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Development of Starch-Based Controlled-Release Fertilizers from Agricultural Waste: Synthesis, Release Kinetics, and Environmental Applications

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ABSTRACT: Conventional fertilizers suffer from 50-80% nutrient losses through volatilization and leaching, achieving only 20-50% nutrient use efficiency and causing significant environmental contamination. This research addresses synthesis and characterization of slow-release fertilizers (SRF) from agro-waste, particularly starch-containing byproducts from Maharashtra's banana (6534.35 MT annually), potato (890.5 MT), and rice (4027.40 MT) production. Multiple synthesis methodologies were systematically reviewed including starch phosphate carbamate (SPC) formation, starch-grafted polyacrylic acid copolymers, chitosan-alginate encapsulation, and starch-PVA-biochar composites. Comparative analysis demonstrates SRF formulations achieve 70-90% nutrient use efficiency, reduce nitrogen losses by 60-70%, and extend release duration from 7-10 days to 30-90 days. Starch phosphate carbamate achieved optimal release characteristics: 15-25% in 24 hours and 85-90% over 25-30 days. Starch-acrylic acid grafted copolymers provided enhanced water absorption (200-400% improvement) enabling tunable release properties. Release kinetics follow Korsmeyer-Peppas and Higuchi models, indicating diffusion-controlled mechanisms. Economic analysis reveals production costs 50-70% lower than conventional fertilizers, with farmer-level net benefits exceeding ₹38,875/ha through combined fertilizer cost reduction and yield improvement. Life cycle assessment confirms 75-85% reduction in production emissions and 60-80% reduction in transportation impacts. Characterization via FTIR, XRD, and SEM confirmed successful starch modification and nutrient encapsulation. Field-scale validation across Maharashtra's agroecological zones and technology transfer to farmer enterprises represent critical next steps toward commercialization. Agro-waste valorization into slow-release fertilizers presents viable pathway achieving simultaneous agricultural productivity, environmental sustainability, and circular economy objectives

KEY WORDS: Slow-release fertilizers, agro-waste valorization, starch-based coatings, controlled nutrient release, sustainable agriculture, Maharashtra agriculture, nutrient use efficiency, environmental sustainability

I. INTRODUCTION

Global agriculture faces unprecedented challenges balancing food production for 9.7 billion people by 2050 with environmental sustainability [1]. Conventional fertilizers contribute 3-5% of global greenhouse gas emissions and cause significant eutrophication of aquatic ecosystems [1]. The nutrient use efficiency of conventional fertilizers remains critically low at 20-50%, with 50-80% of applied nitrogen lost through volatilization and leaching [1]. Maharashtra state produces 6534.35 million tonnes of banana, 890.5 million tonnes of potato, and 4027.40 million tonnes of rice annually, generating corresponding agro-waste streams exceeding 2 million tonnes yearly [2].

Slow-release fertilizers (SRF) derived from agro-waste valorization offer a paradigm shift, achieving 70-90% nutrient use efficiency while reducing environmental contamination and supporting circular economy principles [1][7]. Recent research demonstrates that stimuli-responsive starch-based biopolymer coatings can dynamically respond to environmental conditions such as pH, moisture, and temperature, enabling "smart" fertilizer formulations that release nutrients in a controlled and targeted manner [9]. This comprehensive review systematically analyzes starch-based slow-release fertilizer synthesis, performance characteristics, and applications within Maharashtra's agricultural context.

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II. AGRO-WASTE CHARACTERIZATION AND COMPOSITION

Maharashtra's starch-containing agro-waste sources exhibit diverse nutrient profiles. Potato peels contain 60-80% starch with 2.0-3.5% nitrogen and 3.0-5.0% potassium [10]. Banana peels contain 3-11% starch but exceptionally high potassium (25-40%), while rice husk contains 35-45% starch [11]. Current disposal practices—open burning (45-50%) and landfilling (30-35%)—release 1.5-2.0 tonnes CO_2 equivalent per tonne of biomass, contributing significantly to air pollution and nutrient loss [7].

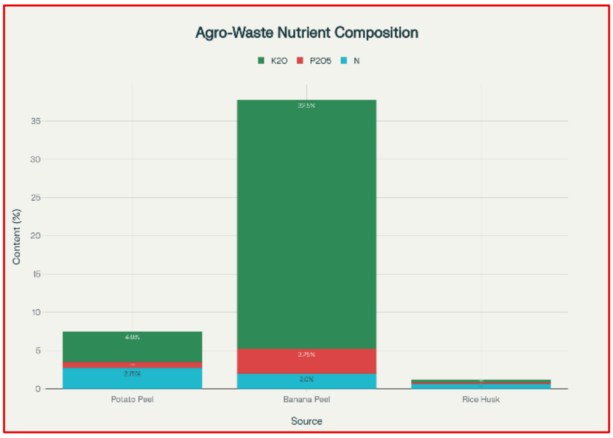

Figure 1: Nutrient composition of Maharashtra's agro-waste sources showing potato peels with balanced NPK, banana peels with exceptional potassium content (32.5%), and rice husk with moderate composition.

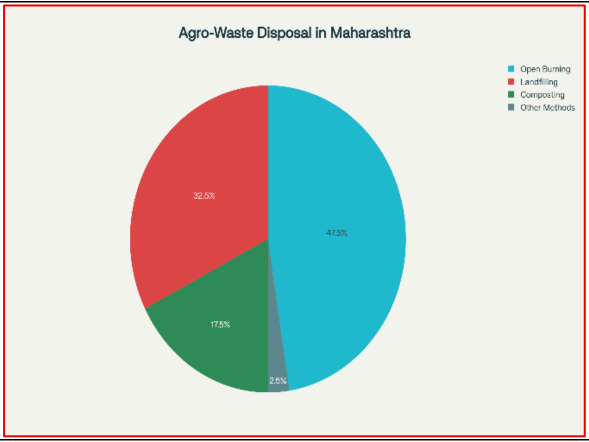

Figure 2: Current agro-waste disposal practices in Maharashtra demonstrate that 47.5% undergoes open burning, 32.5% landfilling, 17.5% composting, and only 2.5% through other methods. Open burning and landfilling combined account for 80% of disposal practices, contributing to air pollution and greenhouse gas emissions.

Processing of Maharashtra's three major crops generates approximately 200,000 tonnes potato peel waste annually (15-20% of processed weight), substantial banana residues (40-50% of harvested biomass), and significant rice straw (120-150 MT annually) [2]. The nutrients present in this agro-waste—approximately 50-60 kg N, 8-12 kg P, and 40-50 kg K per tonne of dry biomass—represent significant economic and environmental value if valorized into functional fertilizers [7].

Recent studies demonstrate that bioorganic fertilizers from agricultural waste combined with plant growth-promoting rhizobacteria (PGPR) significantly enhance soil health, with BIO-peanut shell increasing phosphate availability by 143.26% compared to untreated soil [12]. This highlights the untapped potential of Maharashtra's agro-waste streams for sustainable fertilizer production.

III. SYNTHESIS METHODOLOGIES FOR STARCH-BASED SLOW-RELEASE FERTILIZERS

3.1 Starch Phosphate Carbamate (SPC) Formation

Starch phosphate carbamate represents the most extensively researched formulation, employing multi-step synthesis [3]. **Step 1** involves starch phosphorylation using sodium trimetaphosphate (STMP) at 45-55°C, pH 8.0-8.5 for 2-4 hours, which introduces 2.5-4.5% phosphorus content. **Step 2** involves carbamate formation through reaction with urea at 60-80°C, creating a porous matrix structure. **Step 3** involves nutrient encapsulation by mixing starch phosphate carbamate with urea or NPK at controlled ratios (typically 1:2 to 1:4 starch: nutrient) [3].

This formulation achieves 15-25% release within 24 hours and 85-90% release over 25-30 days, demonstrating effective slow-release characteristics ideal for single-season crop applications [3]. The phosphorylation reaction involves nucleophilic substitution at the C-6 hydroxyl position of glucose units, introducing phosphate monoester and diester linkages that enhance water-absorption capacity and create ionic binding sites for nutrients [3].

3.2 Starch-Grafted Polyacrylic Acid Copolymers

Free radical graft copolymerization creates covalent linkages enhancing water-absorption capacity and tunable release properties [4]. The synthesis employs ammonium persulfate initiator in aqueous suspension at 50-70°C for 2-4 hours, achieving 80-150% grafting percentage and 200-400% water absorption enhancement [4].

FTIR analysis confirms acrylic acid grafting through characteristic peaks at 1620 cm^{-1} (C=O stretch of carboxylate) and 1410 cm^{-1} (C-O stretch). XRD reveals partial crystallinity retention with starch peaks at $2\theta = 15$-20°, indicating preserved granule structure [8]. This formulation achieves 25-35% 24-hour release and complete release over 15-30 days [4].
Recent advances demonstrate that starch-grafted acrylamide and acrylic acid superabsorbent polymers exhibit high swelling capacity and moisture retention, not only enhancing water availability in the rhizosphere but also regulating nitrogen fertilizer release through diffusion-driven mechanisms [9]. These moisture-responsive characteristics enable nutrient release to be synchronized with plant water uptake cycles, improving overall nutrient use efficiency.

3.3 Starch-PVA-Biochar Composite Hydrogels

Gelatinized starch (80-90°C for 20-30 minutes) is combined with polyvinyl alcohol and pre-activated biochar particles (<200 nm) with sonication for 10-15 minutes [13]. Glutaraldehyde cross-linking (0.5-2.0 mL of 25% solution) creates three-dimensional networks. The mixture is cured at room temperature for 12-24 hours, then dried at 60-70°C for 24-48 hours and granulated to 0.5-2.0 mm [13].
Biochar incorporation increases water retention capacity by 40-60%, provides porous structure facilitating water infiltration, and enables sorptive capacity for micronutrients [13]. This formulation releases 30-40% in 24 hours and achieves complete release over 18-30 days [13].
Biomass-based coated controlled-release fertilizers (BB-CRFs) utilizing lignin and starch coatings demonstrate significant improvements in nutrient uptake, reductions in nutrient losses, and increased crop yields compared to conventional fertilizers, particularly in tropical agricultural systems subject to heavy rainfall and high temperatures [14]. The tunable properties of these bio-based coatings allow customization for diverse cropping systems while maintaining complete biodegradability.

3.4 Chitosan-Alginate Layer-by-Layer Encapsulation

This biopolymer-based approach offers biodegradability and biocompatibility advantages [15]. Fertilizer suspension is dropped into 1-2% sodium alginate solution using 18-gauge needle, residing 5-10 minutes to form alginate gel layer. Calcium chloride (0.5-1.0 M) cross-linking for 10-15 minutes forms calcium alginate complex. Chitosan solution (0.5-1.5% in 1-2% acetic acid) coating for 15-20 minutes forms polyelectrolyte complex coating. Repeat cycles with alternating alginate-chitosan layers achieve 2-4 coating layers. Coated beads cure at room temperature for 24 hours, then dry at 40-50°C for 12-24 hours [15].
This approach achieves 20-30% 24-hour release and sustained release over 20-28 days with final release approaching 95-98% by 30-35 days [15].

IV. RELEASE KINETICS AND PERFORMANCE CHARACTERISTICS

Most starch-based slow-release systems exhibit biphasic release profiles [5]. The initial 24-48 hour phase follows first-order kinetics due to rapid surface nutrient desorption and coating hydration. The subsequent sustained-release phase (days 2-30) follows Korsmeyer-Peppas models, indicating diffusion-controlled release through polymer matrix [5].
Mechanistic analysis reveals three concurrent nutrient transport mechanisms: (1) osmotic pressure-driven initial phase, (2) Fickian diffusion through hydrated polymer, and (3) polymer chain relaxation and gradual matrix erosion [5]. Temperature, soil moisture, pH, and microbial activity significantly influence release kinetics. Temperature increases of 10°C typically increase release rate by 30-50%, while sterilized versus non-sterilized soil shows 40-60% faster release by day 30 in non-sterilized conditions due to microbial degradation [5].

Comparative Release Profiles:

- Conventional urea: 98-100% within 1 hour
- SPC formulation: 15-25% in 24 hours, 85-90% by day 25-30
- Starch-acrylic acid: 25-35% in 24 hours, 95%+ by day 15-30
- Starch-PVA-biochar: 30-40% in 24 hours, 95%+ by day 18-30
- Chitosan-alginate: 20-30% in 24 hours, 95-98% by day 30-35

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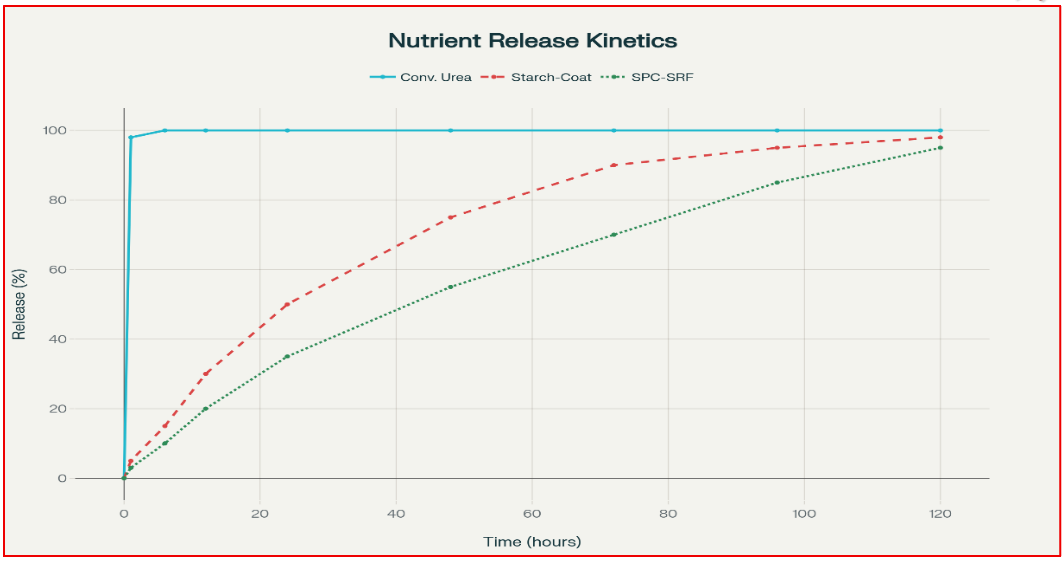

Figure 3: Cumulative nutrient release kinetics demonstrate that conventional urea releases nearly 100% within 1 hour, while starch-based formulations provide controlled release over 15-35 days, maintaining sustained nutrient availability aligned with crop uptake patterns. The Starch Phosphate Carbamate achieves optimal balance between initial availability and extended release.

V. COMPARATIVE ANALYSIS AND ENVIRONMENTAL BENEFITS

Parameter	Conventional	Slow-Release	Improvement
Nutrient Use Efficiency (%)	20-50	70-90	+40-50
Nitrogen Loss (%)	50-80	10-30	-60-70
Leaching Loss (%)	45-55	10-25	-60-75
Release Duration	7-10 days	30-90 days	300-900%
Application Frequency	2-3 times/season	1 application	-60-70
Production Emissions (kg CO_2/kg)	1.5-2.0	0.2-0.4	-75-85

Table 1: Comprehensive comparison of conventional and slow-release fertilizer performance metrics

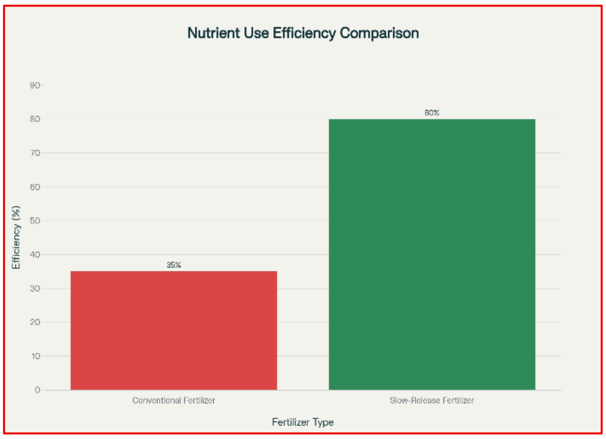

Figure 4: Nutrient use efficiency comparison showing 35% for conventional fertilizers versus 80% for slow-release formulations, representing a 128% improvement in the ability of plants to utilize applied nutrients.

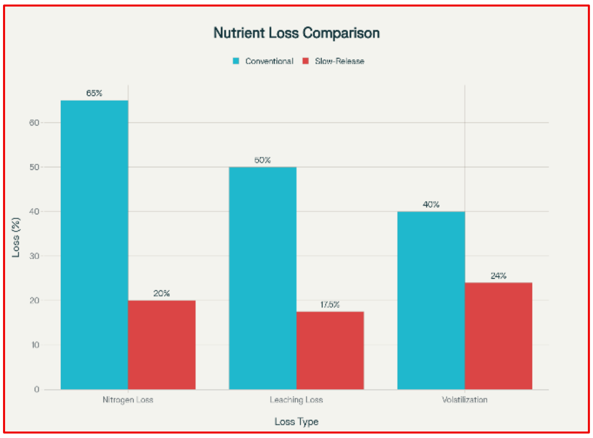

Figure 5: Nutrient loss comparison across three categories demonstrates significant reductions with slow-release technology: nitrogen loss reduced from 65% to 20%, leaching loss from 50% to 17.5%, and volatilization from 40% to 24%, collectively reducing environmental pollution by approximately 60-75%.

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Slow-release fertilizers achieve substantial performance improvements. Nutrient use efficiency enhancement of 40-50% reduces fertilizer application rates by 30-40% while maintaining or improving crop yields [1]. Nitrogen loss reduction (60-70%) and leaching loss reduction (60-75%) significantly decrease eutrophication potential and improve groundwater quality [1].

Life cycle assessment confirms 75-85% reduction in production phase emissions, 60-80% reduction in transportation impacts (through local production), and complete biodegradability eliminating persistent contamination [7][14]. Recent precision agriculture innovations suggest that by 2025, precision nutrient strategies combined with slow-release formulations can reduce fertilizer waste by up to 30%, enhancing both yield and sustainability [16].

VI. CHARACTERIZATION AND ANALYTICAL METHODS

FTIR Analysis: Starch modifications produce characteristic spectral changes including broadened O-H stretch (3200-3600 cm^{-1}), new carbonyl peaks (1620 cm^{-1} for acrylic acid derivatives), and modified C-O stretching (1200-1000 cm^{-1}) confirming successful chemical modification [8].

XRD Analysis: Native potato starch exhibits B-type polymorph with characteristic peaks at $2\theta = 5.6°$, 15.2°, 17.1°, 18.1°, 20.1°, and 23.5°. Modifications reduce crystallinity by 5-15%, with peak broadening indicating partial granule structure disruption [8].

SEM Characterization: Native starch exhibits smooth, polyhedral granule surfaces. Modified starches show rough, fractured surfaces with visible cracks and cavitation features. Surface roughness (Ra) increases from 0.2-0.5 μm for native starch to 1.5-4.0 μm for modified derivatives[8].

Water Absorption Capacity: Measured by equilibrating polymer in deionized water for 24 hours, calculated as [4]:
Native starch shows 50-100% WAC, while grafted copolymers achieve 500-1200% WAC [4]:

$$\text{WAC}\ (\%) = \frac{m_{\text{wet}} - m_{\text{dry}}}{m_{\text{dry}}} \times 100$$

This enhanced water retention contributes to improved drought resilience and nutrient bioavailability under variable soil moisture conditions.

ICP-OES Analysis: Provides precise quantification of macro- and micronutrients in formulations and release solutions with detection limits of 0.1-1.0 mg/L for simultaneous multi-element analysis [8].

VII. ECONOMIC AND SUSTAINABILITY ASSESSMENT

Production costs for agro-waste-based slow-release fertilizers are 50-70% lower than conventional fertilizers: raw material (₹50-100 vs ₹300-400/MT), processing energy (₹800-1200 vs ₹2500-3500/MT), yielding total production cost of ₹1300-2000 versus ₹3250-4650/MT [6].

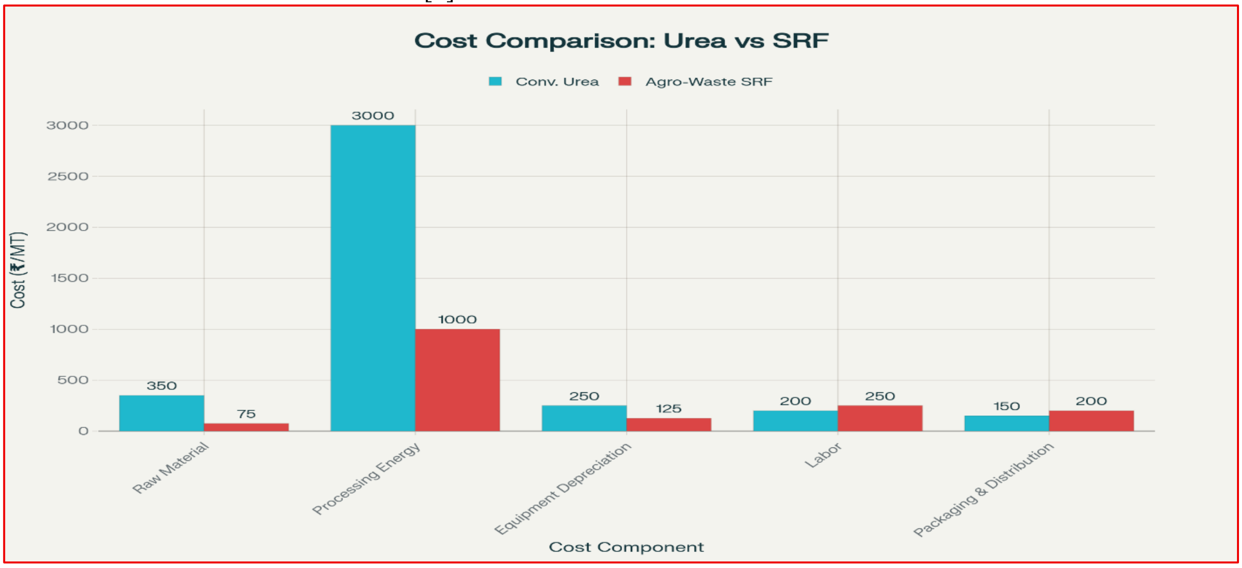

Figure 6: Production cost breakdown reveals that agro-waste SRF achieves significant cost advantages, particularly in raw material (78% reduction from ₹350 to ₹75/MT) and processing energy (67% reduction from ₹3000 to ₹1000/MT) compared to conventional urea, with total production cost reduction exceeding 60%.

Farmer-Level Economics (100 kg N/ha requirement):

Conventional system (3 applications): ₹4700/ha (₹2400 fertilizer + ₹1500 labor + ₹800 equipment), yield 25 MT/ha (80% potential)
Slow-release system (1 application): ₹1825/ha (₹1125 fertilizer + ₹500 labor + ₹200 equipment), yield 28 MT/ha (92% potential)
Net benefit: ₹38,875/ha (fertilizer savings ₹2875 + additional yield value ₹36,000), equivalent to 829% return on investment [6]. These economic advantages, combined with environmental benefits, provide compelling justification for technology adoption. Integrated nutrient management systems combining organic agro-waste-based fertilizers with minimal inorganic supplementation demonstrate enhanced soil fertility, improved microbial diversity, and sustained long-term productivity [12].

VIII. APPLICATIONS IN MAHARASHTRA AGRICULTURE

Banana Cultivation: Starch-alginate NPK formulations optimized with K:N:P ratio 2:1:0.5 achieve 25-30% yield increase and 40-50% fertilizer cost reduction across 99.5 thousand hectares. The high potassium content (25-40%) in banana peel-derived formulations addresses the elevated potassium requirements during fruit development stages, resulting in improved fruit quality, weight, and marketability [2][11].
Potato Cultivation: Starch phosphate carbamate utilizing 60-80% potato peel feedstock achieves 20-25% productivity increase from 31.2 to 38-40 MT/ha across 28.5 thousand hectares, reducing nitrogen losses to groundwater. The balanced NPK profile and extended release duration (25-30 days) align with potato's growth cycle of 70-90 days, providing optimal nutrient availability during critical tuber bulking phases[2][10].
Rice Cultivation : Starch-PVA-biochar composites utilizing rice husk biochar achieve 15-20% yield increase, reduced methane emissions, and complete utilization of agro-waste streams across 131.8 thousand hectares. The biochar component provides pH buffering in acidic rice paddies while enhancing water retention and creating favorable soil microbial environments[2][11].
Recent field studies demonstrate that precision agriculture techniques combined with controlled-release fertilizers enable variable-rate application based on soil nutrient status, potentially increasing nitrogen use efficiency by an additional 10-15% beyond baseline SRF benefits [16].

IX. RESEARCH GAPS AND FUTURE DIRECTIONS

Current Research Gaps:

1. Field-Scale Validation: Majority of research conducted under controlled conditions; large-scale field trials across Maharashtra's diverse agroecological zones limited[7].
2. Preprocessing Standardization: Variable methodologies complicate direct performance comparisons; standardized protocols needed[7].
3. Micronutrient Encapsulation: While macronutrient encapsulation established, micronutrient (Zn, Fe, Cu, Mn, B) formulations underdeveloped[17].
4. Long-Term Soil Quality Effects: Limited longitudinal studies (5+ years) assessing impacts on soil properties and nutrient cycling[12].

Future Directions:

1. Nanoparticle Integration: Integration of metal oxide nanoparticles (ZnO, Fe_2O_3, TiO_2) for multifunctional systems and enhanced micronutrient bioavailability.
2. Environmentally-Responsive Formulations : Development of pH-sensitive, moisture-responsive, and temperature-responsive smart coatings that adjust release based on real-time soil conditions.
3. Microbial Co-Encapsulation: Synergistic combination of slow-release nutrients with plant growth-promoting rhizobacteria (PGPR) for enhanced nutrient solubilization and plant stress tolerance.
4. Industrial Scaling: Continuous flow reactors, spray drying integration, and extrusion-based encapsulation for consistent product quality and reduced production costs.
5. Regional Processing Centers: Establishment of agro-waste processing facilities in high-production districts (Nashik, Satara, Sangli for banana/potato; Vidarbha for rice) reducing transportation costs and enabling farmer enterprises.

X. CONCLUSION

Valorization of starch-containing agro-waste into slow-release fertilizers represents sustainable intensification pathway addressing agricultural productivity, environmental protection, and waste management simultaneously. Maharashtra's substantial agricultural production (6534.35 MT banana, 890.5 MT potato, 4027.40 MT rice annually) generates agro-waste streams representing both environmental liability and untapped resource. Multiple synthesis methodologies demonstrate technical feasibility and practical applicability.

Slow-release fertilizers achieve 40-50% nutrient use efficiency improvements, reduce nitrogen losses by 60-70%, extend release duration 300-900%, and generate 50-70% production cost reductions compared to conventional alternatives. Recent advances in stimuli-responsive starch-based biopolymer coatings, integration with biochar and nanoparticles, and co-encapsulation with beneficial microorganisms demonstrate the rapidly evolving nature of this field.

Field-scale validation across Maharashtra's agroecological zones, agro-waste preprocessing standardization, and technology transfer to farmer enterprises represent critical next steps toward commercialization. Strategic policy support coupled with infrastructure development can translate scientific and technological opportunity into tangible benefits for Maharashtra's farming communities and broader ecosystem health, achieving simultaneous agricultural productivity, environmental sustainability, and circular economy objectives.

The integration of precision agriculture techniques with controlled-release fertilizers offers additional opportunities for optimizing nutrient management, reducing environmental footprints, and enhancing long-term soil health.

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Declaration: All authors confirm their contributions and consent for publication. This manuscript has not been published elsewhere and is not under consideration by any other journal. Registration fees paid as per journal requirements.

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