Soil health–driven cropping system design and resource-efficient planting strategies for sustainable intensification in waterlogged ecosystems of eastern India

1. **Keywords**: Soil health, waterlogged ecosystems, cropping system intensification, resource-use efficiency, direct seeded rice, raised bed planting, eastern India

2. Objectives:
   1. To identify the most productive and regionally suitable cropping systems under diverse planting techniques and crop combinations in waterlogged agro-ecologies.
   2. To evaluate the economic viability and profitability of the identified cropping systems across different waterlogged agro-ecosystems.
   3. To assess resource-use efficiency (water, nutrient, and energy) and overall sustainability of different cropping system scenarios.
   4. To determine the impact of cropping systems and management practices on key soil health indicators and system resilience.
3. **Project team**

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4. Project Duration: **5 years (June, 2025 – May, 2030)**
5. **Practical utility:**

The outcomes of this project will provide scalable and location-specific cropping system models for waterlogged ecosystems of eastern India. The study will help identify productive and economically viable crop combinations along with resource-efficient planting techniques, thereby improving system productivity and farmers' income. It will generate actionable recommendations on water, nutrient, and energy-use efficiency, supporting sustainable intensification of rice-based systems. The findings will also contribute to improving soil health through better carbon management, nutrient cycling, and reduced environmental degradation. The recommended technologies, including suitable cropping systems and planting strategies, can be directly adopted by farmers, extension agencies, and development programs for enhancing climate resilience and sustainability in waterlogged areas. Ultimately, the project will support evidence-based policy formulation for sustainable agricultural development in fragile agro-ecosystems.

6. **Technical programme (in brief):**

(a) **Experiment – I:**

Evaluation of cropping systems and planting techniques for enhancing productivity, profitability, and soil health in waterlogged agro-ecologies of eastern India

Scenario	Planting Technique	Kharif Crop	Rabi Crop	Summer Crop
CS_1	DSR – ZT – ZT	Rice	Wheat	Mung bean
CS_2	DSR – ZT – ZT	Finger millet	Mustard	Sesbania
CS_3	TPR – CT – CT	Finger millet	Wheat	Mung bean
CS_4	TPR – CT – CT	Rice	Mustard	Sesbania
CS_5	ZT – ZT – ZT	Maize	Wheat	Vegetables

CS_6	ZT – ZT – ZT	Maize	Mustard	Mung bean
CS_7	ZT – ZT – ZT	Soybean	Wheat	Mung bean
CS_8	RBP – ZT – ZT	Soybean	Mustard	Vegetables
CS_9	TPR – CT	Rice	Maize	Sesbania
CS_{10}	ZT – ZT – ZT	Pearl millet	Mustard	Mung bean
CS_{11}	Random transplanting - Broadcasting	Rice	Wheat	-

7. Expected Output

- Identification of productive and region-specific cropping systems suitable for waterlogged ecosystems of eastern India under diverse planting techniques and crop combinations.
- Generation of a comprehensive database on crop productivity, resource-use efficiency, profitability, and soil health parameters under different cropping system scenarios.
- Standardization of resource-efficient planting strategies for improving water, nutrient, and energy-use efficiency in waterlogged agro-ecosystems.
- Development of soil health–based sustainability indicators and resilience assessment framework for diversified cropping systems.
- Generation of location-specific recommendations and advisories for farmers, extension agencies, and policymakers for sustainable intensification in waterlogged areas.
- Publication of research findings, technical bulletins, and policy-oriented documents for wider dissemination and adoption.

8. Expected Benefits and Economic Impact

The project will generate scientific information on productive, profitable, and sustainable cropping systems suitable for waterlogged ecosystems of eastern India, where region-specific recommendations are presently limited. Identification of efficient crop combinations and planting strategies will help improve crop productivity, cropping intensity, and farm profitability under excess moisture conditions. The study will also provide insights into resource-use efficiency involving water, nutrients, and energy, thereby reducing input costs and improving economic returns to farmers.

Improvement in soil organic carbon, nutrient dynamics, and overall soil health through suitable management practices will contribute to long-term sustainability and resilience of agricultural systems. Adoption of resource-efficient and soil health–driven technologies is expected to enhance farmers' income, climate resilience, and livelihood security in vulnerable agro-ecologies. The project outcomes will further support evidence-based policy planning, sustainable land and water management, and future research initiatives related to climate-smart and conservation-oriented agriculture in eastern India.

(b) Experiment II: Integrated Tillage and Bio-Organic Phosphorus Management for Improving P Availability, P-Use Efficiency and Productivity of Calcareous Rice-Based Cropping Systems in North Bihar

1. **Rationale**

Phosphorus (P) management is a major constraint to sustainable crop production in the calcareous alluvial soils of North Bihar. These soils commonly contain appreciable reserves of total phosphorus but support comparatively low concentrations of readily plant-available P. This creates an apparent contradiction in which soils may contain substantial amounts of phosphorus and yet crops continue to respond to fresh P fertilization. The problem is associated principally with the alkaline reaction and presence of free calcium carbonate, which favour rapid sorption and precipitation of soluble fertilizer P into comparatively less soluble calcium-associated forms. Consequently, only a relatively small proportion of freshly applied fertilizer P is recovered by crops during the season of application, while the remaining P progressively contributes to a residual or legacy soil-P pool.

Phosphorus is particularly difficult to manage because it is relatively immobile in soil and reaches plant roots mainly through short-distance diffusion. Crop uptake therefore depends not only on the total amount of phosphorus present in the soil but also on its chemical availability, spatial distribution, soil moisture, root proliferation and biological mobilization. These limitations become particularly important in intensive rice-based cropping systems, where repeated fertilizer application, wetting-drying cycles, low soil organic carbon and conventional tillage can progressively reduce the efficiency with which applied P is utilized.

A practical strategy is therefore required that improves access to both freshly applied and accumulated soil P rather than simply increasing fertilizer rates. Band placement can reduce fertilizer–soil contact and concentrate phosphorus close to the developing root system, thereby improving early P availability. Organic amendments such as FYM can contribute directly to the P pool while supplying organic carbon, improving soil physical condition and influencing P sorption and precipitation reactions. Phosphate-solubilizing bacteria (PSB) may further enhance P mobilization through organic-acid production, chelation and phosphatase activity. These mechanisms provide the scientific basis for evaluating reduced mineral-P application in combination with FYM and PSB.

The effectiveness of these P-management strategies may also depend strongly on the cropping and tillage system. Conventional puddling and intensive tillage alter soil structure, porosity and root-zone conditions, whereas reduced/zero tillage with residue retention can improve aggregation, soil moisture conservation and biological activity but can also produce marked vertical stratification of phosphorus near the soil surface. Similarly, rice–wheat–mungbean and rice–maize–mungbean systems differ in crop rooting characteristics, nutrient demand, biomass production and potential P removal. Therefore, P management should be evaluated at the whole cropping-system level rather than for an individual crop alone.

The proposed long-term field experiment consequently integrates cropping system, crop establishment/tillage and phosphorus-management strategies to determine whether mineral-P inputs can be reduced without compromising productivity. Particular emphasis will be placed on crop response, P uptake, soil-solution P, P fractions, biological P cycling, soil physical quality, P balance, system productivity and profitability. The study is expected to provide a mechanistic as well as agronomically practical basis for improving P-use efficiency in the calcareous rice-based production systems of North Bihar.

2. **Research Gaps**
   - Soil P dynamics under calcareous conditions are inadequately characterized. The transformation of applied and residual P among labile, organic, Fe/Al-associated, Ca-associated and residual P pools has not been adequately quantified under long-term contrasting tillage and integrated P-management systems.
   - The potential for reducing mineral-P fertilizer through improved placement remains uncertain. Although band placement should reduce soil–fertilizer contact and improve root access to P, its effectiveness relative to reduced P rates under the strongly calcareous soils of North Bihar requires field validation.
   - The ability of FYM to compensate for reduced mineral-P input is insufficiently quantified. Organic inputs may reduce P fixation, provide mineralizable P and improve biological activity, but their contribution needs to be evaluated within complete rice-based cropping sequences.
   - Field performance of PSB under alkaline-calcareous conditions remains inconsistent. PSB can mobilize sparingly soluble P, but their activity is strongly influenced by soil reaction and availability of organic carbon. The interaction of FYM and PSB therefore needs direct evaluation under field conditions.
   - Tillage-induced vertical P stratification has received inadequate attention. Reduced or zero tillage with residue retention can concentrate P in surface soil layers. Whether such stratification improves or restricts crop access to P in calcareous soil remains unresolved.
   - Cropping-system differences in P demand and residual-P utilization are poorly quantified. Rice–maize–mungbean may differ substantially from rice–wheat–mungbean in P uptake, biomass production and exploitation of residual P.
   - Whole-system P budgeting is rarely undertaken. Most studies emphasize individual crops, whereas fertilizer P, FYM-P, crop uptake, residue recycling and residual P need to be accounted for across the complete annual crop sequence.
   - Integrated soil–plant–canopy responses are poorly understood. Few long-term studies simultaneously relate soil P availability and soil physical properties with root growth, canopy development, crop physiological response, yield and P-use efficiency.
   - There is presently no adequately validated farmer-oriented package for reducing mineral-P use in calcareous rice-based systems of North Bihar.
3. **Objectives**
   - To evaluate the effects of cropping system, tillage/crop establishment and integrated phosphorus management on phosphorus availability, crop growth, productivity and phosphorus-use efficiency in calcareous soils.
   - To compare rice–wheat–mungbean and rice–maize–mungbean cropping systems for productivity, nutrient uptake, residual phosphorus utilization and system-level nutrient-use efficiency.
   - To assess the effect of conventional tillage and direct-seeded/reduced/zero tillage with residue retention on soil physical condition, P stratification, root-zone P availability and crop performance.

- To quantify changes in soil phosphorus dynamics, including available P, soil-solution P, phosphorus fractions, microbial biomass P and phosphatase activity under integrated P-management practices.
- To identify a productive, resource-efficient and economically viable P-management strategy capable of reducing mineral-P fertilizer requirement without compromising system productivity.

4. **Experimental design and treatment details**

The experiment will be conducted as a split–split plot design with three replications.

Main plot factor: Cropping System – 2 levels

Code	Cropping system
C1	Rice–Wheat–Mungbean
C2	Rice–Maize–Mungbean

Sub-plot factor: Tillage/Crop Establishment – 2 levels

Code	Treatment
T1	Conventional/puddled rice followed by conventional tillage
T2	Direct-seeded/reduced-till rice followed by zero/reduced tillage with residue retention

Sub-sub plot factor: Phosphorus Management – 5 levels

Code	Treatment
P0	No phosphorus
P1	100% RDF-P through band placement
P2	50% RDF-P through band placement
P3	50% RDF-P through band placement + FYM@ 5 t ha^{-1}
P4	50% RDF-P through band placement + FYM@ 5 t ha^{-1} + PSB

Total treatment combinations = 2 × 2 × 5 = 20; with 3 replications = 60 experimental units.

5. **Expected Output**

- Development of a validated integrated phosphorus-management strategy combining appropriate P placement, reduced mineral-P application, FYM and PSB for calcareous rice-based cropping systems.
- Generation of a three-year dataset on crop growth, canopy characteristics, root development, yield, nutrient uptake, P-use efficiency and residual-P utilization under contrasting cropping and tillage systems.
- Quantification of treatment-induced changes in Olsen P, soil-solution P and different soil-P fractions, particularly labile and Ca-associated pools.
- Quantification of changes in soil physical condition and P stratification under conventional versus reduced/zero tillage with residue retention.
- Determination of the contribution of soil biological processes, including microbial biomass P, phosphatase activity and PSB populations, to P mobilization.
- Development of crop-wise, annual and cumulative phosphorus budgets for the different management systems.

- Identification of a P-management treatment capable of reducing mineral-P requirement while maintaining productivity and profitability.
- Preparation of farmer-ready recommendations, technical bulletins, research publications and extension material for calcareous soils of North Bihar.

6. **Expected Outcome**

- Improved phosphorus availability and P-use efficiency in calcareous soils.
- Reduced dependence on mineral phosphorus fertilizer.
- Greater utilization of accumulated/legacy soil phosphorus.
- Improved soil physical condition, aggregation and biological activity under suitable tillage-residue management.
- Better synchronization between root development, soil P supply and crop P demand.
- Sustainable productivity of rice–wheat–mungbean and rice–maize–mungbean cropping systems.
- Lower fertilizer expenditure and improved farm profitability.
- Generation of a scientifically validated P-management recommendation suitable for extension through ICAR–MGIFRI and KVKs.
- Improved nutrient-use efficiency and reduced risk of long-term P accumulation in agricultural soils.

7. **History of the Experimental Plot**

Item	**Information**
(a) When the field was developed	
(b) Crops cultivated season-wise	Rice-Wheat/Maize-Green gram
(c) Soil type	Fine Loamy Mixed Hyperthermic Calcareous Fluventic Haplustepts
(d) Soil pH, EC and OC	pH-8.21-8.32, EC-0.24-0.27 dsm^{-1}, OC: 0.67%
(e) Soil depth	More than 100cm
(f) Soil NPK and micronutrient status	
(g) Common pests and diseases	