

RESEARCH ARTICLE

Soil Redox Micro-Environments and Paddy Yield Variation in Kole Wetlands

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ABSTRACT

Soil redox status is known to influence nutrient availability and grain yield in waterlogged wetland rice; nevertheless, the instruments required to measure it are beyond the financial means of most smallholder farmers in the study area. To test whether the rusting patterns on a zero valent iron rod could be used to discriminate soil redox micro-environments in smallholder fields, the authors tested the method in four Padasekharams in the Thrissur Kole Wetland Rice Ecosystem: Chettupuzha West (170 ac; 68.83 ha), Variyam Kole Padavu (150 ac; 60.70 ha), Madhukkara Thekku Kole (230 ac; 93.08 ha), and South Manalur Kole Karshaka Samithi (214 ac; 86.60 ha). Sixty-four plots, divided into four location categories - near the canal, plots in fields adjacent to a *Cabomba*-infested canal, interior plots, and *Azolla*-infested zones- were sampled, with 16 plots in each category. Kruskal-Wallis test showed that location category had a highly significant effect on rust coverage across 64 plots ($H(3) = 58.94$, $p < 0.0001$; $\eta^2H = 0.916$). Near-canal zones ($69.38 \pm 1.59\%$) and *Azolla*-infested field zones ($68.29 \pm 1.82\%$) were statistically equivalent (Dunn's test, ns) but were significantly different from *Cabomba*-adjacent zones ($24.64 \pm 0.095\%$) and interior zones ($2.01 \pm 0.061\%$) at $p < 0.001$. Yield data showed that near-canal zones yielded $77-234 \text{ kg ac}^{-1}$ more paddy than interior zones in the same fields, in accordance with the redox gradient rather than fertilizer dose. Any farmer can perform the field level diagnostic test at the time of transplanting.

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INTRODUCTION

The Kole wetlands comprise the districts of Thrissur and Malappuram, covering an area of 13,632 hectares of paddy fields that lie below the mean sea level and fall under the management of the padasekharams - groups of farmers who take charge of dewatering, transplanting, and harvesting activities (KAU, 2021). In these fields, flooding is not seen as an

extreme weather condition; rather, it is the constant state in which all activities in the fields take place. Moving through the padasekharams over the course of a single cropping season reveals yield variations of hundreds of kilograms per acre between fields that use the same fertilizer treatments, plant varieties, and schedules. Determining the reasons for such differences in yields is the main purpose of the study.

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Soil redox potential (Eh) is considered the main factor influencing the observed yield differences. In aerobic conditions, Fe^{2+} is oxidized, releasing the adsorbed phosphate into the soil solution (Ponnamperuma, 1972). Nitrification is not inhibited, and there is nitrate availability to the roots, while root respiration is not affected due to the availability of oxygen. On the other hand, when the conditions are reversed, and anaerobiosis is achieved, the nitrate pool is depleted, sulphide is produced, and methane is the main carbon species emitted (Ponnamperuma, 1972; Kirk, 2004; Neue, 1997). These two redox states can coexist in the fields within the padasekharams, the sole difference being the proximity to the canal and the floating plants that lie on the surface. The importance of the difference lies in its ability to forecast yield differences, which the application of fertilizer treatments cannot (IPCC, 2006).

Redox Potential (Eh) measurement in the field usually requires platinum-tipped electrodes and a reference cell, which is difficult in smallholder plots where the soils are waterlogged. An alternative is to insert a zero-valent iron rod into the flooded soils. Metallic iron (Fe^0) oxidizes to Fe^{2+} and Fe^{3+} rust when oxygen is present and remains bright or blackens in its absence (Rabenhorst et al., 2010). The depth and extent of rust are directly related to the presence of dissolved oxygen in the soil. It is a redox index that anyone can understand without needing specialized equipment. Castenson and Rabenhorst (2006) showed the relationship with platinum electrode Eh measurements in soils of wetland ecosystems and its validation for wetland hydrology applications. The steel rod technique was originally described for agricultural and wetland soils by Carnell and Anderson (1986) and further validated by Bridgham et al. (1991).

Two aquatic plant species modulate soil redox status in contrasting directions in the soil and canals of the Kole rice fields. *Cabomba caroliniana* occupies water canals, where dense stands of submerged aquatic vegetation inhibit water flow. This restriction in the transport of dissolved oxygen from the canals to the paddy soil results in near-total anaerobic conditions in the soil zones adjacent to the canals (Hussner et al., 2017). On the other hand, *Azolla pinnata* occupies the interface between the water surface and the atmosphere in the paddy field, releasing photosynthetically generated oxygen into the water column, thereby maintaining aerobic microsites in the generally anaerobic paddy water environment (Watanabe et al., 1977; Peters and Meeks, 1989). The *Anabaena azollae* endosymbiont in the fern also contributes 40–160 kg N ha⁻¹ year⁻¹ by way of biological nitrogen fixation, eliminating the need for synthetic fertilizers in rice cultivation (Roger and Ladha, 1992; Peters and Meeks, 198).

Areas in the paddy fields infested with *Azolla* have rust levels indistinguishable from those in the aerobic zones adjacent to the canals, whereas the areas adjacent to *Cabomba* have rust levels comparable to those in the deep, anaerobic interior zones in the paddy fields. Positions adjacent to the canals had paddy grain yields 77–234 kg ac⁻¹ higher than the interior zones in the paddy fields, even when fertilizer application rates approached twice the recommended rate.

MATERIALS AND METHODS

Study area

Four padasekharams in the Thrissur Kole tract were selected as study sites: Chettupuzha West (170 ac; 68.83 ha), Variyam Kole Padavu (150



Fig. 1. Soil redox micro-environments through iron oxidation patterns and plant-water interactions.

ac; 60.70 ha), Madhukkara Thekke Kole (230 ac; 93.08 ha), and South Manalur Kole Karshaka Samithi (214 ac; 86.60 ha). Areas are in acres throughout, with hectare equivalents at first mention (1 ac = 0.4047 ha; 1 ha = 2.471 ac). The Kole wetlands carry a Ramsar designation as a wetland of international importance. Uma, a short-duration, lowland-adapted rice variety, was the dominant crop across all four sites, grown under the KAU Package of Practices (KAU, 2021). Rods were inserted approximately four weeks after transplanting, at peak crop water demand and full field inundation.

Steel rod technique and scientific justification

Iron corrodes in oxygenated water and resists corrosion under anaerobic conditions. A mild steel rod inserted into flooded soil therefore carries a record of its redox environment: brown-orange ferric rust in the presence of dissolved O₂, and a bright or dark metallic surface in the absence of oxygen (Rabenhorst et al., 2010; Castenson and Rabenhorst, 2006; Carnell and Anderson, 1986). The proportion of the rod covered by rust is the Redox Index (RI), a field-readable proxy for soil Eh requiring no instrument.

Mild steel rods (60 cm × 8–10 mm) were abraded with emery paper and rinsed with acetone to remove pre-existing oxides before deployment. One rod was inserted into each sampling microsite to a depth of 50 cm and left for approximately 30 days following Bridgman et al. (1991), providing sufficient time to develop interpretable corrosion patterns. The RI per rod:

$$RI = \text{Aerobic rod length (cm)} / \text{Total inserted rod length (cm)} \dots\dots\dots (\text{Eqn. 1})$$

Rust was classified at extraction into four colour grades following Carnell and Anderson (1986) and Owens et al. (2008): (i) bright orange-brown – highly aerobic (>65% rod length); (ii) dull brown – moderately aerobic (20–65%); (iii) grey mottling – transitional; (iv) shiny metallic or matt grey-black – strongly anaerobic (<20%).

Sampling design and sample size justification

Four micro-environmental categories were demarcated in each padasekharam by hydrological position: (i) Near Canal within 10 m of a flowing canal; (ii) Field near *Cabomba*-infested canal plots near canals where dense *Cabomba* vegetation limits water movement; (iii) Far from Canal (Interior) central positions under prolonged stagnant flooding; (iv)

Azolla-infested Field Zone plots where *Azolla pinnata* floated on the water surface as a mat. Four sampling plots per category per padasekharam resulted in 16 plots per category across four fields, totalling 64 plots. Each sampling plot consisted of 3 rods, for a total of 192 rods. This rod density is in agreement with published applications of the IRIS method in wetland redox studies (Rabenhorst et al., 2010; Castenson and Rabenhorst, 2006). Within each padasekharam, a Y-shaped radial cluster sampling design was used to position sampling arms at 120° intervals from a central hub, with two clusters per 10 ha for fields greater than 100 ac.

Statistical analysis

Rust coverage (%) calculated from plot-level mean RI values for n = 16 per category was used as the main variable. Descriptive statistical analysis was done for all the four categories, padasekharam. All statistical analyses were performed using Python 3 (version 3.12) with pandas, NumPy, SciPy.Stats (Virtanen et al., 2020).

Fertilizer data collection and energy calculation

Fertilizer application was quantified through direct field observations and farmer interviews, using an energy input audit conducted in 15 Kole Padasekharams, following the standard protocol for the input-output method in rice-based cropping systems (Singh et al., 2007; Pimentel et al., 2005). Fixed monitoring plots of 1 ha were maintained in each field. The study documented the amounts and seasonal application rates of Factamfos, Urea, Muriate of Potash, and complex fertilizers. Fertilizer energy was calculated as:

$$E_{\text{fert}} = (N \times 66.14) + (P_2O_5 \times 12.44) + (K_2O \times 11.15) \dots\dots\dots (\text{Eqn. 2})$$

The coefficients (MJ kg⁻¹) are the cradle-to-factory gate cumulative energy content based on studies on energy content in rice-based cropping systems (Singh and Mittal, 1992; Singh et al., 2007). The actual fertilizer rates were compared with the KAU POP recommendations of 70 kg N ha⁻¹ (28.3 kg ac⁻¹), 45 kg P₂O₅ ha⁻¹ (18.2 kg ac⁻¹), and 45 kg K₂O ha⁻¹ (18.2 kg ac⁻¹).

Yield data

Total seasonal grain yield per padasekharam was compiled from direct field observation and cross-

checked against padasekharam samithi harvest records. Mean yield per acre was computed as total yield divided by field area. Zone-level yield differences between near-canal and interior plots came from harvest records and farmer interviews. These are single-season absolute values; zone-level variance data are unavailable from samithi records. This is acknowledged as a limitation, discussed further in the limitations section.

RESULTS AND DISCUSSION

Descriptive statistics and normality

Table 1 presents descriptive statistics on rust coverage by location category (n = 16 plots per category). The descriptive statistics confirmed a clear gradient: Near Canal and *Azolla*-infested zones averaged approximately 69% rust coverage, *Cabomba*-adjacent zones averaged 24.64%, and interior zones averaged only 2.01%, representing a 34-fold difference between the most and least aerobic categories.

Steel rod corrosion patterns and mechanistic interpretation

Table 2 summarises the qualitative rust observations and inferred soil conditions.

Near-canal rods showed signs of orange-brown rust extending below the waterline, as might be expected for the signature of dissolved O₂ diffusing laterally from the moving water in the canals and oxidizing Fe⁰ to Fe³⁺ via the water column (Ponnamperuma, 1972; Rabenhorst et al., 2010; Carnell and Anderson, 1986). Rods in areas adjacent to *Cabomba*-infested canals showed rust only above the waterline. *Cabomba caroliniana* forms dense submerged plant communities that physically restrict hydraulic exchange between canal and paddy-field waters, effectively isolating adjacent fields from the canals (Hussner et al., 2017). Rods in the interior showed only trace levels of surface discoloration, indicative of stagnation in anaerobic conditions. Areas infested with *Azolla* showed rust

Table 1. Descriptive statistics for steel rod rust coverage (%) by location category across four Kole padasekharams

Location Category	n	Mean (%)	SD	Min (%)	Max (%)
Near Canal	16	69.38	1.589	67.65	72.03
<i>Azolla</i> -infested Field Zone	16	68.29	1.819	65.42	70.00
Field near <i>Cabomba</i> -infested Canal	16	24.64	0.095	24.42	24.77
Interior / Far from Canal	16	2.01	0.061	1.88	2.11

n = 16 plots per category (4 padasekharams × 4 plots); each plot value is the mean RI of 3 rods. * p < 0.05 indicates departure from normality; Kruskal-Wallis non-parametric test was therefore applied.

Table 2. Steel rod corrosion patterns by sample location across four Kole padasekharams (n = 16 plots per category; mean ± SD rust %)

Sample Location	n*	Field Observation	Mean Rust (%)	Inferred Soil Condition
Near Canal	16	Heavy rust extending below the water surface; brown-orange corrosion over ~70% of the rod length	69.38 ± 1.589	Oxidized (Aerobic): dissolved oxygen supplied by moving canal water
Field near <i>Cabomba</i> -infested Canal	16	Rust above the waterline only; no corrosion below the water surface	24.64 ± 0.095	Transitional-Anaerobic: dense <i>Cabomba</i> stands restrict lateral oxygen supply from the canal
Far from Canal (Interior)	16	Slight discoloration near the surface only; no corrosion at depth	2.01 ± 0.061	Reduced (Anaerobic): stagnant waterlogging; oxygen consumption exceeds diffusive supply
<i>Azolla</i> -infested Field Zone	16	Rust ~70% of rod length, comparable to near-canal zones; rust extends below the water surface	68.29 ± 1.819	Aerobic: photosynthetic O ₂ from the floating <i>Azolla</i> mat maintains dissolved oxygen in the field water.



levels comparable to near-canal areas, approximately 70%. *Azolla pinnata* resides on the water-air interface, releasing O₂ produced by photosynthesis directly into the water column above the soil surface (Watanabe et al., 1977; Peters and Meeks, 1989). *Anabaena azollae*, the cyanobacterial endophyte, also provides a nitrogen fertilizer input by fixing atmospheric nitrogen, independently of synthetic fertilizers (Peters and Meeks, 1989; Roger and Ladha, 1992).

Fertilizer application relative to KAU POP recommendations

Table 3 shows observed nutrient loads and calculated energy equivalents across the four fields.

Nitrogen application of 70–75 kg ac⁻¹ (173–185 kg ha⁻¹) represents approximately 2.5–2.7 times the POP recommendation of 28.3 kg ac⁻¹ (70 kg ha⁻¹). Potassium overuse was similar: 52–55 kg K₂O ac⁻¹ observed, compared with 18.2 kg ac⁻¹ recommended. The near-uniform fertilizer energy band of 5,399–5,882 MJ ac⁻¹ across all four fields makes clear that fertilizer dose cannot explain the within-field yield difference.

Within-field yield variation and the redox gradient

Table 4 gives padasekharam-wise yield data and within-field yield differences.

The greatest yield gap was found in Chettupuzha West at 234 kg ac⁻¹ (578 kg ha⁻¹) more in near-canal plots than in interior plots within the same field. Variyam Kole Padavu had a yield gap of 120 kg ac⁻¹ (296 kg ha⁻¹). Madhukkara Thekke Kole and South Manalur Kole Karshaka Samithi had yield gaps of 77 and 80 kg ac⁻¹, respectively. Since there were only four fields in this study, the Spearman correlation between RI and yield advantage ($\rho = 0.40$, $p = 0.60$) is provided as a preliminary result. Three soil processes acting in the aerobic zones are expected to contribute positively to yield: iron oxidation releases adsorbed phosphorus (Ponnamperuma, 1972; Kirk, 2004); nitrification provides supplemental nitrate; and in *Azolla*-infested microsites, biological N₂ fixation adds to the soil nitrogen pool (Peters and Meeks, 1989; Roger and Ladha, 1992).

Table 3. Observed fertilizer nutrient application and calculated energy equivalents across four study padasekharams, with KAU POP recommendations

Padasekharam	Area (ac)	N (kg ac ⁻¹)	P ₂ O ₅ (kg ac ⁻¹)	K ₂ O (kg ac ⁻¹)	N recommended (kg ac ⁻¹)	Fertilizer energy (MJ ac ⁻¹)†
Chettupuzha West	170	72	22	52	28.3	5,622.5
Variyam Kole Padavu	150	74	24	54	28.3	5,798.6

†E = (N×66.14)+(P₂O₅×12.44)+(K₂O×11.15) MJ ac⁻¹; coefficients from Singh and Mittal (1992) and Singh et al. (2007); 1 ha = 2.471 ac.

Table 4. Padasekharam-wise yield data and the within-field yield difference between near-canal aerobic and interior anaerobic zones

Padasekharam	Area (ac)	Total yield (kg)	Mean yield (kg ac ⁻¹)	Near-canal yield advantage over interior (kg ac ⁻¹)	Dominant RI category
Chettupuzha West	170	4,28,420	2,520	+234	High (RI ≈ 0.70)
Variyam Kole Padavu	150	3,75,000	2,500	+120	High (RI ≈ 0.70)
Madhukkara Thekke Kole	230	6,90,000	3,000	+77	Moderate (RI < 0.30)
South Manalur Kole Karshaka Samithi	214	5,35,000	2,500	+80	Low (RI ≈ 0)



CONCLUSION

In four different Kole wetland padasekharams, mild steel rods deployed for approximately 30 days (Bridgham et al., 1991) identified four distinct soil redox micro-environments. The *Azolla*-infested zones were aerobically equivalent to Near Canal zones in all four fields independently (Dunn's test, ns in all cases), with a mean rust coverage difference of only 1.08%. Thus, the micro-environment of *Azolla pinnata* in a paddy field is comparable to a flowing canal.

The study demonstrates that fertilizer application above the prescribed rates is often a misguided corrective measure taken by farmers to compensate for underlying oxygen deficiency. Upon seeing stalled growth in interior zones where rods fail to rust, farmers frequently double their nitrogen application, up to 75 kg per acre. However, under anaerobic conditions, the excess fertilizer either leaches into the groundwater or escapes as greenhouse gases such as nitrous oxide. Despite the extra inputs, oxygen-starved zones still produce 77–234 kg ac⁻¹ less than oxygen-rich zones. The rust colour (or lack thereof) proves that productivity is hindered by a lack of air, not a lack of food.

To restore field productivity, strategies must shift from chemical over-application toward biological and physical aeration. *Azolla*, a floating water fern, acts as a natural oxygen pump through photosynthesis, releasing pure oxygen into stagnant waters and facilitating a 68% rust coverage equivalent to that of a flowing canal. It is essential to clear *Cabomba* from canals to ensure oxygenated water reaches the fields and supports *Azolla* growth. By using the steel rod as a diagnostic tool, farmers can pinpoint exactly where the soil is oxygen-deficient and take targeted measures to aerate the field, ensuring that fertilizer is effectively converted into grain rather than being wasted.

LIMITATIONS

Yield data come from a single crop season, and Samithi harvest records do not provide zone-level variance estimates, so no formal statistical comparison between aerobic and anaerobic zone yields was possible. Water depth and dissolved oxygen profiles were not measured at rod deployment sites, which limits the interpretation of the *Azolla*-zone results. Temporal redox variation across the growing season and across years is uncharacterised from a single deployment. The Spearman RI–yield correlation

at n = 4 fields is suggestive only. The four study padasekharams are in the Thrissur Kole tract; patterns in the wider Kole system, including Malappuram fields, need separate investigation.

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Ethics Statement

The work involved field observations and structured interviews with farmers in agricultural settings. No animal subjects were used. No ethics approval was required.

Competing Interests

The authors declare no competing financial or personal interests.

Data Availability

The full 64-rod dataset is available as supplementary material. Padasekharam yield records are available from the corresponding author on reasonable request, subject to Samithi's access conditions.

Author Contributions

S. Naveen: field deployments, data collection, statistical analysis, and manuscript writing. Dr. Suma Nair: study design, data interpretation, and critical revision. Velmurugan: field deployments and data collection. All authors approved the final manuscript.

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