

SOIL AND RHIZOSPHERE BIOMARKER PANEL FOR ARECANUT (*ARECA CATECHU L.*): INTEGRATING DISEASE RISK, NUTRIENT CYCLING, AND RHIZOSPHERE HEALTH

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ABSTRACT

Arecanut (*Areca catechu L.*) is a high-value perennial plantation crop whose productivity depends strongly on the biological condition of the soil–root interface. Unlike annual crops, arecanut remains exposed to cumulative pathogen pressure, seasonal moisture fluctuations, nutrient depletion and continuous organic-matter inputs throughout its production cycle. Conventional diagnosis based largely on visible symptoms may therefore detect disease or nutritional stress only after substantial physiological damage has occurred. A soil and rhizosphere biomarker approach offers an opportunity to shift arecanut management from symptom-based intervention towards early, system-level assessment. This paper proposes a crop-specific biomarker framework integrating five major dimensions- i) pathogen pressure, ii) beneficial microbial activity, iii) nutrient cycling, iv) abiotic stress tolerance, and v) soil-carbon functioning. Among the disease-associated markers, *Phytophthora* sp. represent a major surveillance target because of their association with root, crown, fruit and bud-rot syndromes, while *Pratylenchus*, *Meloidogyne*, *Rhizoctonia*, *Pythium*, *Sclerotium*, and *Fusarium* provide additional indicators of root and nursery health. Beneficial microbial markers including *Trichoderma*, *Bacillus*, *Streptomyces*, *Azotobacter* and *Paecilomyces lilacinus* provide complementary information on biological suppression, nutrient mobilization and nematode regulation. Functional markers such as T22, BS114, BS181, BS019, BS080, BS008, BS214, BS217, BS265, B43 and BS065 further extend the framework from organism detection to biological processes. The proposed panel provides a multidimensional view of arecanut soil health in which pathogen abundance, nutrient availability, microbial functions, moisture resilience and organic-matter turnover are interpreted together. Its future validation across contrasting soils, seasons and plantation management systems could support development of an Arecanut Rhizosphere Health and Disease Risk Index (ARHDI) for precision nutrient, disease and soil-health management.

KEYWORDS: Arecanut; rhizosphere biomarkers; *Phytophthora*; soil health; nutrient cycling; biological control; disease-risk assessment.

1. INTRODUCTION

Arecanut (*Areca catechu L.*) is a perennial plantation crop cultivated under warm and humid conditions where soil moisture, organic-matter inputs and rhizosphere activity strongly influence palm health. The long production cycle of the crop creates a distinctive soil-plant environment in which pathogens, beneficial microorganisms, nutrients, and environmental stresses interact continuously (Bonanomi et al., 2018). Consequently, visible symptoms alone provide only a partial picture of the biological status of an arecanut plantation. Disease pressure is particularly important in humid arecanut-growing regions. *Phytophthora* represents a major disease-risk group, with *P. cinnamomi*, *P. capsici* and related species associated with root, crown, fruit and bud-rot conditions (Naik et al., 2019). Root-associated nematodes, including *Pratylenchus* and *Meloidogyne*, can further weaken the root system and create opportunities for secondary infection. Nursery pathogens such as *Rhizoctonia solani*, *Pythium aphanidermatum* and *Sclerotium rolfsii* add another layer of risk, particularly during establishment (Mendes et al., 2013). The arecanut biomarker mapping identifies these organisms as the core disease-risk component requiring

early surveillance. At the same time, the arecanut rhizosphere contains microorganisms capable of suppressing pathogens, improving nutrient availability, and supporting plant growth. *Trichoderma harzianum*, *T. asperellum*, *Bacillus subtilis*, *B. amyloliquefaciens*, *B. megaterium*, *B. velezensis*, *Streptomyces* sp., *Azotobacter vinelandii* and *Paecilomyces lilacinus* represent complementary biological functions within the proposed panel. Nutrient management (C, N, P, K, S) represents another important dimension of any crop (Kaviraj et al., 2024; 2025; Parmar et al., 2022; Sahoo et al., 2022). Evidence from different cropping systems further demonstrates that soil nutrient availability, fertilizer management and nutrient-use efficiency are closely linked with crop productivity and the distribution and transformation of nutrients within the soil profile (Kumar et al., 2014; Tuti et al., 2022). Arecanut continuously removes nutrients through repeated nut harvests, while plantation soils may experience phosphorus fixation, nitrogen imbalance, and seasonal moisture stress. The importance of biological and plant-level responses to low phosphorus availability is also evident from studies demonstrating substantial morphological and molecular variation among rice germplasm for tolerance to low-soil-P conditions (Kale et al., 2020; Brajendra & Singh, 2012), highlighting the value of integrating nutrient availability with biological indicators rather than relying exclusively on bulk soil concentrations. Therefore, measuring only soil nutrient concentrations may not adequately capture the biological capacity of the rhizosphere to supply and retain nutrients (Pace et al., 2025). Functional biomarkers can provide an additional layer of information by indicating nitrogen fixation, nitrification, phosphorus solubilization, stress tolerance, biofilm-mediated nutrient retention, and organic-matter decomposition. Such functional approaches are increasingly complemented by time-series analysis and artificial-intelligence-based modelling for characterizing environmental stress, including water-stress prediction (Gorlapalli et al., 2022), while microbiome-based and supervised machine-learning approaches provide a broader methodological basis for developing predictive soil-health indicators (Wallenstein et al., 2022; Pace et al., 2025). The main concept of the present framework is therefore that arecanut soil health should be interpreted as a functional biological state rather than as a collection of individual soil measurements (**Figure 1**). A combination of pathogen, beneficial-microbe, and functional biomarkers could provide an early-warning system capable of distinguishing a biologically resilient plantation from one moving towards disease, nutrient, or moisture stress.

2. Conceptual framework for an Arecanut Biomarker Panel

The proposed biomarker system is organized into five interconnected components-

- Disease-risk biomarkers
- Beneficial microbial biomarkers
- Nutrient-cycling biomarkers
- Stress and water-related biomarkers
- Carbon cycling and soil-remediation biomarkers

The framework follows the principle that no single marker can adequately describe plantation health. Instead, disease pressure should be interpreted together with microbial suppressiveness, nutrient availability, moisture resilience, and organic-matter turnover.

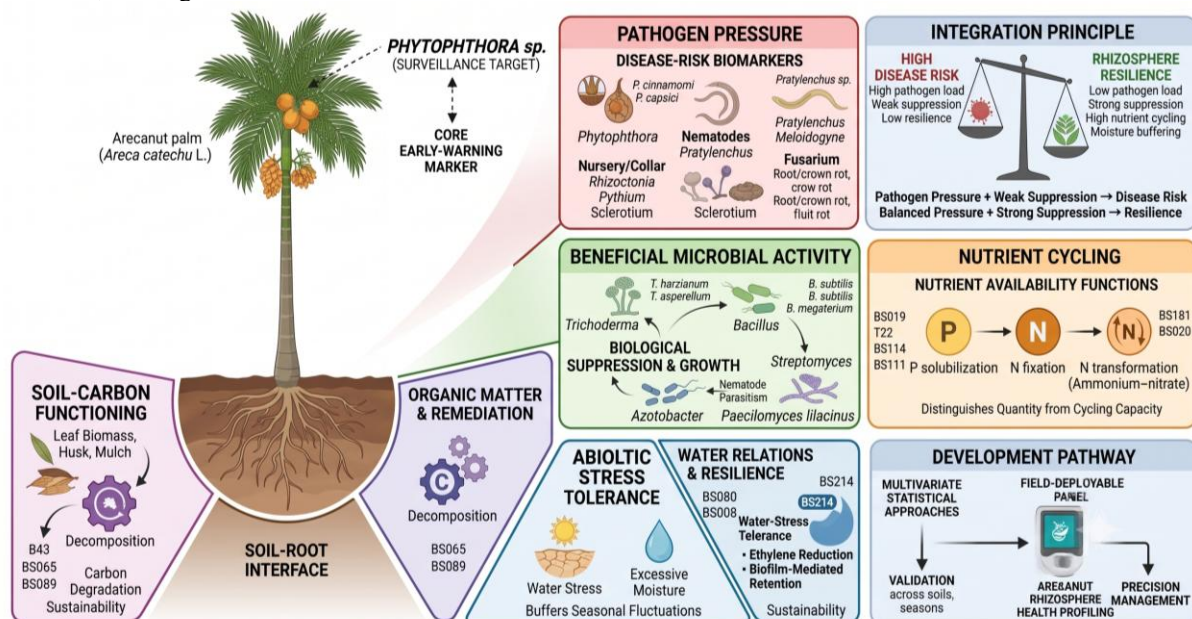


Figure 1. Conceptual framework of the Arecanut Rhizosphere Health and Disease Risk Index (ARHDRI). The schematic illustrates the five core functional dimensions—pathogen surveillance, beneficial biocontrol activity, biological nutrient cycling, moisture/stress buffering, and carbon turnover integrated into a multi-marker balance model to enable early disease-risk prediction and precision soil management in *Areca catechu* plantations.

2.1 Disease-Risk Biomarkers

Phytophthora should constitute the principal disease-surveillance target in the proposed arecanut biomarker system (Table 1). The detection of *P. cinnamomi* and related *Phytophthora* signals in soil, root-zone material or crown debris could provide an early indication of disease pressure, particularly before periods of prolonged rainfall. *P. capsici* and *P. cactorum* provide additional information for genus-level surveillance (Spooren et al., 2024). Root-associated nematodes represent an important secondary component. *Pratylenchus* sp. can damage root tissues and create infection, whereas *Meloidogyne* sp. can interfere with root development and nutrient acquisition (Wallenstei et al., 2022). Nursery-associated pathogens including *R. solani* and *P. aphanidermatum* are particularly relevant during seedling establishment. This framework also includes *Sclerotium rolfsii*, *Fusarium* sp. and *Neopestalotiopsis* sp. as indicators of collar/root disease, root-rot complexes, and foliar or crown disorders, respectively.

Table 1. Priority pathogenic biomarkers for arecanut

Biomarker	Major association	Interpretation
Phytophthora cinnamomi	Root rot, dieback, fruit/bud-rot surveillance	Core early-warning marker for wet-season disease pressure
P. capsici	Crown/fruit rot	Indicator of active oomycete pressure
P. cactorum	Crown/collar rot	Supports Phytophthora risk assessment
Pratylenchus sp.	Root-lesion nematodes	Root injury and secondary infection risk
Meloidogyne sp.	Root-knot nematodes	Root damage and impaired nutrient uptake
Rhizoctonia solani	Nursery damping-off/collar rot	Important seedling-health marker
Pythium aphanidermatum	Damping-off and seedling rot	Indicator of excessive moisture-associated nursery risk
Sclerotium rolfsii	Collar rot	Relevant to seedlings and associated intercrops
Fusarium sp.	Root/crown rot complex	Particularly relevant in stressed or nematode-damaged palms
Neopestalotiopsis sp.	Leaf spot/crown dieback	Indicator of foliar and crown health

The remaining markers in the source library should be treated as situational rather than core arecanut biomarkers, particularly where susceptible intercrops are present. The most useful disease-risk system should combine pathogen detection with functional evidence of suppression. BS217, associated with fungal cell-wall destabilization, and BS265, associated with disruption of fungal cellular metabolism, provide complementary measures of anti-fungal potential. Their combined interpretation could form an Arecanut Rhizosphere Disease-Suppressiveness Index (ARD-SI). A stronger suppressiveness signal by stable or declining pathogen abundance would provide substantially more information than pathogen detection alone. B3 provides a functional indicator associated with bactericidal activity against several bacterial genera, while BS002 reflects resistance of the beneficial community to compounds produced by phytopathogenic bacteria.

The conceptual relationship can therefore be expressed as-

Pathogen pressure + weak microbial suppression → increasing disease risk

whereas,

Balanced pathogen pressure + strong functional suppression → greater rhizosphere resilience

This distinction is particularly important for perennial crops, where complete pathogen exclusion is neither realistic nor necessarily required.

2.2 Beneficial microbial biomarkers and biological suppression

Disease risk cannot be interpreted solely from pathogen abundance. The functional capacity of the rhizosphere to resist pathogen establishment is equally important. *Trichoderma harzianum* and *T. asperellum* represent important fungal biocontrol indicators, particularly in organically amended soil and nursery environments. Similarly, *Bacillus subtilis*, *B. amyloliquefaciens* and *B. velezensis* can contribute to rhizosphere colonization, antagonism and plant-growth promotion. *Bacillus megaterium* is particularly relevant where phosphorus availability is constrained by soil fixation. *Streptomyces griseoviridis* and *S. K61* are especially relevant to nursery health, whereas *Azotobacter vinelandii* provides an indicator of biological nitrogen input. *Paecilomyces lilacinus*, although listed within the original library under pathogen-associated organisms, is functionally important as a nematode egg parasite and therefore fits the biological-control component of the arecanut panel.

Table 2. Beneficial microbial biomarkers relevant to arecanut

Microorganism	Primary function	Relevance
Trichoderma harzianum	Biocontrol/root development	Suppression of Phytophthora, basal rot and nursery pathogens
T. asperellum	Biocontrol/induced resistance	Rhizosphere protection and defence priming

Microorganism	Primary function	Relevance
Bacillus subtilis	Antagonism	Suppression of soil-borne pathogens
B. megaterium	P solubilization	Particularly useful in P-fixing soils
B. amyloliquefaciens	Root colonization/antibiotic production	Feeder-root protection
Azotobacter vinelandii	N fixation	Indicator of biological N contribution
B. velezensisIB32/NC30	Growth promotion/biocontrol	General rhizosphere resilience
Streptomyces sp.	Disease suppression	Nursery and seedling protection
Paecilomyces lilacinus	Nematode egg parasitism	Biological suppression of root-knot and lesion nematodes

An important principle is that microbial abundance alone should not be equated with biological effectiveness. Functional activity provides a stronger indication of whether the rhizosphere is actually expressing disease-suppressive capacity.

2.3 Functional biomarkers of nutrient cycling

The nutrient component of the proposed panel moves beyond conventional soil-test values by examining biological processes controlling nutrient availability. T22 provides a baseline indicator of nitrogen availability, while BS114 and BS181 represent biological nitrogen fixation and regulation of nitrogen-fixation activity, respectively. BS020, BS279 and B357 provide information related to ammonium-nitrate transformation, while BS019 indicates phosphorus-solubilizing capacity.

Table 3. Nutrient-cycling biomarkers for arecanut

Marker	Functional process	Arecanut interpretation
T22	Nitrogen availability	Indicates baseline soil N-supply capacity
BS114	Atmospheric N fixation	Estimates biological N input
BS181	Regulation of N-fixation enzyme	Indicates functional regulation of fixation
BS020/BS279/B357	Ammonium–nitrate conversion	Indicates N transformation and availability
BS019	P solubilization	Particularly relevant to P-fixing acidic soils

The key advantage of this approach is that it distinguishes nutrient quantity from nutrient-cycling capacity. A soil containing adequate total nutrients may still have limited biological availability if microbial transformation and mobilization processes are weak.

2.4 Stress tolerance and water relations

Water is a major determinant of arecanut productivity. The crop requires adequate moisture but is also vulnerable to prolonged water stress and poorly drained conditions. Therefore, water-related biomarkers should be interpreted dynamically across seasons. BS080 represents water-stress tolerance and organic-matter-associated resilience. BS008 reflects stress tolerance through ethylene reduction, whereas BS214 indicates biofilm-associated water retention and nutrient availability around feeder roots.

Table 4. Stress and water-related biomarkers for arecanut

Marker	Function	Interpretation
BS080	Water-stress tolerance	Indicates rhizosphere drought-buffering capacity
BS008	Ethylene reduction/ACC-deaminase-type function	Supports root growth under stress
BS214	Biofilm-mediated water/nutrient retention	Indicates moisture and nutrient stabilization around feeder roots

Together, these indicators could help distinguish a rhizosphere that merely contains moisture from one that possesses biological capacity to buffer seasonal water stress.

2.5 Carbon cycling, organic matter and soil remediation

Arecanut gardens commonly receive continuous inputs of organic material, including leaf biomass, husk and other mulch. Consequently, carbon turnover is a major component of rhizosphere functioning (Parmar et al., 2022; Tuti et al., 2022). B43 and BS065 provide indicators of structural and non-structural sugar degradation and therefore offer a functional measure of organic-matter decomposition. Strong activity would suggest active mineralization of organic inputs, whereas weak activity may indicate slower residue turnover and potential nutrient immobilization. BS089 provides a marker relevant to atmospheric CO₂ sequestration and sustainability assessment. BS202

and BS024 are situational markers for heavy-metal sequestration and degradation of chlorinated compounds and may be incorporated where contamination or intensive agrochemical exposure is a concern.

Table 5. Carbon and soil-quality biomarkers for arecanut

Marker	Function	Arecanut significance
B43/BS065	Carbon degradation and recycling	Indicates decomposition of mulch and organic inputs
BS089	Atmospheric CO ₂ sequestration	Supports carbon and sustainability assessment
BS202/BS024	Metal sequestration/chemical degradation	Useful in contamination-prone plantations

3. Integrating the Biomarkers into an Arecanut Rhizosphere Health Index

The ultimate value of a biomarker panel lies not in generating a large number of measurements but in converting them into an interpretable biological profile. The proposed Arecanut Rhizosphere Health and Disease Risk Index (ARHDRI) could integrate five components-

Disease-risk component: *Phytophthora* spp. + nematode/pathogen abundance

Biological-suppression component: *Trichoderma*, *Bacillus*, *Streptomyces* and functional antifungal markers

Nutrient-cycling component: T22 + BS114 + BS181 + BS019 + N-transformation markers

Stress-resilience component: BS080 + BS008 + BS214

Carbon-function component: B43 + BS065 + BS089

Individual measurements could subsequently be standardized and combined using multivariate statistical approaches. Rather than treating each marker independently, the model should identify combinations that best explain disease pressure, palm vigour, nutrient status and seasonal stress. A high-risk plantation profile would be expected to show elevated pathogen pressure, weak suppressive functions, poor nutrient-cycling capacity and reduced stress resilience. In contrast, a biologically resilient plantation would be characterized by balanced pathogen pressure, active beneficial communities, efficient nutrient transformation, strong antifungal functionality and effective moisture buffering. Importantly, these profiles should be considered hypotheses for validation, not pre-determined diagnostic thresholds.

4. Proposed sampling and validation strategy

A practical validation programme should compare contrasting plantation conditions, including healthy and diseased palms, nursery and mature plantations, different soil types, irrigation regimes and organic-matter management practices.

Sampling should include-

- rhizosphere soil;
- bulk soil;
- feeder-root-associated material;
- crown or collar tissues where disease is suspected;
- nursery substrate where applicable; and
- seasonal samples before and during the major disease period.

Molecular detection of major pathogens can be combined with microbial community profiling, functional-gene analysis, enzyme assays and conventional soil testing. Disease observations should be recorded simultaneously so that biomarker signals can be related to actual disease development. The most informative markers should then be reduced to a minimal field-deployable panel. Independent validation across seasons and locations would be essential before establishing diagnostic thresholds.

5. Practical and realtime significance

The proposed biomarker framework offers three important shifts in arecanut management. First, it moves disease surveillance from symptom detection to early biological warning. Detection of pathogen pressure before extensive tissue damage could provide a window for timely intervention. Second, it changes soil testing from a predominantly chemical assessment to a functional assessment of the rhizosphere. Nutrient availability, microbial activity, stress tolerance, and carbon turnover can be interpreted together rather than as isolated measurements.

Third, it provides a basis for precision biological management. A plantation showing strong pathogen pressure but weak suppressive activity may require biological intervention, whereas a plantation with adequate nutrient-cycling and suppressive capacity may require a different management response. The approach is particularly suited to arecanut because the perennial nature of the crop allows repeated monitoring of the same soil-root system over multiple seasons.

6. Future perspectives and Conclusion

The proposed soil and rhizosphere biomarker framework provides a conceptual foundation for understanding arecanut health as an outcome of continuous interactions among pathogens, beneficial microorganisms, nutrient-cycling processes, soil organic matter, and seasonal water availability. The next critical step is rigorous field validation of the proposed biomarkers against independently measured disease severity, palm growth, nutrient status and yield across contrasting soil and management conditions. Integration of high-throughput sequencing,

quantitative PCR, functional metagenomics and metabolomics could further strengthen the resolution of the framework by linking microbial community structure with functional activity and plant performance. With the accumulation of validated datasets, machine-learning approaches could be explored to identify a smaller and biologically meaningful combination of biomarkers capable of characterizing disease risk, nutrient constraints and overall rhizosphere health. Such predictive models should, however, emphasize biological interpretability, robustness and field applicability rather than simply increasing the number of detectable variables. In the longer term, these developments could support portable diagnostic platforms that combine a limited set of molecular, functional and biochemical indicators to generate plantation-level rhizosphere health profiles. This would represent a shift from conventional, largely static soil testing towards a more dynamic and biologically informed approach to perennial plantation management.

Declaration of competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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