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Managing transboundary banana blood disease through a resilience-based biosecurity framework in East Nusa Tenggara, Indonesia

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Abstract. *Nampa IW, Mudita IW, Widinugraheni S. 2025. Managing transboundary banana blood disease through a resilience-based biosecurity framework in East Nusa Tenggara, Indonesia. Intl J Trop Drylands 9: 120-134.* Banana Blood Disease (BBD), caused by *Ralstonia syzygii* subsp. *celebesensis* has become a critical threat to banana production in Indonesia's dryland archipelago of East Nusa Tenggara (ENT). The fragile socio-ecological systems in this region exacerbate the impacts of biological invasions, necessitating a paradigm shift in biosecurity. This study, a comprehensive effort that combined field surveys, stakeholder interviews, PCR-based pathogen detection, statistical analysis, and policy assessment, was conducted to identify the drivers of management failure and propose an alternative framework. These findings showed that the nationally mandated Integrated Pest Management (IPM) approach, which is reactive and focused on post-incursion responses, was unable to contain the rapid spread of this transboundary pathogen. The result has been catastrophic yield reductions of up to 65% and estimated annual economic losses exceeding IDR 4.61 trillion, alongside severe impacts on household food security, livestock systems, and rural livelihoods. Critical weaknesses were identified in Indonesia's biosecurity governance, including fragmented policies, weak coordination across sectors, insufficient early surveillance, and the absence of effective controls on the movement of infected planting material. To address these systemic gaps, this study advocated for a paradigm shift toward a resilience-based biosecurity framework that is polycentric, adaptive, and multi-scalar. The proposed framework integrates pre-border, border, and post-border measures, empowers community-led surveillance and response, and strengthens linkages between local practices and national regulatory systems. By embedding socio-ecological resilience into crop protection governance, the framework offers a pathway to safeguard banana biodiversity, protect smallholder livelihoods, and promote sustainable agriculture across ENT's vulnerable drylands.

Keywords: Banana Blood Disease, East Nusa Tenggara, polycentric and adaptive governance, resilience-based biosecurity framework, transboundary plant pathogen

INTRODUCTION

The globalization of agricultural trade and intensified human mobility have accelerated the spread of transboundary plant diseases worldwide, placing increasing stress on fragile agro-ecosystems. Climatic variability, land degradation, and ecosystem disruption further amplify the vulnerability of agricultural systems to biological invasions, making conventional pest management approaches insufficient for current challenges (Findlater and Bogoch 2018; Guo et al. 2022; Prajapati et al. 2024). This insufficiency underscores the need for a paradigm shift from reactive Integrated Pest Management (IPM) toward integrated biosecurity is essential. Biosecurity, defined as "strategic and integrated policy instruments assessing and controlling risks to plant life/health and associated environmental risks" (FAO 2007; Renault et al. 2022), provides a proactive approach that spans pre-border, border, and post-border actions. Unlike compartmentalized crop protection, biosecurity encompasses surveillance, quarantine, certification, and mitigation measures, with proven effectiveness in regions such as Australia and New Zealand (Falk et al. 2011; Arndt et al. 2024).

This global challenge is particularly acute in dryland ecosystems, areas defined by UNEP-WCMC (2007) as having an aridity index (AI) ≤0.65. East Nusa Tenggara (ENT), one of Indonesia's most vulnerable provinces, is typified by poor soils, irregular water supply, and dissected topography (Fu and Stafford-Smith 2024). Increasing aridity under climate warming intensifies the ecological susceptibility of ENT's agricultural systems (Lian et al. 2021). Despite these constraints, ENT supports drought-resilient crops such as banana, which plays a central role in household food security, nutrition, and livelihoods (Drenth et al. 2018; Mudita and Benu 2018; Nampa et al. 2022). The province's geographic proximity to Australia and Timor-Leste, coupled with growing inter-island trade and travel, exposes it to heightened risks of biological invasions. Banana Blood Disease (BBD), caused by *Ralstonia syzygii* subsp. *celebesensis* represents a pressing example of a transboundary pathogen that capitalizes on these vulnerabilities (Ray et al. 2021, 2022).

The devastating impacts of BBD highlight both ecological and institutional weaknesses. First reported in Indonesia in the early twentieth century, the disease has re-emerged as a major constraint, severely reducing banana yields and threatening smallholder livelihoods (Safni et al.

2014; Prior et al. 2016). In ENT, BBD was first detected on Sumba around 2010, before spreading to Flores by 2022, causing incidence rates of up to 44% in some districts (Mudita et al. 2018; Nampa et al. 2022; Hahuly et al. 2025). Economic impacts have been severe, with losses exceeding IDR 25 million per hectare annually and regional yield reductions surpassing 65% (Nampa et al. 2025). The collapse of banana production undermines food and feed security, erodes rural incomes, and reduces biodiversity, while the misuse of pesticides has disrupted pollinator and soil microbial communities (Hadiwiyono et al. 2007). This trajectory exemplifies how a transboundary pathogen can destabilize social and ecological systems, especially in regions already facing climate and economic pressure.

A major factor behind this failure is Indonesia's continued reliance on IPM as the dominant crop protection paradigm under Law No. 22 of 2019. IPM is inherently reactive, initiating measures only after outbreaks occur, and it fails to address the epidemiology of BBD. Its shortcomings include neglect of pre-border surveillance and inter-island quarantine, inadequate cross-sector coordination, and the absence of certified pathogen-free planting material (Mudita and Benu 2018; Ray et al. 2022). As a result, control efforts have been fragmented, delayed, and ultimately ineffective, allowing BBD to spread unchecked. This has led to significant economic losses and threatens food security, highlighting the urgent need for a shift from reactive to anticipatory measures. This demonstrates a clear misalignment between the reactive IPM framework and the anticipatory measures needed to combat transboundary bacterial wilt pathogens.

The persistence of this gap underscores the urgency of shifting toward a resilience-based biosecurity system tailored to the socio-ecological realities of ENT's drylands. Such a framework must integrate proactive surveillance, internal quarantine, certification systems, and farmer participation within a multi-level governance structure (FAO 2007; Grafton et al. 2019). It must also account for local contexts, including smallholder livelihood dependence, indigenous knowledge, and the socio-cultural dimensions of dryland agro-ecosystems (Wilbanks and Kates 1999; Noywuli et al. 2024). By strengthening resilience, such a system would enable communities to anticipate, absorb, and adapt to biological shocks, while improving coordination across agricultural, environmental, and trade sectors (Arndt et al. 2024; Henry and Ramirez-Marquez 2012).

The study aimed to develop a comprehensive and systemic biosecurity model tailored to ENT's dryland environment that enhances socio-ecological resilience against BBD. Specifically, the objectives were: (i) to assess the agro-ecological factors and multidimensional impacts of BBD through field surveys, molecular diagnostics, and economic analysis; (ii) to identify institutional gaps in current biosecurity governance by examining policy fragmentation, coordination issues, and technical capacity limitations; and (iii) to design a scalable resilience-based framework that combines pre-border surveillance, border quarantine, and post-border community actions with engagement from stakeholder participations.

MATERIALS AND METHODS

Study site and timing

This study employed a longitudinal, multi-site design to trace the progression and impact of BBD across two major islands in East Nusa Tenggara Province, Indonesia: Sumba and Flores (Figure 1). Surveys were first initiated on Sumba Island in 2019 following the initial reported outbreak of BBD there (Mudita and Benu 2018). This site served as a baseline to understand the disease's established socio-economic and agronomic impacts. Subsequent surveys were then conducted on Flores Island in 2023 in direct response to the disease's recent invasion, which was first officially reported in mid-2022 (Jejak Flores 2022; Pos Kupang 2022).

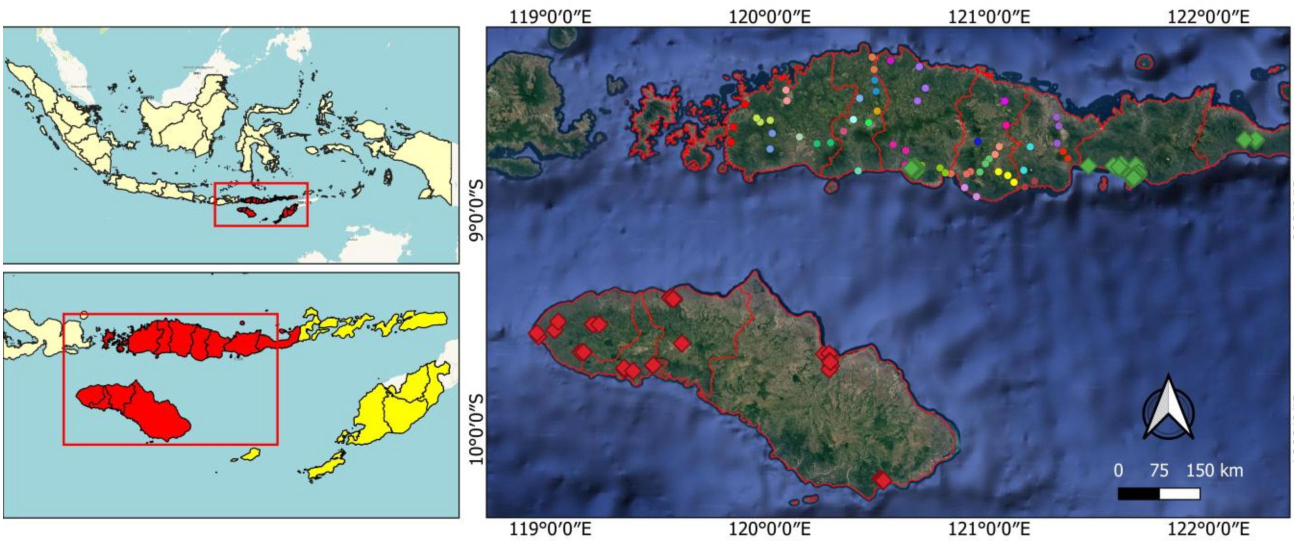

Figure 1. Consolidated sites for data collection, Sumba Island and Flores Island in East Nusa Tenggara Province, Indonesia. Different icon colors indicate different sampled sub-districts in each surveyed district (Note: ●: Aesesa, ●: Aimere, ●: Bajawa, ●: North Bajawa, ●: Boawae, ●: Boleng, ●: Borong, ●: Cibal, ●: Golewa, ●: Inerie, ●: Komodo, ●: Kota Komba, ●: Lamba Leda, ●: Langke Rembong, ●: Lelak, ●: Lembor, ●: Mauponggo, ●: Mbeliling, ●: Nangaroro, ●: North Rahong, ●: Reok, ●: Riung, ●: Ruteng, ●: Sambi Rampas, ●: Sano Nggoang, ●: Satar Mese, ●: Soa, ●: Wae Rii, ●: Welak, ●: Wolomeze, ◆: Non BDB, ◆: BDB) —source: Georeferenced Site Data (2019, 2023)

The survey conducted in 2023 at flores island was focused on measuring the incidence of the disease on ABB 'Pisang Kepok' and ‘Pisang Klutuk’ cultivars in the central and western parts of the island, as well as identifying the pathogen, its means of transmission, and the governance of the local government responses. Meanwhile, the surveys conducted in 2019 in Sumba Island and 2023 in Flores Island were focused on evaluating the economic values of the banana and the potential loss caused by the disease in the eastern and central parts of the island. The chronological sequence of the surveys—from Sumba to Flores—was a deliberate design feature that mirrors the documented eastward trajectory of BBD in Sumba Island and then northward spread to Flores Island. This approach allowed for a comparative analysis of the disease's immediate incursion phase in Flores against its more entrenched status in Sumba, providing critical insights into the epidemiological progression of the pathogen and the evolving effectiveness of management responses over time and geography, with significant implications for future study and management strategies.

Data collection and research design

Data collection in this study was carried out through a series of longitudinal interviews and field observation surveys. The study started with interviews and field surveys on Sumba Island, aimed at determining the initial incidence rate, pattern of BBD spread, and the eventual socio-economic impacts of the disease on communities after the outbreak. For the detailed economic implications, conducted a subsequent series of interview surveys in eastern and central Flores to specifically assess the economic value of the banana industry and estimate losses caused by the disease. To support this economic emphasis, a simultaneous field survey along with in-depth interviews in central and west Flores focused entirely on etiological, agro-ecological, and policy aspects, including disease occurrence and spread, disease diagnosis and pathogen identification, disease progression, and government policy responses taken by the sub-district levels. Covering this array of different facets in a multi-pronged approach provided a complete picture of the impacts of BBD from the angle of a low-level agro-economic perspective and broader bio-security policy frameworks.

The sampling design for this study was a collaborative effort, employing a multi-stage, purposive approach (Ramanujan et al. 2022). It was initiated through consultations with district agricultural service officials, a crucial step that ensured the study's local knowledge and expertise. These consultations helped to identify villages with confirmed BBD reports and to document policy responses. For the surveys conducted in 2019 in Sumba Island, accessible villages along inter-district roads reporting BBD outbreaks were selected for assessment. Within these villages, sampling was conducted opportunistically by stopping at locations where symptomatic banana clumps were visible. At each site, disease incidence was quantified, a structured interview with the landowner was administered, and geographic coordinates were recorded, with all data captured digitally using the KoboToolbox platform (Nampa et al. 2020). Meanwhile, for the survey focused on evaluating the economic value and the potential loss conducted in Flores Island, samples were taken in purposefully selected sub-districts representing high, medium, and low disease strata, also after consulting the district agricultural service officials. In each selected sub-district, samples were taken opportunistically at different altitudes. In contrast, the survey focusing on measuring the incidence of the deseases utilized a more stratified methodology. Following in-depth interviews with agricultural officials, three sub-districts in each district were purposively selected to represent high, medium, and low disease strata. From each sub-district, three accessible villages were chosen, and within each village, three to five fixed sites along village roads were assessed. Data collection in this survey, including disease incidence measurements, GPS coordinates, and qualitative interview responses, was recorded manually. Across all sites, disease incidence was consistently calculated as the percentage of symptomatic individuals relative to the total number of plants within each sampled clump.

In addition to primary field data collection, a comprehensive literature review formed an integral component of the design of this study. Secondary data were systemically sourced from articles in scientific journals discussing the global origin, transmission, and epidemiology of BBD, in conjunction with Indonesian policy sources on plant protection (e.g., Law No. 22 of 2019) and global guidelines on the implementation of biosecurity (e.g., FAO Biosecurity Toolkit 2007). The overall study utilized a sequential exploratory mixed-methods design (Creswell and Plano Clark 2017), with a marked feature of discrete but repeated iterations in the different phases of study execution. The procedure began with a first literature review in laying the theoretical groundwork that followed the sequential acquisition of qualitative (e.g., in-depth interviews of agricultural officials) and quantitative data (e.g., structured surveys of farmers and disease assessments). A final, synthesizing literature review was then conducted after field data analysis to frame the empirical results in the body of existing scholarship and policy literature. Such a design created the opportunity for the qualitative results to inform the quantitative study, with the entire study procedure framed and refined through the incorporation of the secondary sources.

Data analysis

Data analysis in the current study employed a mixed-methods approach to gain a synoptic understanding of the research problem. Qualitative data from field interviews and literature reviews were coded systematically and subjected to thematic analysis using the NVivo 14 software in line with the six-phase procedure specified by Braun and Clarke (2022). Meanwhile, the quantitative data--for example, disease incidence and economic indicators--were tabulated in Microsoft Excel and statistically examined using the R software environment (Hothorn and Everitt 2014) in order to carry out descriptive and inferential statistics. In order to reveal the geographical evolution of

BBD, all of the georeferenced incidence data were spatially represented and mapped in the Google Earth software in order to reveal the spatial pattern and dynamics of the disease (Visser et al. 2014; Retkute and Gilligan 2025). Finally, a methodological triangulation combined the results from the qualitative thematic analysis, the quantitative statistical analysis, and the inferred themes from the secondary literature (Flick 2018) to strengthen and deepen the trustworthiness of the findings. This integrative approach ensured that the empirical results remained aligned with the broader scholarly and policy discussions on plant disease management and biosecurity.

RESULTS AND DISCUSSION

Agro-ecological aspects and multidimensional impacts of BBD

Bananas are a central feature of the dryland agricultural systems in the islands of Sumba and Flores in Indonesia, where produced in a diverse and complex manner. Almost every household yard (*pekarangan*) on both islands is involved in banana production. This home garden production of bananas is most prominent in Sumba, particularly in areas where open grasslands are used for free-grazing livestock in the landscape. On more consolidated agricultural land on both islands, bananas are also produced in a mixed agroforestry system with a variety of fruit trees and perennial cash crops interspersed with banana clumps. Thematic analysis of in-depth interviewing disclosed that the main historical function of banana production was to contribute to household food and feed security (Table 1). However, a significant shift in function occurred. With rising market demand for bananas triggered by massive production losses from the severe disease Fusarium wilt (*Fusarium oxysporum* f. sp. *cubense*) and, more recently, BBD in the islands of Java and subsequently in Bali, bananas from Sumba and Flores are pulled into commercial trade circuits. This shift has upgraded the status of bananas from a staple underpinning food security to a critical item in the household economy (Damayanti et al. 2021; Vellema et al. 2021).

The incidence, etiology, spread trajectory, and impact of BBD on Sumba Island have been reported by Mudita and Benu (2018), Ray et al. (2021), and Nampa et al. (2022). Ray et al. (2021) verified the identity of the banana disease in Sumba Island as BBD and suggested its first introduction to the island around the year 2010. Previously, a disease diagnosed by disease symptoms and pathogen signs typical of BBD was observed to have wiped out Musa ABB 'Pisang Kepok' in the Southwest Sumba District by the year 2016 (Bore 2016; Henci 2016), though it had not yet spread to the island's three other districts (West, Central, and East Sumba) at that time. Nonetheless, in subsequent surveys, Nampa et al. (2020) showed that BBD had extended to East Sumba District, presenting a clear west-to-east pattern of eastward dispersal of the pathogen across the island. Long-distance dispersal of BBD has been described by Ray et al. (2021) to follow an arbitrary, indicative pattern aligned with the movement of infected banana plant material by humans. Conversely, since short-distance and local spread reveals a circular pattern from the source of the first infection, it has been interpreted to involve the activity of transmission agents like insects, birds, and nectar-feeding bats, in addition to other probable transmission through diseased tools, water, or soil (Ray et al. 2021; Molina et al. 2020).

Table 1. Comparative themes on banana cultivation and utilization practices on Sumba and Flores Islands

Second-level theme	First-level theme	
	Sumba Island	Flores Island
Sites of Cultivation	Predominantly confined to homegardens due to free-grazing livestock, with outer-yard planting requiring protective fencing.	Cultivation occurs in both homegardens and mixed agroforestry systems intercropped with cash crops.
Common Cultivars	Dominated by the cultivar 'Pisang Kepok' (called Marmi), with rare cultivation of other dessert types.	'Pisang Kepok' is dominant, but is supplemented by a wider diversity of other dessert and cooking cultivars.
Use as a Staple Food	Serves as a critical dietary staple and caloric substitute for rice, especially during periods of shortage.	Primarily consumed as a fresh fruit, utilization as a staple is occasional and geographically specific to lean seasons.
Other Uses (By-products)	Pseudostems are repurposed as livestock feed and an emergency water source for cattle; the inflorescence is consumed as a vegetable.	Pseudostems are processed into livestock feed; the inflorescence is used as a vegetable and for commercial sale.
Use as a Source of Income	The recent transition from subsistence to commercial production, driven by external demand from off-island traders.	Nascent integration into commercial value chains, with traders sourcing for export to major Indonesian markets.

Source: Thematic Analysis of Interview data (2017 for Sumba Island, 2023 for Flores Island)

Initial reports of BBD on Flores Island emerged in 2022, although media coverage exhibited inconsistencies regarding the disease's etiology, initial point of entry, and the primary agents responsible for its dissemination (Table 2). Despite scientific consensus identifying the causative agent as the bacterium *Ralstonia solanacearum* subsp. *celebesensis* (commonly referred to as the Blood Disease Bacterium or BDB), certain media sources erroneously attributed the disease to a viral pathogen (Flores Editorial 2022; Viral NTT 2025). Similarly, discrepancies were noted in reports identifying the first affected location, with some sources citing East Manggarai Regency and others Ende Regency; however, accounts were consistent in describing a westward and eastward trajectory from its first entry point in the island (Pos Kupang 2022; Ekoran NTT 2023). Regarding transmission vectors, widespread reporting indicated that the primary mechanism of spread was the use of contaminated harvesting tools (e.g., machetes or parangs) by traders hiring local farmers during fruit harvesting (Floresa 2024; Mongabay Indonesia 2024). In-depth interviews with agricultural department officials revealed that BBD was first officially reported in Borong, East Manggarai Regency, though the exact cause was initially pending laboratory confirmation. It was hypothesized that the pathogen may have entered the island through the maritime port of Aimere in Ngada Regency (Table 3). Table 3 also shows that farmers and traders largely lacked awareness of the disease's cause and transmission dynamics, mainly due to insufficient official outreach and information.

Based on comprehensive field observations and molecular diagnostics conducted across multiple districts in the central and western parts of Flores Island, BBD presents a complex array of diagnostic symptoms and pathogen signs, particularly evident in susceptible cultivars (Figure 2). While several cultivars, including Pisang Ambon, Pisang Barangan, Pisang Cavendish, Pisang Raja, and Pisang Tembaga, were affected, Musa ABB 'Pisang Kepok' and 'Pisang Klutuk' experienced the most severe destruction, with the highest disease incidence observed in East Manggarai and Ngada districts. The disease initially manifests through foliar symptoms including hanging, broken leaves typically beginning in younger ones (Figure 2.A), progressive yellowing and drying along leaf margins (Figure 2.H), and asymmetric sucker developments (Figure 2.I). Vascular discoloration appears as characteristic reddish-brown streaks and spots in leaf sheaths visible in both longitudinal and transverse sections of the pseudostem (Figures 2.B-2.E). Advanced infection leads to pseudostem necrosis with mature leaf petioles showing brown rotting before breaking (Figure 2.F) and brown decay along the grooves of suckers' petioles (Figure 2.G). The most distinctive disease symptoms appear in reproductive tissues: fruit bunches exhibit reddish-brown streaking on peduncles (Figure 2.K), while pathogen signs manifest as externally healthy fruits that conceal advanced internal decay ranging from light brown to dark brown with reddish-brown mucoid exudate in severely infected fruits (Figure 2.L-2.O). The disease also affects male buds, showing reddish-brown streaks on oblique sections of the flower stalk (Figure 2.P) and decaying brown spots on transverse sections of the rotting bud (Figure 2.Q). The PCR using the BDB-specific primer pair 121F/121R that produces a 317-bp amplicon validated the occurrence of *R. solanacearum* subsp. *celebesensis* in 22 of the sampled sites where symptomatic expression was observed (Figure 2.R). The spatial pattern of disease incidence of the affected sites (Figure 3) indicated that the disease spread along the inter-district road, moving westward initially and later eastward. The appearance of disease symptoms and pathogen signs illustrates the systemic spread of the pathogen and its destructive capacity throughout the entire plant tissue. At the same time, its spatial pattern of incidences explains the epidemiological pattern of transmission of the pathogen across the island.

Table 2. Spatiotemporal spread, etiology, and themes of BBD on Flores Island as documented in online news media (2022-2025)

Year	Site	District	Pathogen	Theme	Source
2022	Borong area	East Manggarai	Bacterium	Human movement of infected material; contaminated tools	Pos Kupang (2022)
2022	Bamo	East Manggarai	Bacterium	Not specified	Suara Buruh (2022)
2022	Not specified	East Manggarai	Incorrectly reported as a virus	Not specified	Flores Editorial (2022)
2023	Various	West Manggarai	Bacterium	Suspected insect vectors and human activity	Victory News (2023)
2023	Various	Ngada	Bacterium	Human-mediated spread (tools, seedlings)	Ekoran NTT (2023)
2024	Nangalimang, Hoba	Sikka	Bacterium	Contaminated tools (parangs); insects	Mongabay Indonesia (2024); Floresa (2024)
2024	Warupele 1	Aimere (Ngada)	Bacterium	Not specified	Suara Flores (2024)
2024	16 sub-districts	Ende	Bacterium	General spread from neighboring regions	Flores Pos (2024)
2024	Various	Nagekeo	Bacterium	Lack of effective containment measures	Ekoran NTT (2024)
2025	Various	Ende	Bacterium	Persistent environmental presence	Flores Pos (2025)
2025	Not specified	Sikka	Incorrectly reported as a virus	Not specified	Viral NTT (2025)

Source: Thematic analysis of online media content (2023)

Table 3. Comparative perceptions regarding BBD introduction and spread across stakeholder groups in the central and western parts of Flores Island

Second-level theme	**First level-theme**		
	District agriculture officers	**Banana traders**	**Farmers**
Initial Disease Identification and Verification	Official confirmation of the first outbreak was established through field verification following community reports, correcting misattributed initial locations.	Initial awareness of the disease arose from direct encounters with unmarketable, symptomatic fruit, though specific details were not formally recorded.	First-hand observation of disease incidence began at a highly localized level (individual gardens), before the pathogen spread to surrounding areas.
Hypothesized Initial Pathogen Entry Point	Epidemiological tracing points to the introduction of the pathogen through contaminated goods via a major inter-island maritime port.	Anecdotal information suggests the pathogen originated from an external source and was introduced through existing agricultural trade routes.	A significant knowledge gap exists regarding the origin of the pathogen due to a lack of formal communication and extension services.
Perceived Primary Vectors of Pathogen Spread	Human activity, specifically the use of contaminated tools during harvest, is the suspected primary vector, while insect transmission remains a secondary, unconfirmed risk.	Harvesting practices that involve external labor using their own or provided tools are recognized as a potential pathway for pathogen dissemination.	The mechanisms of spread are not understood, with symptoms recognized only by their severe and visible final presentation (e.g., internal rot and oozing).
Perceived Rate of Disease Spread	The pathogen exhibited a rapid rate of spread, with official reports confirming new infections across multiple sub-districts within a week of initial detection.	The disease progression was perceived as exceptionally rapid, with simultaneous emergence of symptoms across multiple villages, suggesting multiple infection points.	The spread was perceived as alarmingly fast, moving from single-garden infections to area-wide infestation within one week.
Understanding of Disease Spread Trajectory	Official monitoring documented a clear spatial trajectory of spread from the initial epicenter to adjacent western regencies, with limited initial data from eastern regions.	Understanding of the geographical spread is limited and focused on the practical challenge of identifying latent infections in apparently healthy fruit.	The geographical direction and pattern of the disease's spread are unknown, with its arrival perceived as sudden and unexplained within the community.

Source: Thematic Analysis of In-depth Interview Data (2023 for Flores Island)

Table 4. Result of paired sample T-Test of farmers' income before and after BDB outbreaks

Condition	**Income**	**StDev**	**T-calculated**	**T-table**	**Significance**
Before BBB (IDR/ha/year)	38,585,513.04	29,705,675.25	7.16	1.67	0.00
After BBB (IDR/ha/year)	13,453,214.49	6,087,927.80			
Decrease (IDR/ha/year)	25,132,298.55	29,159,452.01			
Decrease (%)	65.00				

Source: Statistical Analysis of Survey Data (2019, 2023)

The epidemic of BBD in ENT has caused deep and multifaceted consequences, wiping out rural economies, jeopardizing food security, and disrupting socio-ecological systems on a significant scale. At the economic level, the pathogen decreased banana production in Sumba Island, especially in East Sumba District, since 2018 (Figure 4.A). In Flores Island since 2022, except for Sikka District since 2020, for an unknown cause (Figure 4.B). The widespread presence of banana clumps exhibiting BBD symptoms along the inter-district road was noted (Figure 4.C), concurrently with the continued transit of trailers laden with banana bunches (Figure 4.D), indicating a potential disconnect between disease observation and biosecurity risk management. Statistical analysis showed that BBD wrought disastrous losses for smallholder producers; a paired sample t-test resulted in a statistically significant ($p < 0.001$) 65% reduction in annual revenue per hectare, crashing from IDR 38.6 million to IDR 13.5 million upon BBD infestation (Table 4), consistent with results from Sumba Island, where production reduction of 60-90% translated into estimated district-level losses of USD 0.5 to 3.7 million (Mudita et al. 2018). However, the consequences go far beyond loss of livelihoods and income. By being a linchpin of dryland agro-ecosystems, the devastation of Musa ABB 'Pisang Kepok' —an indispensable cultivar for subsistence and cash crops— disproportionately jeopardizes household food security for the 26.6% of producers depending on it as a staple food source, while also engendering severe shortages of banana stem livestock fodder, hence compromising integrated farming systems (Nampa et al. 2022). The local emergency echoes the national losses, where BBD has rendered 27-80% of land in primary production areas such as South Sulawesi and Lampung unproductive, at an estimated loss of USD 1 million in export (Vos et al. 2020). The crisis reveals a strategic vulnerability: the future spread of BBD, exacerbated by the threat of the other destructive Fusarium wilt Tropical Race 4 (TR4), risks initiating a cascade failure in regional food systems. This highlights that BBD is more than a phytopathological phenomenon but a multifaceted socio-ecological disaster deserving of a holistic biosecurity approach to protect livelihoods, nutrition, and ecological integrity, particularly in NTT's vulnerable dryland ecosystems.

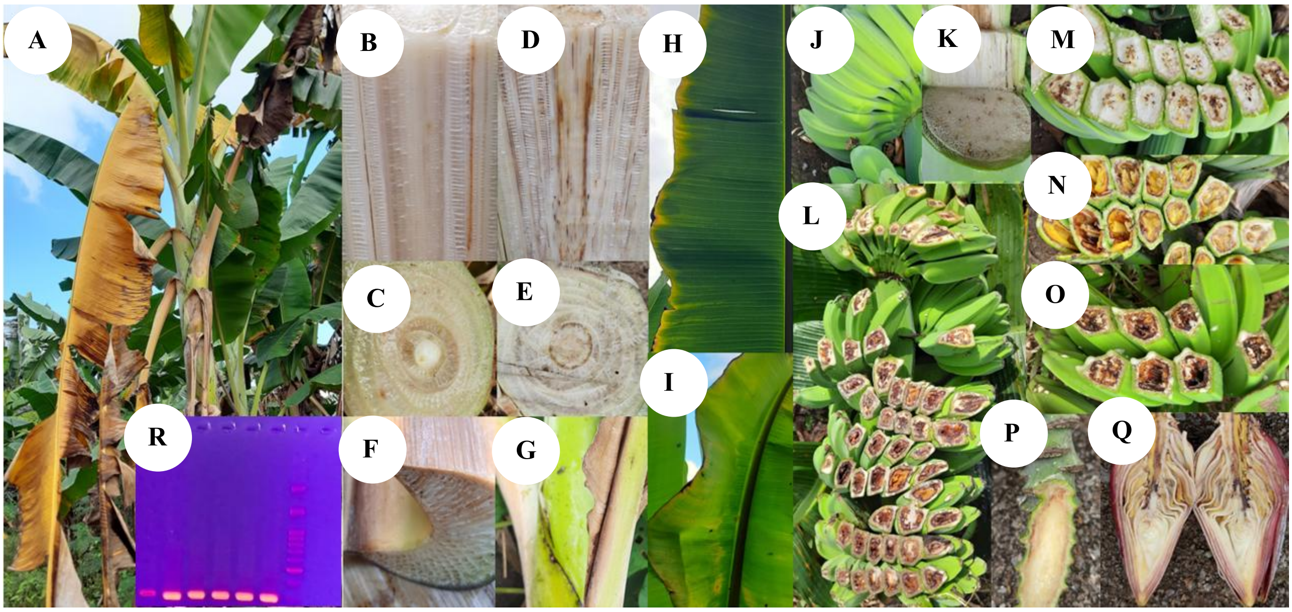

Figure 2. Disease symptoms and pathogen signs of BBD observed in Musa ABB 'Pisang Kepok' across the West Manggarai, Manggarai, East Manggarai, Ngada, and Nagekeo, in Flores Island, the Province of East Nusa Tenggara: A. Broken leaf lamina hanging down, typically initiating from younger leaves; B. Leaf sheath with reddish-brown streaks visible on a longitudinal section of the pseudostem; C. Leaf sheath with reddish-brown spots and blotches visible on a transverse section of the pseudostem; D. Leaf sheath and true stem (constituting the base of the fruit bunch stalk) exhibiting reddish-brown streaks on a longitudinal section of the pseudostem; E. Leaf sheath and true stem (constituting the base of the fruit bunch stalk) exhibiting reddish-brown spots and blotches on a longitudinal section of the pseudostem; F. Browning and rotting petiole of a mature leaf prior to abscission; G. Browning decay along the groove edges of a sucker leaf petiole; H. Leaf lamina exhibiting yellowing and drying along the margins; I. Sucker leaf lamina showing yellowing and drying along the margins, developing asymmetrically; J. Fruit appeared externally fresh; K. Fruit bunch stalk displaying reddish-brown streaking and spotting on longitudinal and transverse sections; L. Internal fruit pulp rot upon cutting a fruit that appears fresh externally; M to O. Progressive stages of rotting and discoloration of the fruit pulp, from tan to reddish-brown to dark brown, accompanied by reddish-brown mucoid exudate in advanced stages of fruit decay; P. Male bud stalk exhibiting reddish-brown spotting and streaking on an oblique section; Q. Decaying brown lesions on a transverse section of the initial rotting male bud, and R. Result of PCR test. Source: Field photos and PCR analysis (2023)

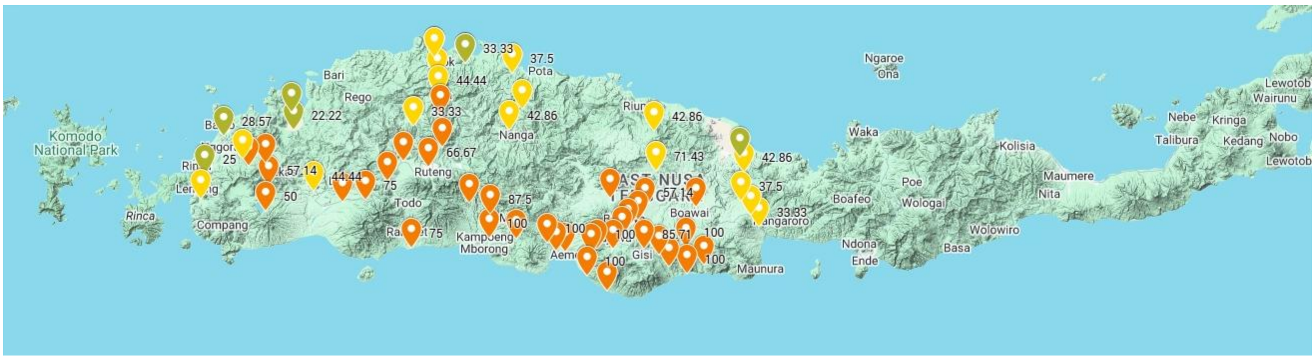

Figure 3. Map showing the spatial distribution of BBD incidences across surveyed areas in the central and western parts of Flores Island. Orange represents high, yellow represents medium, and green represents low incidence, respectively. Source: Georeferenced Incidence Data (2023)

Biosecurity governance and technical capacity constraints

The Indonesian biosecurity governance for agriculture is not regulated by a single Biosecurity Act, but is based on a hierarchy of laws, government regulations, and ministerial decrees. Its main goal is to prevent the entry, establishment, and spread of quarantine pests and diseases and is consistent with international standards established by the International Plant Protection Convention (IPPC). The most important documents in managing threats like BBD include: (i) Law No. 21 Year 2019 concerning Animal, Fish, and Plant Quarantine, which replaces the earlier 1992 Quarantine Law and provide the legal basis for biosecurity activities; (ii) Government Regulation No. 14 Year 2002 concerning Plant Quarantine, which enforce the older law and remains relevant in the present for specific quarantine procedures; (iii) Government Regulation No. 6 Year 1995 concerning Crop Protection, outlining the operational framework for pests control within the country after border defenses are breached; (iv) Minister of Agriculture Regulation No. 25 Year 2020 concerning the Designation of Quarantine Pests, Pathogens, and Weeds, which officially declares certain pathogens, including *Ralstonia syzygii* subsp. *celebesensis*, as quarantine diseases; and (v) The Surveillance Guidelines for Quarantine Plant Pest, Pathogens, and Weeds, issued by the Agricultural Quarantine Agency's to regulate the national system of surveillance important for early detection and rapid response. Thematic analysis of these instruments, summarized in Table 5, shows that Indonesia has a strong regulatory framework on paper that covers the core pillars of biosecurity. However, the effective management of an endemic threat like BBD is severely hampered by systemic gaps in implementation, primarily related to resource shortages, enforcement capacity issues, socio-economic constraints, and stakeholder engagement challenges.

Building upon the thematic analysis of Indonesia's regulatory documents, which identified robust laws hampered by implementation failures in prevention, surveillance, control, and coordination, the findings from in-depth interviews on Flores Island (Table 6) provided stark empirical evidence of these systemic gaps manifesting on the ground. The interview data conclusively showed that the absence of an explicit, overarching biosecurity policy—the core failure identified in the regulatory analysis—directly cascaded into every critical aspect of banana cultivation. For instance, the surveillance and control measures (Agricultural Quarantine Agency 2007; Government of Indonesia 1995) were rendered ineffective because of reliance on reactive, *ad-hoc* responses and a complete lack of early detection systems. Similarly, the strong exclusion principles enshrined in Law No. 21 Year 2019 concerning Animal, Fish, and Plant Quarantine were wholly undermined by the identified gap in the planting material sector, where the absence of pathogen-free certification and controls directly facilitated the anthropogenic spread of the bacterium, a known critical failure in managing bacterial wilt diseases (Molina et al. 2020). This disconnection between the formal regulatory framework and the actual on-the-ground reality, where community-driven initiatives attempt to fill the gap cause by missing technical support and incentives, breaks the integrated, knowledge-based approach to sustainable farming mandated by Law No. 22 Year 2019 concerning Sustainable Agricultural Cultivation Systems. The interview results thus clearly show that without a dedicated national strategy prioritizing biosecurity as a fundamental principle and providing the institutional framework and resources needed for its implementation, policies will likely continue to fail in controlling pandemics like BBD, leaving smallholder farmers at risk and harming national food security (Narvaez et al. 2020).

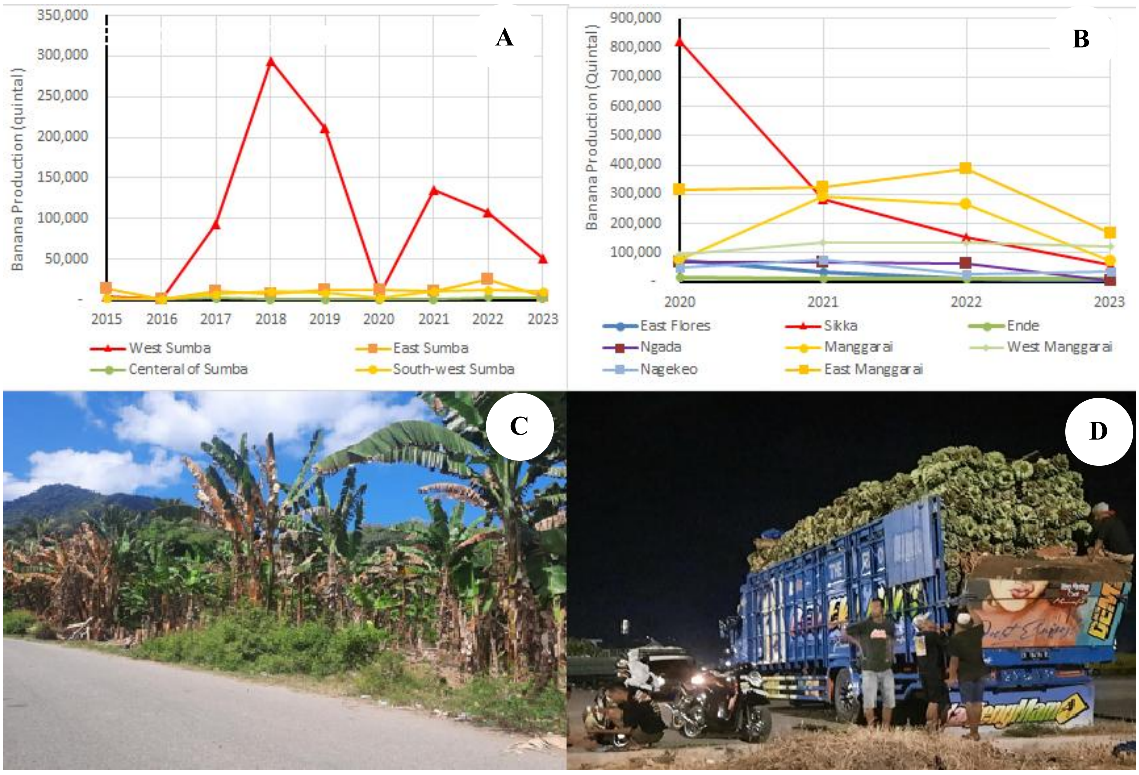

Figure 4. Decrease in Banana Production Associated with BBD: A. In Sumba Island since 2018; B. In Flores Island since 2022; C. Banana Clumps showing BBD Symptoms along the Inter-District Road in Flores Island; and D. Trailers Laden with Bananas amid BBD Outbreaks. Source: BPS (2016, 2018, 2021, 2023, 2024) and Field Photos (2025)

Table 5. Themes, gaps, and implementation challenges emerging from key Indonesian biosecurity laws and regulations

Theme	Core objective	Key regulatory instruments	Relevance and strengths	Gaps and implementation challenges (in context of BBD)
Prevention and Exclusion	To prevent the introduction of quarantine pests into Indonesian territory through stringent import controls.	• Law No. 21 Year 2019 concerning Animal, Fish, and Plant Quarantine (Arts. 8, 9) • Government Regulation No. 29 of 2023 concerning the Implementation Regulation of Law No. 21 Year 2019 • MoA Regulation No. 25 Year 2020 (Designation of Quarantine Pests, Pathogens, and Weeds)	Provides a strong legal basis for inspecting, treating, rejecting, or destroying imported plant material, crucial for preventing the entry of new pathogens or strains	Reactive to External Threats: BBD is already endemic. The framework is less effective against the internal movement of infected planting material between islands, which is a major pathway for BBD spread.
Surveillance and Early Detection	To establish a proactive system for monitoring, quickly detecting, and identifying new pest incursions.	Surveillance Guidelines for Plant Pests, Pathogens, and Weeds or Quarantine Plant Pests, Pathogens, and Weeds (Agricultural Quarantine Agency 2007)	Establishes a formal, top-down system for pest surveillance, mandating roles for local agricultural offices (*Dinas Pertanian*).	Resource and Capacity Limitations: Implementation is often under-resourced. Detection of BBD frequently relies on farmer reports after establishment, not proactive government scouting. Diagnostic delays hinder rapid response.
Management and Containment	To mandate immediate action to contain, suppress, and eradicate a pest upon detection to prevent further spread.	• Government Regulation No. 6 Year 1995 concerning Crop Protection • MoA Decree No. 887/Kpts/OT.210/9/1997 concerning Guidelines for Pest, Pathogen, and Weed Control	Authorizes critical response measures: eradication (destruction of plants), establishment of quarantine zones, and sanitation procedures.	Socio-Economic and Enforcement Challenges: • Compensation: Lack of feasible compensation schemes disincentivizes farmers from reporting outbreaks. • Enforcement: Restricting the movement of host material via informal trade networks is extremely difficult. • Resources: Large-scale eradication is logistically complex and costly.
Stakeholder Coordination and Awareness Raising	To define clear mandates for coordination between agencies and engage stakeholders in biosecurity efforts.	• Law No. 21 Year 2019 concerning Animal, Fish, and Plant Quarantine • Law Number 9 of 2015 concerning the second amendment of the law on regional government	Clearly designates the Quarantine Agency (*Balai Karantina Pertanian*) for border security and the Local Agriculture Services (*Dinas Pertanian*) for internal control	Fragmented Implementation and Lack of Outreach: • Coordination Gaps: Can occur between national and local authorities. • Top-Down Approach: Regulations lack strong mechanisms for mandatory farmer and trader education. Low awareness of BBD pathways and regulations is a critical vulnerability.

Source: Thematic Analysis of Indonesian Biosecurity Laws and Regulations (2025)

The biosecurity response to BBD in ENT is critically undermined by significant technical and knowledge-transfer gaps, as exemplified by two stark inconsistencies. First, despite published research confirming the presence and spread of BBD on Sumba Island since the 2010s (Mudita and Benu 2018; Ray et al. 2021; Nampa et al. 2022), the Provincial Agricultural and Food Security Services inaccurately designate the entire island as a BBD-free zone on its public maps (Department of Agriculture and Food Security of NTT Province 2024). This discrepancy highlights a severe breakdown in surveillance and knowledge translation, where policymakers fail to use scientific findings to inform the public, creating a dangerous blind spot in regional biosecurity awareness. Second, a profound misunderstanding of the pathogen's biology is evident in the widespread recommendation by district agricultural services and agricultural extension officers to apply the antifungal agent *Trichoderma* for controlling the pathogen. This recommendation is fundamentally misaligned with the etiology of BBD, which is caused by the bacterium *Ralstonia syzygii* subsp. *celebesensis* (Safni et al. 2014) and is primarily transmitted through inflorescences via insect, bird, and bat vectors (Sahetapy et al. 2020a; 2020b; Ray et al. 2022). Scientifically validated short-term mechanical control methods, such as the early removal and bagging of the male bud to prevent vector access and long-term cultural control by planting of Musa ABB 'Pisang Kepok' without male inflorescence, a variant known as 'Kepok Tanjung' (Hermanto et al. 2013; Drenth et al. 2018), are neglected in favor of ineffective intervention. These gaps—the failure to integrate expert knowledge into official systems and the dissemination of incorrect control advice—reveal a deep disconnection between research, policy, and extension. This disconnection perpetuates a cycle of ineffective responses, wasting limited resources, eroding farmer trust, and ultimately facilitating the unimpeded spread of the pathogen, as criticized in assessments of plant health systems (Mudita and Benu 2018; Narvaez et al. 2020).

Table 6. Biosecurity gaps and the absence of biosecurity measures resulting from the thematic analysis of in-depth interviews with BBD stakeholder groups in the central and western parts of Flores Island

Identified first-level theme	Second-level policy aspect theme	Identified gaps	Indication of absence of biosecurity measures
• No active cultivation policy has been implemented since the 1990s. • Community-driven initiatives dominate current development efforts. • No technical support or government incentives provided.	Banana Cultivation	The absence of a proactive cultivation strategy that integrates disease prevention mechanisms is a key issue.	Cultivation practices are not integrated with disease-free zoning or crop rotation systems.
• Reactive measures such as public awareness campaigns and the distribution of Trichoderma. • Limited and fragmented coordination across government levels. • Extension activities are non-specific and opportunistic.	Disease Management	• Lack of an established early detection and rapid response system. • No biosecurity protocol based on zoning or quarantine.	No standard operating procedures for sanitation, internal quarantine, planting material movement restrictions, or farmer awareness training.
• The use of certified planting material is only encouraged after disease outbreaks have occurred. • No certified local seed sources available. • Weak regulatory control over seedling distribution.	Seed/Banana Planting Material	Absence of a proactive policy for the supply and distribution of disease-free planting materials.	Seed movement is not subject to pathogen-free certification, inspection, or quarantine controls.
• No dedicated or systematic engagement with technical experts. • Responses rely on *ad hoc* coordination and community reports.	Technical Expertise and Institutional Support	No institutional framework for scientifically-informed biosecurity implementation.	Absence of expert involvement in developing biosecurity protocols or disease surveillance systems.
• No explicit biosecurity policy is currently in place. • Plant quarantine measures are not yet prioritized.	Explicit Biosecurity Policy	Lack of a comprehensive biosecurity system covering upstream (seedlings) to downstream (post-harvest) stages	Biosecurity has not been adopted as a fundamental principle in the design of disease prevention and control strategies.

Source: Thematic Analysis of In-Depth Interview Data (2023)

The government officials in Indonesia are organizationally committed to the Integrated Pest Management (IPM) approach with its guiding philosophy of the Economic Threshold (ET) due to variously related reasons in policy path dependency, adherence to bureaucracy, as well as political economy. Firstly, IPM is constitutionally codified as the country's national crop protection system through Law No. 22 Year 2019 concerning Sustainable Agricultural Cultivation Systems, which superseded Law No. 12/1992 concerning Plant Cultivation Systems. Such legislation creates a formidable institutional path dependency, where officials are obligated to operate within this legally sanctioned framework, regardless of its technical appropriateness for all threats (Thornburn 2014). The ET is a transparent, measurable, and legally justifiable threshold for intervention that facilitates decision-making for inexperienced local extension services that are incapable of working under more sophisticated, proactive monitoring (Thornburn 2014). This is compounded by regional decentralization that has occurred since 1998, whereby agricultural power has shifted to regional governments that have extensive technical limitations as well as short-term perspectives (Resosudarmo 2012). Regional head of governments, looking to obtain tangible outcomes in th foreseen 5-year election period, tend to prefer short term, visible application of pesticide spraying—a response facilitated due to attaining the ET—a solution that contrasts with the more subtle, long-term approach of augmenting ecological resilience through classical IPM that was promoted in the first-phase National IPM Program (McClelland 2002; Winarto 2004). Furthermore, the reactive ET model aligns with the commercial interests of a powerful pesticide industry, which actively promotes chemical solutions. This creates a perverse incentive structure where the response to any pest outbreak, even a bacterial one for which pesticides are ineffective, is often channeled towards chemical control, as this is a well-established and lucrative pathway within the existing system (Thornburn 2015). Consequently, in the case of a systemic, transboundary disease like BBD that needs pre-emptive, area-wide control and stringent quarantine prior to symptom manifestation, the reactive IPM approach is not only ineffective but also adversative. What this does is guarantee that actions are always taken too late after the disease is already widespread and economically destructive, effectively institutionalizing failure as a strategy against invasive species (Mudita and Benu 2018; Deguine et al. 2021).

Designing a scalable, locally feasible, and resilience-based biosecurity framework

The disastrous outbreak and proliferation of BBD throughout the drylands of ENT is a quintessential example of a "global-local" environmental issue, where global biological and economic impulses converge with hyper-local agricultural systems and socio-economic vulnerabilities. A multi-scalar analytical approach is thus adopted from that put forward by Wilbanks and Kates (1999), not merely as an academic exercise but as a critical prerequisite for designing an effective, resilience-based, and locally feasible biosecurity system (Table 7). The BBD pandemic is illustrative of the key principles in their model: the pathogen itself originates from outside ENT. It is dispersed through regionalized trade pathways, while impacts are most severely experienced in the local domain, where smallholder farmers suffer from entire crop destruction and acute food insecurity. A standard top-down, one-size-fits-all approach to biosecurity policy will in this case inevitably fail, as it is likely to become "disembodied from experience" (Wilbanks and Kates 1999), neglecting the extreme local variation in cultivation systems, the powerful though unofficial agency of merchants and farmers, as well as the unique socio-ecological interactions in ENT's drylands agro-ecosystems. A purely local answer, on the other hand, has neither the institutional backstop, scientific capacity, nor regulatory powers to respond to a pathogen that transcends village, district, and provincial borders. Therefore, a framework that explicitly recognizes the importance of scale is needed to span this gap, ensuring that both national and international resources and policies work together to enhance, rather than replace, locally accessible and culturally-compatible actions for containment, monitoring, and sustainable restoration.

Table 7. A Multi-Scalar Framework for Designing a Resilience-Based Biosecurity System against Banana Blood Disease (BBD) in East Nusa Tenggara

Scale dimension	Definition	Global and national scale (Implications for BBD)	Local scale (Implications for BBD in NTT drylands)
Domain	The systemic and cumulative processes by which local problems become global ones and vice versa.	BBD is part of a global pandemic of bacterial wilt affecting bananas. International travel and trade can introduce new pathogen strains. Climate change may alter disease suitability zones.	BBD spread is extreme and devastating at the local level due to shared planting material (suckers), contaminated tools, and a lack of awareness, destroying livelihoods and food security.
Agency	The intentional human actions and the formal and informal institutions that guide them.	Mandates from the International Plant Protection Convention (IPPC) and Indonesian national law (e.g., UU No. 21/2019) provide a structure for quarantine and control but are poorly enforced locally.	Actions are voluntary and community-driven. Farmers and local traders are the primary agents of spread or control. Their practices (e.g., using shared machetes, moving suckers) dictate disease trajectory.
Interaction	The driving forces and consequences of the relationship between global/ national structure and local agency.	National policies must internalize the complexity of local socio-economic realities (e.g., farmer poverty, informal seed systems) to be effective.	Local actions are distinctive but are profoundly influenced by broader forces. E.g., demand from Java/Bali drives traders to enter villages, inadvertently spreading BBD through their operations.
Tractability	How easily a phenomenon can be understood, traced, and grounded in effective actions.	Difficult to ground in direct action. National goals for "BBD control" can become disembodied from the actual experience of farmers, leading to generic, ineffective top-down solutions.	Much more traceable and actionable. Pathogen spread can be directly linked to specific practices (e.g., harvest from infected clumps). Solutions (e.g., community-led sanitation protocols, rogueing) can be grounded in local knowledge and immediate benefits.
Variance	The degree of difference or inconsistency across the system.	Less variance in policy design (a single national strategy), but high variance in implementation success across different islands and provinces.	Extreme variance between and even within villages. Some areas may have a high incidence, while neighboring ones are disease-free, based on specific trade routes and farmer networks.
Perspective	The point of view regarding cause, effect, and responsibility.	Risk of misdiagnosis by viewing BBD only as a biosecurity failure without seeing its roots in rural poverty, lack of alternative planting material, and weak agricultural extension systems.	Risk of misdiagnosis by attributing outbreaks purely to local negligence ("farmer error"), while ignoring the role of broader factors like the lack of affordable, clean seed or effective national quarantine.

Source: Adapted from Wilbanks and Kates (1999)

Table 8. Priority Actions for a Resilience-Based Biosecurity Framework in Managing the Transboundary BBD

Stage of the resilience process	Priority action for BBD biosecurity
Anticipate	• Establish a community-led surveillance network for early detection and reporting of BBD symptoms, supported by mobile technology and rapid diagnostic tools. • Conduct participatory mapping with farmers to identify and prioritize high-risk pathways for pathogen introduction and spread.
Mitigate	• Implement immediate, community-organized rogueing and destruction of infected plants, with agreed-upon compensation mechanisms. • Enforce localized, culturally-sanctioned internal quarantine and movement restrictions on banana planting material. • Promote immediate farm-level biosecurity measures (e.g., tool sanitation protocols) through farmer-to-farmer training.
Adapt	• Evaluate and adapt control measures based on community feedback and local efficacy. • Develop and distribute locally adapted, disease-tolerant banana cultivars through the establishment of community-based seedling gardens. • Promote agro-ecological diversification (e.g., intercropping, livestock integration) to reduce systemic reliance on bananas and build broader livelihood resilience.

Source: Synthesis of Data Analysis Results (2025)

The multi-scalar analysis shows that a resilience-based biosecurity framework for BBD must be intentionally designed to operate across multiple levels, not just one. The global and national levels provide essential support—policy, resources for producing clean seed, and international research collaboration (Molina et al. 2020). However, as Table 7 indicates, these top-down measures are often disconnected from local realities and show wide variation in implementation. On the other hand, the local level is where actions are most manageable, and specific practices influence disease spread. Yet, local actors often lack the resources and knowledge needed to act effectively and may misdiagnose the causes. Therefore, for the framework to work well, feedback between levels is necessary: national policies should consider local differences and perspectives to stay relevant, while local stakeholders need support from national systems to access disease-free planting materials and scientifically-informed protocols (Narvaez et al. 2020). A practical and scalable strategy hinges on using national authority to empower local actions—such as funding local clean seedling gardens and conducting farmer-to-farmer biosecurity training—thus bridging the gap between regional disease transmission systems and the severe local impacts on dryland farmers in ENT.

Designing a resilience-based biosecurity framework for the management of BBD in the dryland agro-ecosystems of ENT requires a significant departure from traditional, top-down control. Instead, a comprehensive strategy that integrates biosecurity into the broader socio-ecological context of resilience is needed. The province's inherent vulnerabilities—degraded lands, low soil fertility, climatic variability, and complex cultural institutions (Seran et al. 2021; Ngongo et al. 2022)—mean that a disturbance like BBD does not simply cause crop loss but risks triggering a cascade of failures across food security and livelihood systems. Therefore, the framework must move beyond reactive measures and integrate the entire resilience process: anticipation, mitigation, and adaptation (Table 8). This approach recognized that a system's recovery depends on its inherent resistance to initial impact and its capacity to reorganize afterwards (Grafton et al. 2019; Walker 2020). As illustrated in Table 8, key elements of the framework should include community-based surveillance for early detection, organized local action for containment, and the long-term adaptation of farming systems through diversified and localized resources. This multi-stage process is essential for building the necessary resistance and reorganization capacity to navigate current and future biological threats, thereby ensuring that the biosecurity system itself is resilience-based and does not exceed critical performance tipping points under pressure from multiple stressors (Pimm et al. 2019; Arndt et al. 2024).

The resilience-based biosecurity framework proposed here requires a radical change in crop protection. It shifts from a centralized, top-down approach to a polycentric and adaptive governance model. This model actively involves stakeholders on various scales (Cook et al. 2010). National and provincial agencies transition from being the sole directors to facilitators and enabling agencies. They decentralize power and funds to district-level entities as well as community collectives to conduct scale-specific anticipatory and mitigation measures (Morrison et al. 2019). Such a structure is essential for managing the complex, cross-scale interactions inherent in biological invasions, as highlighted by Wilbanks and Kates (1999). Effective implementation requires clearly defined yet complementary roles from all the stakeholders. The National and provincial governments provide the broad policy directive, secures financing for compensation schemes, and support large-scale production of clean planting material. Local district government requires technical as well as funding capacity to orchestrate surveillance, enforce localized quarantine, and channel resources. Agricultural extension services require retraining to function as knowledge brokers and facilitators of participatory learning rather than merely disseminating top-down instructions. Above all, farmers and local traders must be recognized as co-implementers, not just beneficiaries; their contributions are vital for ground-truthing surveillance, adhering to community-sanctioned biosecurity protocols, and reorganizing farming systems through diversification (Djalante et al. 2020). Without this genuine devolution of responsibility and the building of trust through transparent communication and shared decision-making, the framework is likely to remain a document exercise, failing to produce the desired collective action to create durable resilience against BBD in ENT's challenging dryland context. Therefore, transparent communication is crucial to keep all stakeholders informed and involved in the process.

This study shows that the current reactive IPM approach mandated under Indonesian law is ineffective in managing Banana Blood Disease (BBD) caused by *Ralstonia syzygii* subsp. *celebesensis* in East Nusa Tenggara. As key stakeholders, your role in implementing the proposed changes is crucial. The current approach has led to a 65% reduction in farmer income, triggered food insecurity, and eroded banana biodiversity. The core challenges, including policy fragmentation, weak cross-sectoral coordination, lack of proactive surveillance, and absence of pathogen-free planting material, are exacerbated by technical capacity gaps and ineffective control advice. A paradigm shift is therefore required toward a resilience-based biosecurity framework that bridges national regulations with local realities and functions across pre-border, border, and post-border levels. Key recommendations include establishing compensation schemes, promoting farm-level biosecurity and agro-ecological diversification, legislating a National Banana Biosecurity Strategy, forming a provincial multi-stakeholder task force, retraining extension officers, strengthening community-based surveillance networks, developing certified seedling gardens, and redefining governance roles from centralized control to enabling locally adapted biosecurity actions.

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REFERENCES

Agricultural Quarantine Agency. 2007. Surveillance Guidelines for Plant Pest, Pathogens, and Weeds or Quarantine Plant Pest, Pathogens, and Weeds. Plant Quarantine Center, Agricultural Quarantine Agency. https://repository.pertanian.go.id/server/api/core/bitstreams/b02c8a60-5219-403b-a797-c08f664cfec1/content.

Arndt N, Falk I, Wallace R. 2024. Integrated biosecurity for sustainable agriculture: Lessons from Oceania. CABI Publishing.

Bore F. 2016. Penyakit-penyakit pembuluh angkut pada kultivar-kultivar tanaman pisang di Kecamatan Wejewa Timur, Kabupaten Sumba Barat Daya (Vascular diseases of banana cultivars in East Wejewa Sub-District, the District of Southwest Sumba). Undergraduate Project, Faculty of Agriculture, Nusa Cendana University, Kupang. [Indonesian]

BPS. 2024. Nusa Tenggara Timur in Figure 2024. BPS-Statistics Nusa Tenggara Timur Province. Vol. 40, Catalogue: 1102001.53, Publication Number: 53000.24005. [Indonesian]

BPS. 2023. Nusa Tenggara Timur in Figure 2023. BPS-Statistics Nusa Tenggara Timur Province. Publication Number: 53000.2307. Catalog: 1102001.53. [Indonesian]

BPS. 2021. Nusa Tenggara Timur in Figure 2021. BPS-Statistics Nusa Tenggara Timur Province. Publication Number: 53000.2106. Catalog: 1102001.53. [Indonesian]

BPS. 2018. Nusa Tenggara Timur in Figure 2018. BPS-Statistics Nusa Tenggara Timur Province. Publication Number: 53560.1810, BPS Catalog: 1102001.53. [Indonesian]

BPS. 2016. Nusa Tenggara Timur in Figure 2018. BPS-Statistics Nusa Tenggara Timur Province. Publication Number: 53560.1618, Catalog: 1102001.53. [Indonesian]

Braun V, Clarke V. 2022. Thematic analysis: A practical guide. SAGE Publications.

Cook DC, Liu S, Murphy B, Lonsdale WM. 2010. Adaptive approaches to biosecurity governance. Risk Anal 30 (9): 1303-1314. DOI: 10.1111/j.1539-6924.2010.01439.x.

Creswell JW, Plano Clark VL. 2017. Designing and conducting mixed methods research (3rd ed.). SAGE Publications.

Damayanti R, Purwanto E, Suroso E. 2021. Commercialization of smallholder banana farming: A case study in Sumba Island, Indonesia. J Agric Sci 13 (5): 112-125. DOI: 10.5539/jas.v13n5p112.

Deguine J-P, Aubertot J-N, Flor RJ, Lescourret F, Wyckhuys KAG, Ratnadass A. 2021. Integrated pest management: Good intentions, hard realities. A review. Agron Sustain Dev 41 (3): 38. DOI: 10.1007/s13593-021-00689-w.

Department of Agriculture and Food Security of NTT Province. 2024. Bacterial Wilt Disease or Blood Disease in Banana Plants. https://scholar.google.com/scholar?hl=en&as_sdt=0%2C5&q=opportunistic+sampling+&btnG=. [Indonesian]

Djalante R, Lassa J, Setiamarga D, Sudjatma A, Indrawan M, Haryanto B, Mahfud C, Sinapoy MS, Djalante S, Rafliana I, Gunawan LA. 2020. Review and analysis of current responses to COVID-19 in Indonesia: Period of January to March 2020. Prog Dis Sci 6: 100091. DOI: 10.1016/j.pdisas.2020.100091.

Drenth A, Mudita IW, Ray J, Subandiyah S. 2018. Blood Disease of Banana: Diagnostics and Distribution (PBCRC SI20063 Final Report) (CRC SI20063; Research Impact Report/Final Report). Plant Biosecurity Cooperative Research Centre.

Ekoran NTT. 2023. Outbreak of banana blood disease spreads in Ngada. https://www.ekorantt.com/wabah-penyakit-darah-pada-pisang-meluas-di-ngada/. [Indonesian]

Ekoran NTT. 2024. Nagekeo farmers complain of banana disease attack. https://www.ekorantt.com/petani-nagekeo-keluhkan-serangan-penyakit-pisang/. [Indonesian]

Falk I, Wallace R. 2011. Managing Plant Biosecurity Across Borders. In: Falk I, Wallace R, Ndoen ML (eds.). Managing Biosecurity Across Borders (pp. 3-19). Springer Netherlands. DOI: 10.1007/978-94-007-1412-0_1.

FAO. 2007. Biosecurity toolkit. Food and Agriculture Organization of the United Nations. http://www.fao.org/3/a1140e/a1140e00.htm.

Findlater A, Bogoch II. 2018. Human mobility and the global spread of infectious diseases: A focus on air travel. Trends Parasitol 34 (9): 772-783. DOI: 10.1016/j.pt.2018.07.004.

Flick U. 2018. An introduction to qualitative research (6th ed.). SAGE Publications.

Flores Editorial. 2022. Outbreak of banana blood virus attacks East Manggarai. https://floreseditorial.com/wabah-virus-darah-pada-pisang-serang-manggarai-timur/. [Indonesian]

Flores Pos. 2024. 16 sub-districts in Ende exposed to banana disease. https://florespos.com/16-kecamatan-di-ende-terpapar-penyakit-pisang/. [Indonesian]

Flores Pos. 2025. Banana blood disease in Ende still threatens. https://florespos.com/penyakit-darah-pisang-di-ende-masih-mengancam/. [Indonesian]

Floresa. 2024. Spread of banana blood disease in Sikka suspected to be through pruning tools. https://www.floresa.co/2024/03/10/penyebaran-penyakit-darah-pisang-di-sikka-diduga-melalui-alat-pangkas/. [Indonesian]

Fu B, Stafford-Smith M. 2024. Resilience and sustainability in drylands. Springer Nature. DOI: 10.1007/978-981-99-0903-2.

Government of Indonesia. 1992. Law of the Republic of Indonesia umber 12 Year 1992 concerning Plant Cultivation Systems. https://peraturan.bpk.go.id/Details/46604/uu-no-12-tahun-1992. [Indonesian]

Government of Indonesia. 1995. Government Regulation Number 6 Year 1995 concerning Crop Protection. https://peraturan.bpk.go.id/Details/57024/pp-no-6-tahun-1995. [Indonesian]

Government of Indonesia. 2015. Law Number 9 of 2015 concerning the Second Amendment to Law Number 23 of 2014 concerning Regional Government. https://peraturan.bpk.go.id/Details/38209/uu-no-9-tahun-2015. [Indonesian]

Government of Indonesia. 2023. Government Regulation (PP) Number 29 of 2023 concerning the Implementation Regulations of Law Number 21 Year 2019 concerning Animal, Fish, and Plant Quarantine. https://peraturan.bpk.go.id/Details/250096/pp-no-29-tahun-2023. [Indonesian]

Government of Indonesia. 2019. Law of the Republic of Indonesia Number 22 Year 2019 concerning Sustainable Agricultural Cultivation Systems. https://peraturan.bpk.go.id/Details/123688/uu-no-22-tahun-2019. [Indonesian]

Grafton RQ, Williams J, Jiang Q. 2019. Resilience and adaptation in agriculture. Nat Sustain 2 (10): 898-900. DOI: 10.1038/s41893-019-0394-z.

Guo Q, Fei S, Potter KM, Liebhold AM, Wen J. 2022. Tree diversity regulates forest pest invasion. Proc Natl Acad Sci 119 (25): e2113871119. DOI: 10.1073/pnas.2113871119.

Hadiwiyono S, Subandiyah S, Sumardiyono C. 2007. The impact of pesticide use on dryland agricultural environments. Jurnal Ilmu Pertanian 14 (2): 45-53. [Indonesian]

Hahuly MV, Mudita IW, Simamora AV, Nge JA, Yuliadhi KA, Tjitra A, de Neergaard E, van den Bosch F. 2025. Insect vectors of banana blood disease in Flores Island, East Nusa Tenggara, Indonesia. Biodiversitas 26 (8): 3791-3802. DOI: 10.13057/biodiv/d260853.

Henci J. 2016. Menentukan Distribusi Geografik Penyakit-penyakit Jaringan Pembuluh Angkut Tanaman Pisang di Kecamatan Wejewa Timur, Kabupaten Sumba Barat Daya, dengan Menggunakan Program Aplikasi SIG OpenJump. [Undergraduate Thesis]. Faculty of Agriculture, Nusa Cendana University, Kupang. [Indonesian]

Henry D, Ramirez-Marquez JE. 2012. Generic metrics and quantitative approaches for system resilience as a function of time. Reliability Eng Syst Saf 99: 114-122. DOI: 10.1016/j.ress.2011.09.002.

Hermanto C, Eliza, Emilda D. 2013. Bunch management of banana to control blood disease. Australasian Plant Pathol 42 (6): 653-658. DOI: 10.1007/s13313-013-0248-5.

Hothorn T, Everitt BS. 2014. A handbook of statistical analyses using R (3rd ed.). Chapman and Hall/CRC.

Jejak Flores. 2022. Mysterious disease outbreak attacks residents' banana gardens in Borong. https://www.jejakflores.com/2022/06/wabah-penyakit-misterius-serang-kebun-pisang-warga-di-borong/. [Indonesian]

Lian X, Piao S, Chen A, Huntingford C, Fu B, Li LZX, Huang J, Sheffield J, Berg AM, Keenan TF, McVicar TR, Wada Y, Wang X, Wang T, Yang Y, Roderick ML. 2021. Multifaceted characteristics of dryland aridity changes in a warming world. Nat Rev Earth Environ 2 (4): 232-250. DOI: 10.1038/s43017-021-00144-0.

McClelland W. 2002. Indonesia's integrated pest management in rice: A model for Asia. J Intl Affairs 55 (2): 499-502. DOI: 10.1017/S1466046602990095.

Ministry of Agriculture (MoA). 1997. Minister of Agriculture Decree Number concerning Guidelines for Pest, Pathogen, and Weed Control. https://psp.pertanian.go.id/storage/557/kepmentan-no-887-TH-97-ttg-pedoman-pengendalian-org-pengg-tnm.pdf. [Indonesian]

Ministry of Agriculture (MoA). 2020. Regulation of the Minister of Agriculture Number 25 Year 2020 concerning Designation of Quarantine Pests, Pathogens, and Weeds. https://peraturan.bpk.go.id/Details/201266/permentan-no-25-tahun-2020. [Indonesian]

Molina AB, Sinohin VG, Fabregar EG. 2020. Field guide to banana diseases and pests. ProMusa. https://www.promusa.org/publications.

Mongabay Indonesia. 2024. Banana blood disease threatens food security in Flores. https://www.mongabay.co.id/2024/04/05/penyakit-darah-pisang-ancam-ketahanan-pangan-di-flores/. [Indonesian]

Morrison TH, Adger WN, Brown K, Lemos MC, Huitema D, Phelps J. 2019. The black box of power in polycentric environmental governance. Global Environ Change 57: 101934. DOI: 10.1016/j.gloenvcha.2019.101934.

Mudita IW, Benu FL. 2018. Go bananas no more: Socio-economic and biosecurity implications of blood disease of banana in Sumba Island, the Province of East Nusa Tenggara, Indonesia. Hortic Intl J 2 (6): 347-350. DOI: 10.15406/hij.2018.02.00075.

Nampa IW, Mudita IW, Kaho NPLBR, Widinugraheni S, Natonis RL. 2020. The kobocollect for research data collection and management (An experience in Researching the socio-economic impact of blood disease in banana). SOCA: Jurnal Sosial Ekonomi Pertanian 14 (3): 3. DOI: 10.24843/SOCA.2020.v14.i03.p15.

Nampa IW, Mudita IW, Widinugraheni S, Natonis RL, Surayasa MT. 2022. Impacts of banana blood disease outbreak to the farmers' households food security in Sumba Island, East Nusa Tenggara Province, Indonesia. IOP Conf Ser: Earth Environ Sci 1107 (1): 012089. DOI: 10.1088/1755-1315/1107/1/012089.

Nampa IW, Pudjiastuti SS, Darlen MF, Widinugraheni S, Tay B, Pero YE, Usman FNJ. 2025. Value chain and threat of spreading new disease in banana agroindustri in Flores Island, NTT Province. Jurnal Rekayasa dan Manajemen Agroindustri 13 (2): 229-239. DOI: 10.24843/JRMA.2025.v13.i02.p08.

Narvaez AI, Guzmán M, Sandoval JF. 2020. Challenges in plant health systems: A case for integrated pest and disease management. Crop Prot 132: 105136. DOI: 10.1016/j.cropro.2020.105136.

Ngongo Y, Seran AE, de Rosari I. 2022. Soil fertility status and its constraints for sustainable dryland agriculture in East Nusa Tenggara, Indonesia. J Degraded Mining Lands Manag 9 (2): 3301-3311. DOI: 10.15243/jdmlm.2022.092.3301.

Noywuli N, Haigh T, Widinugraheni S. 2024. Vulnerability of smallholder dryland agriculture to biological invasions: A systematic review. Global Food Security 40: 100765. DOI: 10.1016/j.gfs.2024.100765.

Pimm SL, Donohue I, Montoya JM, Loreau M. 2019. Measuring resilience is essential to understand it. Nat Sustain 2 (10): 895-897. DOI: 10.1038/s41893-019-0393-0.

Pos Kupang. 2022. Outbreak of banana blood disease reported to attack East Manggarai. https://kupang.tribunnews.com/2022/06/30/wabah-penyakit-darah-pada-pisang-dilaporkan-serang-manggarai-timur. [Indonesian]

Prajapati M, Smith GR, Jones RAC. 2024. Plant virus pandemics: Assessing the risks and developing mitigation strategies in a changing world. Virus Res 341: 199307. DOI: 10.1016/j.virusres.2024.199307.

Prior P, Ailloud F, Dalsing BL, Remenant B, Sanchez B, Allen C. 2016. Genomic and proteomic evidence supporting the division of the plant pathogen *Ralstonia solanacearum* into three species. BMC Genomics 17: 90. DOI: 10.1186/s12864-016-2413-z.

Ramanujan P, Bhattacharjea S, Alcott B. 2022. A multi-stage approach to qualitative sampling within a mixed methods evaluation: some reflections on purpose and process. Can J Program Eval 36 (3): 355-364.

Ray,JD, Subandiyah S, Prakoso AB, Rincón-Flórez VA, Carvalhais LC, Drenth A. 2022. Transmission of blood disease in banana. Plant Dis 106 (8): 2155-2164. DOI: 10.1094/PDIS-10-21-2373-RE.

Ray JD, Subandiyah S, Rincon-Florez VA, Prakoso AB, Mudita IW, Carvalhais LC, Markus JER, O'Dwyer CA, Drenth A. 2021. Geographic expansion of banana blood disease in Southeast Asia. Plant Dis 105 (10): 2792-2800. DOI: 10.1094/PDIS-01-21-0149-RE.

Renault V, Humblet M-F, Moons V, Saegerman C. 2022. Biosecurity concept: Origins, evolution and perspectives. Animals 12 (1): 63. DOI: 10.3390/ani12010063.

Resosudarmo BP. 2012. Implementing a national environmental policy: Understanding the 'success' of the 1989-1999 Integrated Pest Management programme in Indonesia. Singapore J Trop Geogr 33 (3): 365-380. DOI: 10.1111/sjtg.12006.

Retkute R, Gilligan CA. 2025. Developing a spatio-temporal model for banana bunchy top disease: Leveraging remote sensing and survey data. Front Plant Sci 16: 1521620. DOI: 10.3389/fpls.2025.1521620.

Safni I, Cleenwerck I, De Vos P, Fegan M, Sly L, Kappler U. 2014. Polyphasic taxonomic revision of the *Ralstonia solanacearum* species complex: Proposal to emend the descriptions of *Ralstonia solanacearum* and *Ralstonia syzygii* and reclassify current *R. syzygii* strains as *Ralstonia syzygii* subsp. *syzygii* subsp. nov., *R. solanacearum* phylotype IV strains as *Ralstonia syzygii* subsp. *indonesiensis* subsp. nov., banana blood disease bacterium strains as *Ralstonia syzygii* subsp. *celebesensis* subsp. nov. and *R. solanacearum* phylotype I and III strains as *Ralstonia pseudosolanacearum* sp. nov. Intl J Syst Evol Microbiol 64 (9): 3087-3103. DOI: 10.1099/ijs.0.066712-0.

Sahetapy B, Maryana N, Manuwoto S, Mutaqin KH, Latumahina F. 2020a. Test of blood disease bacterium (BDB) transmission by potential insect vectors. Jurnal Hama dan Penyakit Tumbuhan Tropika 20 (1): 71-77. DOI: 10.23960/j.hptt.12071-77.

Sahetapy B, Maryana N, Manuwoto S, Latumahina F, Mutaqin KH. 2020b. Bacterium in the isolates derived from insects' body. J Crit Rev 7 (08): 2827-2941.

Seran AE, Ngongo Y, de Rosari I. 2021. Indigenous knowledge and adaptation to climate variability in dryland farming systems of East Nusa Tenggara, Indonesia. J Agric Sci Technol 23 (5): 1123-1135.

Suara Buruh. 2022. Banana disease outbreak in Borong, farmers ask government to step in. https://www.suaraburuh.com/wabah-penyakit-pisang-di-borong-petani-minta-pemerintah-turun-tangan/. [Indonesian]

Suara Flores. 2024. Banana blood disease outbreak hits Aimere, Ngada. https://www.suaraflores.com/wabah-penyakit-darah-pisang-landa-aimere-ngada/. [Indonesian]

Thornburn C. 2014. The rise and demise of integrated pest management in rice in Indonesia. J Agric Food Syst Commun Dev 4 (3): 47-60. DOI: 10.5304/jafscd.2014.043.006.

Thornburn C. 2015. The pesticide paradox: The misuse of insecticides in Indonesia's rice sector. Insects 6 (2): 381-391. DOI: 10.3390/insects6020381.

UNEP-WCMC. 2007. Aridity index (AI). United Nations Environment Programme World Conservation Monitoring Centre. http://www.unep-wcmc.org.

Vellema W, Jansen K, van Wijk J. 2021. The transformation of food security and sovereignty in Eastern Indonesia. J Rural Stud 88: 443-452. DOI: 10.1016/j.jrurstud.2021.07.023.

Viral NTT. 2025. Banana crisis in Sikka due to blood disease, prices soar. https://www.viralntt.com/krisis-pisang-di-sikka-akibat-penyakit-darah-harga-melambung/. [Indonesian]

Visser V, Langdon B, Pauchard A, Richardson DM. 2014. Unlocking the potential of Google Earth as a tool in invasion science. Biol Invasions 16 (3): 513-534. DOI: 10.1007/s10530-013-0604-y.

Vos P, Hogendoorn C, de Lange W. 2020. Economic impact of Banana Blood Disease on the Indonesian banana industry. Trop Plant Pathol 45 (3): 234-241. DOI: 10.1007/s40858-020-00357-6.

Walker B. 2020. Resilience: What it is and is not. Ecol Soc 25 (2): 11. DOI: 10.5751/ES-11647-250211.

Wilbanks TJ, Kates RW. 1999. Global change in local places: How scale matters. Climatic Change 43 (3): 601-628. DOI: 10.1023/A:1005418924748.

Winarto YT. 2004. Seeds of knowledge: The beginning of integrated pest management in Java. Yale University, USA.