ardestani	0.25 and 0.50 g nN/L	Increased fruit yield and number per plant. The quality of fruit improved with nano-nitrogen compared to urea [35]
Triticum aestivum L.	120–240 kg N/ha	Higher chlorophyll content, spike length, and grain yield. Foliar application of n-NF enhanced photosynthetic pigments [36]
Lactuca sativa L.	75% nN (drip irrigation) and 25% nN (foliar spray)	Efficient soil and foliar treatments improved biomass, leaf area, and productivity. Reduced recommended N rate for lower environmental impact [37]
Solanum tuberosum L.	¼, ½, ¾, and 100% of recommended fertilizer	Superior plant development, increased yield, and quality observed with nano-fertilizer spraying [38]
Triticum aestivum L.	37–110 kg N/ha (17% n-NF)	Significant effects on root water content, ion leakage, protein content, and photosynthetic responses. Suggested replacement of nano-fertilizers for synthetic ones, especially in sandy soils [39]
Olea europaea L.	2.21 and 2.95 g N	6–8 g nN [40]
Zea mays L.	300 kg N/ha	1 and 2 mL/L nN [41]
Triticum aestivum L.	100–200 ppm	Optimal macro- and micro-nutrient concentrations in grains, excluding N, Zn, and Mn [42]
Solanum tuberosum L.	40 L/ha (25% N)	Enhanced water use efficiency, NUE, PUE, and KUE. Fertigation and good irrigation strategies are recommended for better crop yield [43]
Pennisetum americanum L.	80 ppm	Significant improvement in root morphology, length, perimeter, tips, diameter, and biomass with n-NF application [44]

Pleurotus ostreatus (Jacq. Ex Fr.) P. Kumm	3–5 g kg−1 n-NF	Increased protein, total carbohydrates, and fiber contents. Essential amino acids improved, while mineral elements reduced with minor changes [45]
Salvia officinalis L.	40–80 kg N/ fed and 250–500 ppm n-NF	Agronomic traits enhanced with increasing nano-N and N application. Highest nitrogen use efficiency achieved with nano-nitrogen [46]
Camellia sinensis L.	100 kg N acre−1	Increased plant height, canopy, fresh tea leaves, and productivity with N application [47]
Camellia sinensis L.	15N-Urea	Foliar N application improved mature leaf N content and enhanced tea quality and productivity [48]
Asparagus racemosus L.	100–300 kg N ha−1	Higher number, length, diameter, and biomass of tuberous roots with N and n-NF application. Significant effects on plant length, leaves, and root protein content [49]

Limitations of Conventional Fertilizers:

Limitations of conventional fertilizers include their low utilization efficiency, with only 30–35% of nutrients being absorbed when directly administered to plants. Urea, a commonly used nitrogen fertilizer, exhibits nitrogen use efficiency levels of only 50%. Approximately 2–20% is lost through volatilization, 15–25% reacts with organic compounds in the soil, and 2–10% is lost through leaching into water systems, raising environmental concerns. The nitrogen cycle in the soil illustrates the transformation of naturally occurring nitrogen and fertilizer from one form to another. Urea-derived nitrogen undergoes conversion by urease enzymes to ammonium through mineralization, then progresses to nitrite and nitrate ions via the nitrification process. Excessive water from irrigation or heavy rainfall can lead to the leaching of nitrate ions into the ground and surface water bodies, posing risks to human health.

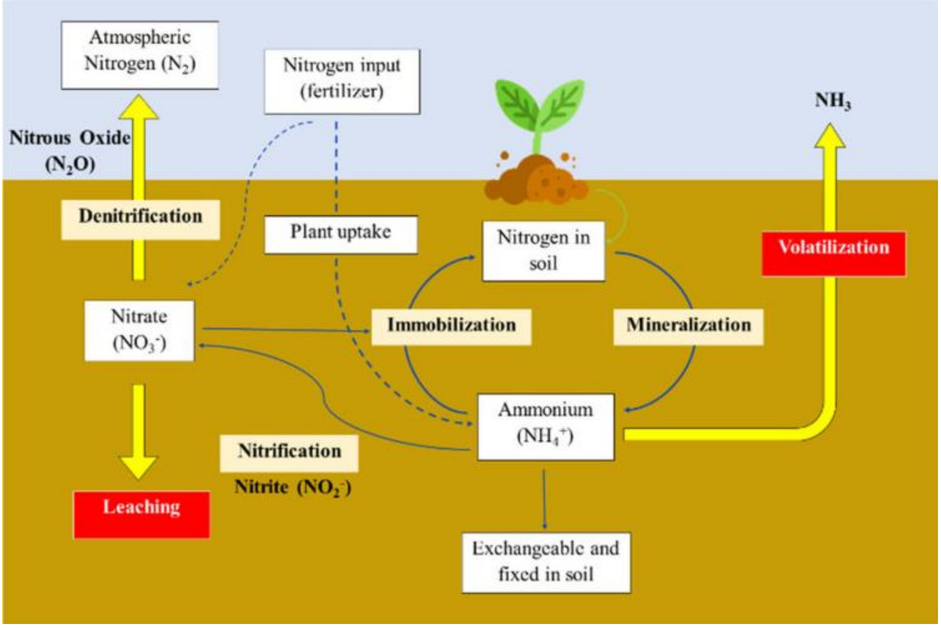

Figure 1: Nitrogen Cycle [38].

Apart from water pollution, nitrogen is lost through volatilization as N_2 and N_2O, through complete and incomplete denitrification processes, respectively. Ammonium may also be lost as NH_3 through volatilization. Nitrogen-based fertilizers contribute to the emission of N_2O, a major contributor to ozone depletion in the 21st century [50]. Controlled-Dispersion Fertilizers, a category including Slow-Release Fertilizers (SRFs), address some of these limitations. SRFs are characterized by low solubility compounds with a complex/high molecular weight chemical structure that releases nutrients through microbial or chemically decomposable compounds. CDFs, a subset of SRFs, are defined as products containing water-soluble nutrients with their release in the soil controlled by a coating applied to the fertilizer. The simplified classification of CDFs is presented. While the required nutrient release rate by CDFs varies for each plant based on metabolic requirements, expectations include a release rate slower than conventional fertilizer, not exceeding 15% of nutrient release within 24 hours, not surpassing 75% of nutrient release within 28 days, and at least 75% of nutrient release within the specified release time. Additionally, CDFs are expected to be cost-effective, environmentally friendly, and sustainable [51].

Coating Materials for Controlled-Dispersion Fertilizers:

Coating materials for CDFs fall into two main categories: inorganic materials and organic polymers. Inorganic materials encompass sulfur, bentonite, and phosphogypsum, while organic polymers include synthetic options like polyurethane and polyethylene, natural choices such as starch and chitosan, and recent additions like biochar, rosin, and polyphenol. This section divides these materials into four groups: inorganic material-based, synthetic polymer-based, natural polymer-based, and other organic materials.

Inorganic Material-Based Coatings:

Coatings predominantly derived from sulfur and minerals make up the inorganic material-based category. Sulfur-based coating CDFs, like SCU developed by the Tennessee Valley Authority (TVA) in 1961, faced challenges with imperfect coatings leading to the "burst effect," causing an immediate release upon contact with water. Hybrid coatings combining low-cost sulfur and polymers were introduced to address this issue, albeit with persistent burst and lock-off characteristics [52]. Recent studies explored alternative sulfur-based materials such as gypsum and phosphogypsum, proving advantageous as they are slightly soluble in water, do not alter soil pH, and readily provide sulfate ions to plants. Studies varied gypsum and sulfur ratios as coating materials, demonstrating improved efficiency and lower urea release. Additionally, the incorporation of hydrophobic sealants like paraffin and polyol enhanced efficiency. Phosphogypsum/paraffin CDF, enhanced with an emulsifier, exhibited superior controlled release properties and met European Standardization Committee criteria.

Minerals like hydroxyapatite, bentonite, zeolite, and attapulgite were investigated for their soil conditioning properties and ion exchange capabilities. Nanotechnology contributed to the development of urea-hydroxyapatite nanohybrid CDFs, exhibiting slow release for up to a week. Zeolite-coated urea fertilizers, using acrylic polymer as an effective binder, showed stable CDFs with high crushing strength. Bentonite nanocomposites modified with hydrophilic or hydrophobic polymers demonstrated varying degrees of urea release, with hydrogels proving effective in slowing down the process. In summary, inorganic material-based coatings, including sulfur-based, gypsum-based, and mineral-based options, exhibit diverse characteristics influencing urea release rates. These coatings, whether combined with polymers or used alone, offer potential solutions for enhancing the controlled release of nutrients in CDFs.

Synthetic Polymer-Based Coatings for Controlled-Dispersion Fertilizers:

In the realm of CDFs, synthetic polymer-based coatings offer advantages over inorganic materials, showcasing sensitivity to environmental factors and adaptability for controlled fertilizer release. The release patterns of polymeric coatings are influenced by factors such as thickness and soil temperature, impacting diffusion rates. To address the challenge of rapid nitrogen release, researchers have explored single or blended polymeric materials. [53] experimented with polystyrene coated with wax and a polyurethane (PU) additive for urea. PU proved more effective than wax in reducing release rates, with tablet size playing a role in reducing both rate and coating material requirements. [10] developed coated urea using pure PU and mesoporous silica fillers, with rod-like morphology proving the most effective for an extended-release period. [14] synthesized coated urea with varying hydrophobicity levels using PU and hydroxypropyl-terminated polydimethylsiloxane, achieving a release period exceeding 60 days.

A novel polymer, polyether sulfone, was employed with Fe_2O_3 nanofillers as a CDF, where the addition of Fe_2O_3 nanoparticles increased coating thickness and facilitated recovery using magnetic power. Research into biodegradable synthetic polymers revealed the potential of aliphatic polyesters, confirming hydrolytic degradation's susceptibility. [10] reported on aliphatic polyesters as coating materials, emphasizing the impact of size and crystal dispersion on degradation rates. [54] achieved up to 82% degradation after three months. Addressing environmental concerns, [54] explored bio-based epoxy coatings using liquified bagasse and bisphenol-A diglycidyl ether, demonstrating how variations in the ratio affect material properties and release characteristics. Increasing BDE enhanced compactness and hydrophobicity, thereby slowing down the release rate.

Hydrogels, known for their water-absorbing properties, gained attention for their potential to reduce irrigation frequency and improve water retention in soil. [16] synthesized a polyvinyl alcohol-based hydrogel for urea release, exhibiting controlled release and the ability to adsorb Fe (III) ions, reducing toxicity to plants. [15] formulated PVA/biochar CDF to enhance mechanical strength and biodegradability, with rice biochar proving the most effective in encapsulating urea and releasing nutrients over 22 days.

Natural Polymer-Based Coatings for Controlled-Dispersion Fertilizers

While synthetic polymers offer versatility in CDFs, their non-biodegradable nature poses environmental concerns. Accumulation of non-degradable polymers in soil can lead to white pollution. In response, research has shifted towards natural polymers, known for their biodegradability and environmental friendliness. Natural polymers are often used in composite formulations due to their insufficient mechanical integrity for standalone CDFs. Several studies explored oil-based polymer coating materials. [16] developed a double-layer polymer-coated urea CDF, utilizing corn stover-based polyurethane as the inner layer and chicken feather meal-based superabsorbent as the outer layer. Castor oil-based polyurethane coatings were investigated, emphasizing improved adherence and prolonged release times. Castor-oil-based PU was also found to reduce N_2O emissions without affecting maize grain yield in sandy soil.

Studies on soybean oil-based polyurethane-coated urea indicated that the isocyanate index influenced morphology, crosslinking density, water absorption, and release rate. Biodegradable synthetic polymers were explored, with aliphatic polyesters exhibiting hydrophilic properties and susceptibility to hydrolytic degradation. Polysulfone coatings synthesized using SO_2 and eugenol exhibited superior nutrient release. Hydrophilic coatings using latex and coatings from natural rubber grafted with cassava starch (NR-g-ST) were also investigated, demonstrating the influence of swelling degree and hydrophobicity on release rates. In summary, natural polymer-based coatings, including those derived from castor oil, soybean oil, and starch, offer promising solutions for environmentally friendly and controlled nutrient release in CDFs.

Hydrogel Coatings Based on Starch and Natural Polymers:

In recent years, the development of starch-based hydrogel CDFs has gained prominence due to their advantageous water retention properties. [55] introduced a partially degradable starch/poly (acrylic acid-co-acrylamide) superabsorbent (SAAmF), where an increased starch ratio slowed the release to 55% over 30 days. Incorporating bentonite in the enhanced adsorption leads to a slower release. [55] reinforced starch hydrogel with natural char nanoparticles, reducing the release rate to 70% over 21 days. [56] created a double-coated CDF using ethyl cellulose and starch-based superabsorbent, resulting in improved release rates.

Cellulose and lignin, abundant and low-cost raw materials, were explored for coatings. [56] developed poly(dimethylurea phosphate) (PDPU) with wheat straw superabsorbent coating, achieving a 67.6% release over 30 days. [55] reported an 85% release in 8 days using a similar approach. Hydrogels composed of polyacrylamide, methylcellulose, and montmorillonite demonstrated increased loading and decreased water absorption, favoring adsorption. [18] formulated a carboxymethyl cellulose-based nanocomposite with silica NPs, resulting in 56.4% release in 30 days. Commercial lignins with hydrophobic alkenyl succinic anhydride (ASA) showed promise for slow release. Alginate, a marine algae-derived biodegradable polymer, found application in CDFs. [18] developed a double-coated CDF with sodium alginate/ϰ-carrageenan (ϰC) and ϰC-g-PAA/celite layers, achieving 90% release in 25 days.

The incorporation of cellulose nanofibrils (CNF) into alginate and starch-based hydrogel showed potential for sustainable preparation without significant effects on release properties. In conclusion, these studies highlight the versatility of starch and natural polymers in creating hydrogel coatings for CDFs with enhanced water retention and controlled nutrient release. Chitosan, derived from crustacean exoskeletons and fungal cell walls, has garnered attention in the realm of CDFs due to its unique properties. In a study a chitosan-based coating material was developed, incorporating humic substances such as peat, humic acid, and humin. The release rate of urea was found to be influenced by the specific type of humic substances and the pH of the aqueous medium, showcasing the intricate interplay of functional groups and interactions within the system. Another investigation focused on a chitosan/starch composite enriched with allicin, a urease inhibitor. The inclusion of allicin demonstrated a reduction in urea hydrolysis, effectively delaying the availability of nutrients to plants. The study revealed that urea crystals of varying sizes influenced the rate of release from the chitosan hydrogel, adding a layer of complexity to the controlled release dynamics. Overall, these studies highlight the versatility and potential applications of chitosan in tailoring the release characteristics of CDFs to optimize nutrient availability for plants.

CDFs employ various coating techniques, broadly categorized into physical and chemical processes. Physical methods, including spray coating through rotary drums, pan coating, and fluidized bed technologies, have been extensively utilized in commercial applications. These continuous processes are cost-effective and scalable, making them suitable for large-scale production. However, challenges such as the unpredictability of porous membrane formation in sprayed coatings, wastage of raw materials in rotary drum coating, and poor coating quality in pan coating due to humidity fluctuations have been reported. The fluidized bed spray technology offers advantages in producing more uniform coatings with a wider range of coating materials. Despite its benefits, drawbacks such as expensive equipment, potential filter blockage, and limitations with larger granules have been noted. Additionally, these techniques often involve the use of organic solvents, posing health and environmental risks. In response, environmentally friendly methods like melting and extrusion using single or twin-screw extruders have emerged. This approach avoids the use of organic solvents but requires careful monitoring of torque and temperature. While it provides a cost-effective alternative, challenges include the involvement of hot melts and the need for specialized equipment. Various studies employing these techniques have explored coatings with materials ranging from polyurethane and gypsum to starch, polyesters, and clay minerals, showcasing the diversity of approaches in CDF preparation.

Chemical processes play a crucial role in the preparation of hydrogel-controlled-dispersion Fertilizers (CDFs), particularly when utilizing superabsorbent polymers. Several methods are employed, including solution polymerization, inverse suspension polymerization, and polymerization by irradiation. In solution polymerization, the monomer and initiator, both soluble in the chosen solvent, are mixed. While the solvent reduces the reaction's viscosity, facilitating operation, solvent recovery can be challenging, and the slower reaction rate may result in lower encapsulation efficiency. In inverse suspension polymerization, hydrophilic monomers and initiators are dispersed in a hydrocarbon phase, creating a water-in-oil emulsion. Continuous agitation is required due to its thermodynamic instability. Despite the advantage of solvent recovery and a higher reaction rate, potential contamination within the suspension necessitates additional purification steps. These methods are applied to produce hydrogel CDFs using natural polysaccharides like starch, alginate, and gelatin, or synthetic hydrophilic polymers such as polyvinylpyrrolidone. Commonly used cross-linkers include N, N-methylene biacrylamide, and ammonium persulfate is a frequently used initiator. Most formulations are water-soluble, ensuring environmental friendliness, although some may require organic solvents like isopropanol, N, N-dimethylformamide (DMF), or 2,2-dimethoxypropane (DMP). The irradiation method involves the formation of macroradicals through microwave irradiation, leading to covalent bonds and cross-linked structures. This method is employed for synthesizing semi-interpenetrating networks based on cotton stalks, corn cobs, and biochar, offering a greener pathway for chemical synthesis characterized by simplicity, high efficiency, and low energy consumption.

The release rate of CDFs is influenced by various factors, including temperature, pH, ionic strength, granule radius, and coating thickness. Temperature escalation accelerates nutrient release due to increased solubility and diffusion rates, alongside greater swelling and pore size. The linear release rate exhibits a temperature dependence represented by an activation energy formula. pH significantly affects hydrogel behavior, with optimal swelling occurring in a neutral environment. An acidic or alkaline pH reduces swelling, impacting release. Ionic strength, especially multivalent cations, diminishes swelling by forming complexes, limiting hydrogel expansion. Granule radius and coating thickness influence the lag period and release rate. Larger granules or thicker coatings extend the lag period and slow down release in linear and decay phases, offering economic benefits. However, an optimum granule size is vital for effective nutrient distribution in the root zone [56].

The mechanism of nutrient release from CDFs unfolds in three stages: lag period, constant release, and decay period. The lag period involves water penetration without nutrient release, followed by constant release as the osmotic pressure builds up. The decay period witnesses diminishing release rates as fertilizer dissolves and exits the granule. A sigmoidal release profile, resembling an S-shape, characterizes the complex, non-linear release process. Achieving this profile is a goal for researchers, as it aligns with controlled release characteristics matching plant nutrient requirements. Modeling approaches for predicting nutrient release from CDFs fall into mechanistic and empirical categories. The selection of appropriate models depends on the formulation, with diffusion, swelling, erosion, or their combination influencing release rates. Hydrophilic materials typically release nutrients through diffusion, while hydrophobic materials involve swelling or erosion of the matrix. Accurate modeling aids in understanding mass transport mechanisms, contributing to optimal CDF design.

Conclusion:

In conclusion, the comprehensive exploration of precision fertilization technologies, deep fertilization methods, and Controlled-Dispersion Fertilizers presented in this study offers valuable insights into the sustainable cultivation of rice and addresses global food security challenges. The research underscores the pivotal role of efficient fertilizer use, particularly in rice cultivation, as a key strategy to enhance yield, reduce production costs, and contribute to sustainable agricultural development. The adoption of precision side-depth fertilization application technology, with its emphasis on synchronizing seed sowing and fertilization processes, stands out as a promising approach. This method not only streamlines operations and cuts labor costs but also prevents damage to rice seedling roots, optimizes nutrient uptake, and minimizes nutrient loss, thereby improving overall efficiency in the cultivation process. The study delves into the development and optimization of various side-depth fertilizer application devices, showcasing advancements such as the disc ejector-type and air-blower side-depth precision rice fertilizer application devices. While these devices exhibit superior performance in either precision fertilization or side-deep fertilization, the need for seamless integration of both aspects remains a challenge. The spatial distribution of particle fertilizer and depth stability issues persist, emphasizing the ongoing pursuit of innovative solutions for achieving fully mechanized rice production.

Moreover, the investigation into the impact of fertilizer discharge devices on uniformity, utilizing the Discrete Element Method and considering real-world working parameters, provides a nuanced understanding of the complex interactions influencing fertilization uniformity. This deeper insight is crucial for refining fertilizer application machinery and optimizing efficiency while minimizing environmental pollution. The study also sheds light on the limitations of conventional fertilizers, emphasizing the challenges associated with low utilization efficiency, resource depletion, and environmental concerns. The transition to CDFs, including both synthetic and natural polymer-based coatings, emerges as a promising avenue. These CDFs offer solutions to enhance nutrient release rates, reduce environmental impact, and promote sustainable agricultural practices. Furthermore, the investigation into the mechanical properties of fertilizers and the potential fragmentation of fertilizer granules underlines the need for a nuanced understanding of how these properties impact the design and performance of distribution devices. The study's validation of advancements in fertilizer application methods, particularly through the scrutiny of mechanical properties, contributes to the ongoing efforts to optimize fertilization processes. Overall, the multifaceted approach presented in this research contributes significantly to the ongoing discourse on precision agriculture, sustainable farming practices, and the crucial role of fertilizers in addressing global food security. The findings provide a foundation for further research, innovation, and policy development aimed at fostering efficient, environmentally friendly, and sustainable agricultural practices to meet the ever-growing demand for food in the 21st century.

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