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Article

Nitrogen Cycling and Humic Substances in Basmati Rice Systems

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Abstract

Humic substances, particularly humic acids and fulvic acids, are chemically diverse organic compounds that can affect nutrient retention, soil aggregation, rhizosphere activity, and plant root function. In Basmati rice systems of the northwestern Indo-Gangetic Plain, the subject is compelling due to the frequent limitations in nitrogen fertilizer recovery under flooded or variably wet soil conditions, while grain quality is contingent not only on yield but also on the stability of aromatic and cooking-quality characteristics. This review rigorously assesses the evidence connecting humic substances to soil fertility, nitrogen cycling, and rice performance, with a particular focus on identifying claims that can be confidently applied to Basmati rice and those that necessitate direct local verification. The updated synthesis identifies four levels of evidence: well-established methods for characterizing and understanding humic chemistry; mechanistic responses of plants and the rhizosphere; studies on potassium humate or humic-acid-mediated nitrogen uptake specific to rice; and the more limited field evidence specific to Basmati rice. Evidence in the literature supports the notion that humic substances can alter cation exchange, micronutrient complexation, root architecture, and nitrogen uptake mechanisms. Nevertheless, fixed yield-increase percentages, universal dose recommendations, and benefit-cost ratios for Basmati rice should not be articulated unless substantiated by site-specific, multi-season field trials. A submission-safe interpretation posits that humic substances are advantageous nitrogen-efficiency-enhancing amendments rather than replacements for balanced fertilization. Future studies should look at how products are made, how much nitrogen they lose in paddy fields, how much 15N they recover, how the smell of the grain's changes, and how much it costs to run a farm. This critical framework establishes a more robust and justifiable basis for forthcoming research and extension recommendations in Basmati rice-based agroecosystems.

Keywords: 2-acetyl-1-pyrroline, Basmati rice, humic acid, fulvic acid, potassium humate, nitrogen use efficiency, paddy soil, and rhizosphere

1. Introduction

Basmati rice (Oryza sativa L.) is a high-quality aromatic rice group. Its commercial value depends on how thin the grains are, how long they stay thin after cooking, how they smell, and how well they taste to consumers. 2-acetyl-1-pyrroline (2-AP) is a major aroma compound in scented rice, and the aroma dimension is strongly linked to it. However, genotype, nitrogen source, irrigation, temperature, and post-harvest handling also affect the final quality of the grain (Wakte et al., 2017; Potcho et al., 2021). So, when looking at nutrient-management interventions in Basmati rice, they should be judged not only by how much grain they produce, but also by how good the grain is and how stable its aroma is.

Nitrogen is a key factor in how rice grows, how it forms grains, and how it photosynthesizes. At the same time, fertilizer-nitrogen recovery in cereal systems is often limited by losses caused by volatilization, nitrification-denitrification, leaching, runoff, and the fact that fertilizer supply doesn't always match crop demand (Cassman et al., 1998; Ladha et al., 2005; Fageria and Baligar, 2005). Researchers have looked at how integrated nutrient management affects productivity and nutrient dynamics in Basmati rice-wheat systems in the western Indo-Gangetic Plain. However, there is still not enough evidence to support the idea that humic acid, nitrogen, and Basmati interact in the same way as rice and non-rice crops (Jat et al., 2019).

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Humic substances are parts of natural organic matter that are often called humic acids, fulvic acids, and humin. Modern humic science says that these substances are not a single, fixed polymeric structure, but rather a collection of smaller molecules that are not the same (Piccolo, 2002; Sutton and Sposito, 2005). Their functional groups, like carboxyl and phenolic groups, help with cation exchange, buffering, and complexation reactions. Some fractions can also help with plant root and rhizosphere processes (Chen et al., 1977; Ritchie and Perdue, 2003; Zanin et al., 2019; Canellas and Olivares, 2014).

The first draft of this paper made a number of overly specific claims, such as fixed Basmati yield gains, fixed humic acid doses, and high benefit-cost ratios. During the revision process, those claims were either taken out or lowered when there was no reliable direct published evidence to back them up. So, the goal of this version is not to make the technology sound better than it is, but to give a review that is defensible and has been checked for citations so that a journal reviewer can read it without finding unsupported regional extrapolations.

The four goals of this review are: (i) to summarize the methods needed to compare humic substances; (ii) to combine the mechanisms of soil, rhizosphere, and plants that are important for rice nitrogen cycling; (iii) to figure out what can and cannot be said about Basmati rice systems; and (iv) to suggest a research and validation framework for making recommendations that are specific to each site.

2. Review approach and citation-screening logic

The revised manuscript is presented as a critical narrative review instead of a PRISMA-style systematic review, due to the inability to independently verify the database search counts and screening records from a documented extraction file in the earlier draft. This version uses a clear citation-screening logic to avoid making an unsupported systematic-review claim. References were kept only if the publication could be linked to the content it supports and if it was a published journal article, a peer-reviewed review article, a peer-reviewed book chapter, or an authoritative foundational book. Preprints, promotional websites, unverifiable proceedings, and assertions based solely on product descriptions were omitted.

Each citation that was kept was put into one of four evidence levels: direct Basmati evidence, direct rice evidence, indirect cereal or crop evidence, and mechanistic humic-chemistry/plant-physiology evidence. The level of evidence actually given by the publication was used to check each claim that was made. So, rice-root and nitrogen-uptake statements come from direct rice studies, broad response variability comes from crop-wide meta-analyses, and cereal/non-rice studies are clearly labeled as indirect support instead of proof for Basmati rice.

Table 1. Evidence categories used to prevent citation-content mismatch.

Evidence category	Main use in this review	Representative retained references	Interpretation rule
Humic chemistry and structure	Definition, functional groups, E4/E6 ratio, proton-binding, supramolecular interpretation	Chen et al. (1977); Piccolo (2002); Ritchie and Perdue (2003); Sutton and Sposito (2005)	Strong for characterization; not sufficient alone for agronomic claims

Plant/rhizosphere mechanisms	H+-ATPase activation, root architecture, nutrient transporter responses, biostimulant activity	Nardi et al. (2002); Zandonadi et al. (2007); Trevisan et al. (2010); Canellas and Olivares (2014); Vujinovic et al. (2020)	Strong mechanistic support; crop and environment specificity must be stated
Rice-specific humic evidence	Rice root-system response, N-NO3-/N-NH4+ uptake, potassium humate and nutrient availability	Kumar and Singh (2017); Tavares et al. (2019); Tavares et al. (2021)	Useful for rice inference; not automatically Basmati-specific
Crop-wide meta-analysis/review	General crop yield and NUE response; variability by soil, crop, rate and product source	Rose et al. (2014); Ampong et al. (2022); Ma et al. (2024)	Helpful for context; avoid converting average effects into local recommendations
Basmati/fragrant rice context	Basmati/aromatic-rice quality and nutrient-management relevance	Wakte et al. (2017); Jat et al. (2019); Potcho et al. (2021)	Supports rationale; direct humic x Basmati evidence remains limited

3. Physicochemical characterization of humic substances

There are marked differences between humic substances for source, extraction method, pH history, ash content, molecular-size distribution and degree of oxidation. This variation is critical to manuscript quality, because it's hard to compare an agronomic trial that just says "humic acid was applied" without product characterization, with another trial. The safest way to submission is to require each humic material to be described by source, extraction protocol, humic/fulvic fraction content, ash or mineral residue, pH, electrical conductivity, total acidity, carboxyl and phenolic groups and at least one spectroscopic fingerprint. FTIR spectroscopy yields a practical fingerprint of functional groups, including hydroxyl, carboxyl, aromatic C=C, and aliphatic C-H bands. People have used UV-visible indices like E4/E6 in the past to guess about humification and condensation, but they shouldn't be seen as a full structural descriptor (Chen et al., 1977). Potentiometric titration is useful to estimate the number of proton binding sites and the distribution of acidity (Ritchie and Perdue, 2003). NMR-based approaches can differentiate between aromatic, aliphatic and carboxyl carbon environments, whereas the modern supramolecular perspective warns against the interpretation of apparent molecular weight as a fixed polymer size (Piccolo, 2002; Sutton and Sposito, 2005).

Characterization is not a decorative analytical section for Basmati rice research; it is needed for reproducibility. Humic acid derived from leonardite, potassium humate derived from coal, humic fractions from compost and humic substances from vermicompost may be biologically different even when applied at the same nominal mass. As a result, future trials should report both the application rate and active humic fraction, as well as the method of estimating that fraction.

Table 2. Characterization methods that should be reported in humic-substance studies.

Method	What it measures	Why it matters for rice studies	Published support
FTIR spectroscopy	Functional groups such as -OH, C=O, aromatic C=C and aliphatic C-H	Shows whether the material contains functional groups relevant to complexation and soil reactions	Piccolo (2002); Sutton and Sposito (2005)
UV-visible E4/E6 ratio	Relative optical index linked to aromaticity and humification state	Useful as a quick comparative index, but not a full structural proof	Chen et al. (1977)
Potentiometric titration	Total acidity, carboxyl and phenolic acidity, proton-binding behavior	Relevant to pH buffering, CEC and cation complexation	Ritchie and Perdue (2003)
Solid-state or solution NMR	Aromatic, aliphatic, O-alkyl and carboxyl carbon environments	Supports source comparison and interpretation of molecular composition	Piccolo (2002); Sutton and Sposito (2005)
Elemental analysis and ash content	C, H, N, O, S and mineral residue	Identifies dilution by mineral ash and helps compare active organic fraction	Ampong et al. (2022)
Product source and extraction method	Leonardite, lignite, compost, vermicompost, soil-derived extracts; alkaline extraction or other method	Essential for reproducibility and regulatory quality control	Rose et al. (2014); Jindo et al. (2020)

4. Mechanisms relevant to flooded rice soils

Humic substances can influence rice systems via indirect soil mechanisms and direct plant/rhizosphere mechanisms. Indirect effects encompass enhanced surface charge, augmented cation retention, micronutrient complexation, and modified soil aggregation. Direct or semi-direct effects are associated with the stimulation of root growth, activity of membrane H+-ATPase, kinetics of nutrient uptake and changes in plant metabolism (Nardi et al., 2002; Zandonadi et al., 2007; Canellas and Olivares, 2014). These mechanisms are plausible in rice, but they will likely be expressed differently under flooded paddy conditions than under well-aerated upland systems due to the impact of redox gradients on nitrogen form, iron chemistry, microbial communities and organic-matter mobility (Cassman et al., 1998; Fageria and Baligar, 2005).

In flooded rice soil, ammonium is generally the dominant mineral nitrogen form in the reduced layer, whereas nitrate is produced mainly in thin oxidized zones near the floodwater–soil interface and around oxygen-releasing roots (Cassman et al., 1998; Fageria and Baligar, 2005). This system can be influenced by humic substances by complexing cations, modifying pH microenvironments, acting as electron-active organic materials and by affecting microbial enzyme activities. However, in the literature, variable responses depending on humic source, soil pH, salinity, dose and crop stage have been reported, thus mechanism sections should discuss pathways as hypotheses or context-dependent effects rather than as guaranteed outcomes (Rose et al., 2014; Ampong et al., 2022).

The most relevant direct rice evidence comes from studies that demonstrated the capability of humic acid to boost rice nitrogen uptake kinetics and root-system development under controlled conditions (Tavares et al., 2019; Tavares et al., 2021). The findings support a mechanistic rationale for testing humic substances in Basmati rice but do not warrant blanket field recommendations without local agronomic validation.

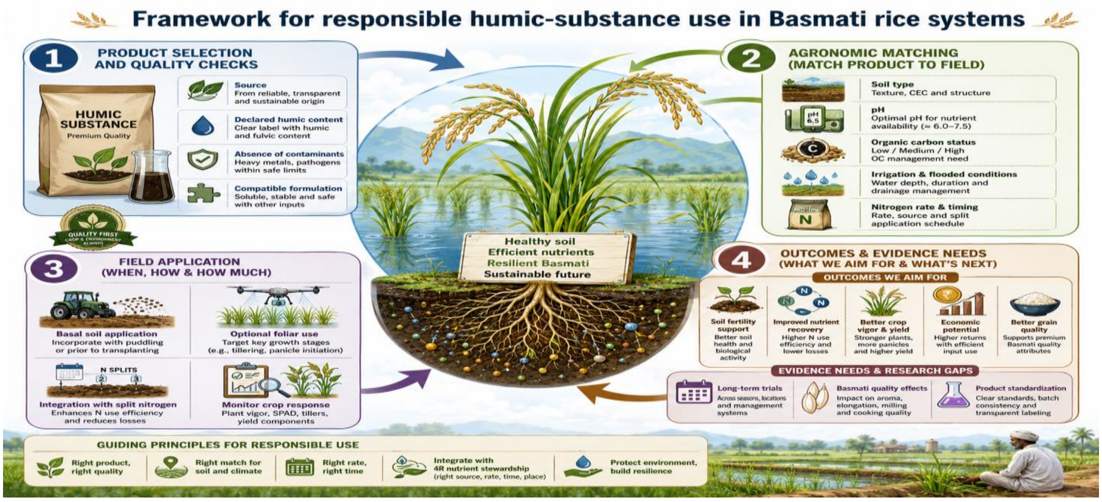

Figure 1. Humic substances: sources, characterization and functional traits relevant to rice systems. Original conceptual figure prepared for this review, synthesizing evidence on humic-substance sources, analytical characterization and core functional traits relevant to soil and plant responses in rice systems (Piccolo, 2002; Sutton and Sposito, 2005; Canellas and Olivares, 2014; Jindo et al., 2020; Ampong et al., 2022).

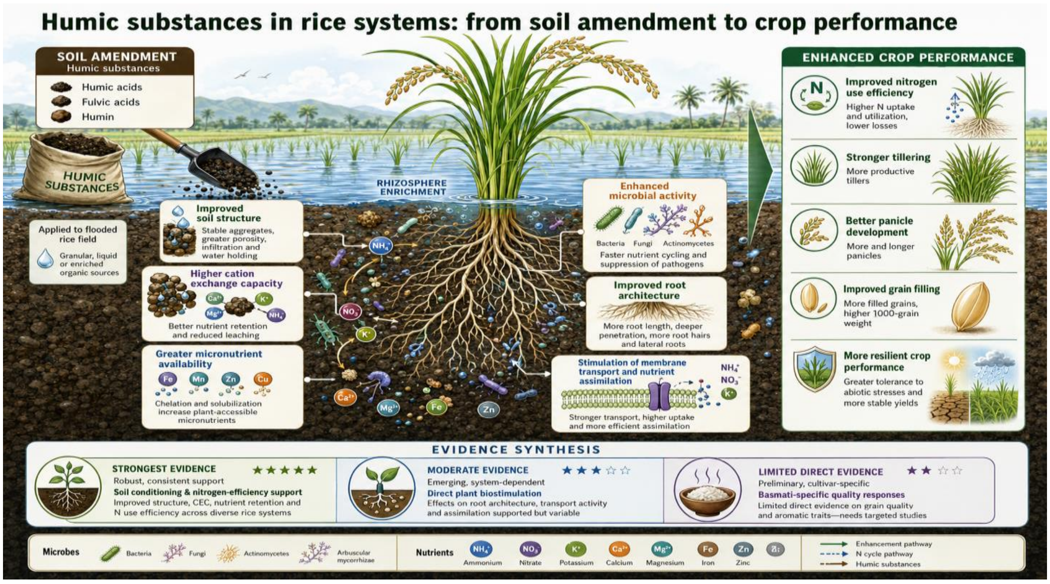

Figure 2. Humic substances in rice systems: from soil amendment to crop performance. Original conceptual figure prepared for this review, summarizing the principal pathways linking humic-substance application with soil conditioning, rhizosphere activity, root development, nutrient uptake and crop performance in rice systems (Nardi et al., 2002; Trevisan et al., 2010; Canellas and Olivares, 2014; Rose et al., 2014; Ampong et al., 2022).

5. Humic substances and nitrogen use efficiency

Nitrogen-use efficiency (NUE) is not a single trait, but is a composite of nitrogen recovery, internal utilization and agronomic output per unit nitrogen applied. The source of fertilizer, when it is applied, the water regime, the texture of the soil, the pH, the amount of organic matter, and the type of rice all have a big effect on NUE (Cassman et al., 1998; Ladha et al., 2005; Fageria and Baligar, 2005). Humic substances can improve the apparent NUE if they increase root uptake, slow some loss pathways or improve the synchrony between nitrogen availability and crop demand. However, they should not be called a primary source of nitrogen unless their contribution of nitrogen is quantified.

Humic-acid urea and humic-acid-based fertilizers have been investigated in crop systems as a strategy to mitigate nitrogen loss and improve crop performance. Kong et al. (2022) indicated enhanced nitrogen use efficiency (NUE) and diminished nitrogen loss in a maize-wheat rotation utilizing humic acid urea, in contrast to conventional urea. Humic acid urea was also studied in a summer maize-winter wheat lysimeter system by Liu et al. (2024). These studies are useful to nitrogen-cycling mechanisms, but they are not rice or basmati studies and so should be cited only as indirect support.

Kumar and Singh (2017) showed that potassium humate with chemical fertilizers affected rice yield and soil nutrient availability for rice. Tavares et al. (2019) assessed humic acid as a biotechnological method to enhance nitrate or ammonium absorption in rice plants, whereas Tavares et al. (2021) simulated the stimulation of the rice root system by humic acid. These studies are consistent with the hypothesis that rice can respond to humic substances via root and nutrient-uptake pathways. There is no universal Basmati dose or guaranteed benefit-cost ratio.

A recent crop-wide meta-analysis reported positive average effects of humic-acid fertilizers on yield, NUE and nitrogen uptake, but also found that responses vary by crop type, soil condition, nitrogen rate and environmental context (Ma et al., 2024). This variability is significant: a review paper should cite such meta-analyses as a justification for further testing, not as a promise of fixed gains to farmers in a particular region.

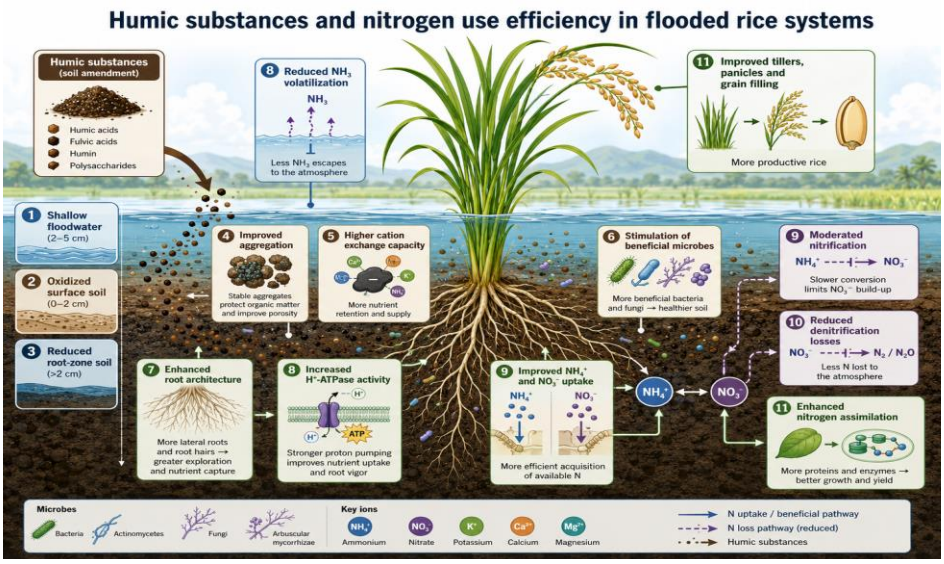

Figure 3. Humic substances and nitrogen use efficiency in flooded rice systems. Original conceptual figure prepared for this review, illustrating plausible interactions between humic substances, ammonium-nitrate dynamics, nitrogen losses, root uptake and nitrogen assimilation under flooded paddy conditions (Cassman et al., 1998; Fageria and Baligar, 2005; Tavares et al., 2019; Tavares et al., 2021; Kong et al., 2022; Ma et al., 2024). The figure is conceptual and does not provide quantitative flux estimates.

Table 3. Published evidence relevant to humic substances, rice and nitrogen cycling.

Source	Experimental scope	Main outcome used here	How it is used safely
Kumar and Singh (2017)	Rice pot experiment using potassium humate with chemical fertilizers	Yield and soil nutrient availability patterns	Direct rice evidence; useful for potassium humate, but not Basmati-specific field evidence
Tavares et al. (2019)	Rice plants under nitrate or ammonium supply with humic-acid treatment	N-NO3- or N-NH4+ uptake and N metabolism	Direct rice physiological evidence
Tavares et al. (2021)	Rice root-system response modeling	Root stimulation and response surface interpretation	Direct rice root evidence
Kong et al. (2022)	Humic acid urea in a maize-wheat rotation	Crop yield, NUE and nitrogen loss compared with urea	Indirect cereal-system support for humic-acid urea mechanisms
Liu et al. (2024)	Humic acid urea in a summer maize-winter wheat lysimeter experiment	Productivity and active nitrogen-loss reduction	Indirect cereal-system support; not rice-specific
Ma et al. (2024)	Meta-analysis of humic-acid fertilizers across crops	Average effects on crop yield, NUE and N uptake	Broad context; responses should not be converted into fixed Basmati recommendations

6. Relevance to Basmati rice systems

The framing of Basmati needs care. Even if a nutrient-management treatment boosts biomass or grain yield in regular rice, Basmati may still need to be tested for quality because the market value depends on the length, elongation, milling quality, aroma, and cooking behavior of the grain. Wakte et al. (2017) reviewed 2-AP as a principal aroma compound in scented rice. Potcho et al. (2021) showed that nitrogen sources can affect 2-AP biosynthesis, cooked-rice elongation and amylose content in rice. The results indicate that in humic acid x nitrogen experiments, it is more appropriate to include grain-quality measurements than only focus on yield.

Jat et al. (2019) provide relevant evidence for the western Indo-Gangetic Plain that nutrient-management options influence productivity, profitability and nutrient dynamics in Basmati rice-wheat systems. However, those works should not be cited as evidence of humic-acid efficacy unless humic substances were part of the tested treatments. Such evidence should be used to demonstrate regional need for integrated nutrient management and economic assessment.

A safe recommendation arising from this review is thus methodological rather than prescriptive: future Basmati rice studies should test humic products only after product characterization, should include multiple nitrogen rates, and should measure both agronomic and quality outcomes. This framing is stronger for journal submission because it acknowledges the evidence gap rather than hiding it behind broad, unsupported claims.

Table 4. Submission-safe practical interpretation and research requirements.

Decision area	Submission-safe statement	Evidence level	Supporting references
Product selection	Require source, HA/FA content, ash, pH, EC and contaminant statement	High for characterization; variable for efficacy	Rose et al. (2014); Jindo et al. (2020); Ampong et al. (2022)
Nitrogen management	Use humic products with balanced N management, not as N substitutes	High for NUE principles; moderate for humic-N mechanisms	Cassman et al. (1998); Ladha et al. (2005); Fageria and Baligar (2005); Tavares et al. (2019)
Basmati quality	Include 2-AP, cooked-grain elongation, milling quality and amylose where possible	High for aromatic-rice quality relevance	Wakte et al. (2017); Potcho et al. (2021)
Economic analysis	Calculate partial budgets from actual local field data and product costs	Conceptual; direct Basmati x humic economics limited	Jat et al. (2019) for regional nutrient-management economics context
Recommendation threshold	Use site-specific recommendations only after multi-season field validation	Strong methodological requirement	Ma et al. (2024); Ampong et al. (2022)

7. Knowledge gaps and future research priorities

The most critical gap is not the lack of humic-acid literature but the absence of well-characterized, replicated and multi-season Basmati-specific studies linking product chemistry, nitrogen recovery, yield, grain quality and farm economics. Without such a link, a manuscript can sound agronomically confident but poorly supported.

Five areas should be priorities for future studies. First, humic products need to be chemically tested before they can be used in farming. Second, factorial field trials should look at the effects of different types of humic sources, rates of humic, rates of nitrogen, and Basmati varieties on local soil and water conditions. Third, we should measure nitrogen dynamics using 15N recovery, mineral nitrogen monitoring, ammonia volatilization, and nitrous oxide measurements when possible. Fourth, Basmati quality traits, specifically 2-AP and cooked grain elongation, should be studied in the context of yield. Fifth, economics should be calculated based on the local response, product quality, product cost, grain quality premium and risk under different market prices.

This research agenda will enable future authors to move from a plausible mechanism-based review to a bona fide recommendation-oriented agronomic paper.

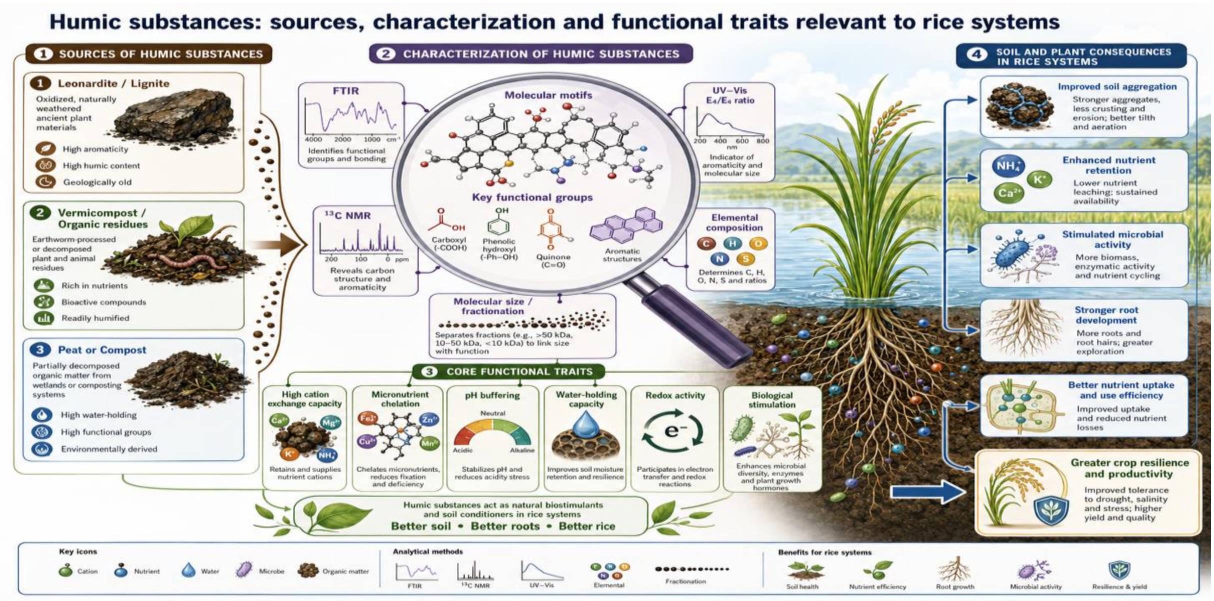

Figure 4. Framework for responsible humic-substance use in Basmati rice systems. Original conceptual figure prepared for this review, showing a validation-oriented framework that links product quality, field matching, application strategy, expected outcomes and research needs for Basmati rice systems (Jat et al., 2019; Wakte et al., 2017; Potcho et al., 2021; Ampong et al., 2022; Ma et al., 2024).

8. Conclusions

Humic substances are a scientifically sound component of soil and plant bio stimulant research, since the functional groups, charge behaviour and biological activity of humic substances can influence nutrient retention, root development and rhizosphere processes. For rice, published studies warrant further investigation of humic acid and potassium humate with respect to root growth, nutrient availability and nitrogen uptake. However, for Basmati rice, the present evidence does not support the making of universal fixed statements such as “10 kg ha-1 humic acid increases yield by a certain percentage” or “humic acid gives a certain benefit-cost ratio” unless these values are derived from local replicated Basmati trials.

Therefore, the best submission-ready message is a balanced and critical one: humic substances are promising amendments for improving the efficiency of nutrient-management programs; however, their performance is product-, soil-, water-, nitrogen-rate- and genotype-dependent. A high-quality Basmati review should emphasize this potential while clearly delineating direct evidence from extrapolation. Such prudent interpretation stands a better chance of passing peer review than a manuscript that oversells unverified regional claims.

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