

Epidemiology of *Enterocytozoon hepatopenaei* (EHP) in East Java: Spatiotemporal Distribution and Risk Factors in Shrimp Aquaculture

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ABSTRACT

Enterocytozoon hepatopenaei (EHP) remains a persistent challenge in shrimp aquaculture because it severely reduces growth rates. This study investigated the spatio-temporal dynamics of EHP infection in East Java, Indonesia, and identified key risk factors relevant to local production systems. Over one year, 990 samples were collected, comprising 523 from shrimp and 467 from pond water, across five major regions: Banyuwangi, Jember, Madura, Probolinggo, and Situbondo. Statistical analyses commenced with Chi-square tests to assess associations, followed by multivariate logistic regression to identify significant predictors of infection. The overall EHP prevalence was 27.07%, with substantial variation by sample type and region. Infection rates were significantly higher in shrimp (40.54%) than in water samples (11.99%), and Banyuwangi exhibited the highest prevalence at 32.50%. The regression model demonstrated that water samples were significantly less likely to test positive than shrimp, and that Jember, Madura, and Situbondo had lower odds of infection compared to Banyuwangi. Seasonal trends were evident, with July representing a period of elevated risk and September a period of reduced transmission. These findings indicate that biological, spatial, and seasonal factors influence EHP infection dynamics in East Java. Targeted monitoring of shrimp tissues in high-risk regions such as Banyuwangi during mid-year months is recommended for effective disease management.

INTRODUCTION

The emergence of the microsporidian parasite *Enterocytozoon hepatopenaei* (EHP) is a major constraint in the global shrimp industry, particularly affecting *Penaeus vannamei* (Cao *et al.*, 2025; Qiao *et al.*, 2025; Utami *et al.*, 2025). EHP infects epithelial cells in the hepatopancreatic tubules, causing cell lysis and severe organ dysfunction (Utami *et al.*, 2025). Clinical signs include severe growth retardation, asynchronous size variation, and reduced feed consumption, which collectively cause substantial economic losses (Duan *et al.*, 2021; Qiao *et al.*, 2025; Garlock *et al.*, 2024). In Indonesia, aquatic diseases impose a considerable

economic burden. Meyer *et al.* (2026) estimated that the national Animal Health Loss Envelope (AHLE) for the shrimp grow-out sector reached approximately 43.3 trillion IDR (around US\$ 2.9 billion) in 2022. Morbidity losses associated with reduced growth rates constitute the largest component of this burden, accounting for 67% of total national losses, while health expenditures account for only 5% (Meyer *et al.*, 2026; Verner-Jeffreys *et al.*, 2025). Investigating spatio-temporal changes and risk factors for EHP infection is therefore key to identifying targeted interventions, especially in major shrimp-producing regions such as East Java. This study tackles these knowledge gaps by examining EHP prevalence and its determinants across this key Indonesian aquaculture landscape.

Recent studies indicate that EHP is prevalent in major Asian shrimp-producing countries, including Thailand, Vietnam, India, Malaysia, and Indonesia (Charoenwai *et al.*, 2025; Sajiri *et al.*, 2023; Amelia *et al.*, 2021). Environmental and management factors play a significant role in EHP transmission and severity. Elevated salinity (30 ppt), pH, nitrite, and alkalinity have been shown to increase both the occurrence and impact of the pathogen (Utami *et al.*, 2025). Interspecies transmission is facilitated by green mud crabs (*Scylla paramamosain*) and other macrofauna, which act as mechanical vectors dispersing EHP spores through water and sediment (Sajiri *et al.*, 2023; Tanpichai *et al.*, 2025). Furthermore, management practices such as high stocking density, shared water sources, and inadequate pond preparation increase the risk of infection and EHP persistence in the environment (Kumar *et al.*, 2026; Utami *et al.*, 2025).

Despite significant economic impacts and well-established risk factors, comprehensive data on EHP trends in East Java are limited. Previous studies in this region have been localised or have focused on specific parameters, such as water quality correlations in restricted sites like Situbondo (Utami *et al.*, 2025). A substantial research gap remains in understanding broader spatial dynamics across multiple cultivation centres and temporal variation across months and seasons. Additionally, interactions among sample matrices, geographical locations, and harvest periods remain poorly characterised. To date, no study has employed a robust multivariate logistic regression model to simultaneously analyse these primary risk factors within the East Javanese shrimp farming context.

This research aimed to determine the prevalence of EHP in East Java shrimp farms and to identify which factors—sample matrix, location, and time of year—are most strongly associated with infection risk. By applying a multivariate logistic regression model, the study sought to clarify these relationships to inform practical management. The objective was to map the spatial and temporal distribution of EHP and to support shrimp producers in developing more effective biosecurity and mitigation strategies tailored to local conditions.

METHODS

This study utilized a quantitative observational research design with a cross-sectional approach. Sampling was conducted in five of East Java's primary shrimp-producing regions: Banyuwangi, Jember, Madura, Probolinggo, and Situbondo. In 2025, we collected 990 samples—523 from shrimp and 467 from pond water—using a cross-sectional approach designed to capture ecological transitions and changes in pathogen presence. We randomly selected shrimp, and collected water samples aseptically. All samples were promptly preserved and maintained at low temperatures until laboratory analysis to ensure sample integrity.

EHP detection was performed using quantitative PCR assays with commercially available ShrimpProtect & X-kit detection kits (Riset Nusantara Genetika Corp., Indonesia), following the manufacturer's instructions. All molecular analyses were conducted at PT. Feed and Care Indonesia Laboratory in Situbondo. This standardised methodology ensured that results were both sensitive and reproducible, regardless of whether samples originated from healthy or infected shrimp or from water.

Data analysis was conducted using JASP software (Version 0.98.1), with the significance threshold set at 0.05. Categorical variables were organised to reflect differences in location, time, and sample type. We initially used Pearson Chi-Square or Fisher's Exact Tests, along with crude odds ratios, to screen for associations. To account for confounding, we then applied multivariable logistic regression, reporting adjusted odds ratios and confidence intervals to identify the factors most strongly influencing EHP outbreaks.

RESULTS

Prevalence and Spatio-Temporal Dynamics of EHP Infection Across Areas, Sample Matrices, and Monthly Periods

Analysis of 990 samples revealed considerable variations in the prevalence of *Enterocytozoon hepatopenaei* (EHP) infection across geographic locations, sample matrices, and monthly periods (Table 1). Spatial analysis showed statistically significant differences in EHP case distribution among regions ($\chi^2 = 23.89$, $p < 0.001$). Banyuwangi and Probolinggo recorded the highest infection rates, whereas Jember exhibited the lowest frequency of cases.

A pronounced contrast was observed between shrimp and water samples in terms of sample matrices ($\chi^2 = 101.80$, $p < 0.001$). EHP infections were mainly concentrated in shrimp samples, which exhibited a substantially higher positivity rate than water samples. Temporal fluctuations throughout the year were also statistically significant ($\chi^2 = 82.62$, $p < 0.001$). Infection positivity peaked in specific months, including February and July, while transmission was lowest in August and September.

Table 1. Prevalence and Association of *Enterocytozoon hepatopenaei* (EHP) Infection Across Location, Months, and Sample Matrices (N = 990)

Variable	Total Sample (N)	EHP Negative (n, %)	EHP Positive (n, %)	χ^2 Value	df	p-value
Location	990	722.0 (72.93)	268.0 (27.07)	23.89	4	< 0.001**
- Banyuwangi	240	162.0 (67.50)	78.0 (32.50)			
- Jember	88	81.0 (92.05)	7.0 (7.95)			
- Madura	78	57.0 (73.08)	21.0 (26.92)			
- Probolinggo	397	277.0 (69.77)	120.0 (30.23)			
- Situbondo	187	145.0 (77.54)	42.0 (22.46)			
Kind of Sample	990	722.0 (72.93)	268.0 (27.07)	101.80	1	< 0.001**
- Shrimp	523	311.0 (59.46)	212.0 (40.54)			
- Water	467	411.0 (88.01)	56.0 (11.99)			
Months	990	722.0 (72.93)	268.0 (27.07)	82.62	11	< 0.001**
- JAN	24	15.0 (62.50)	9.0 (37.50)			
- FEB	26	12.0 (46.15)	14.0 (53.85)			
- MAR	51	31.0 (60.78)	20.0 (39.22)			

Variable	Total Sample (N)	EHP Negative (n, %)	EHP Positive (n, %)	χ^2 Value	df	p-value
- APR	58	35.0 (60.34)	23.0 (39.66)			
- MAY	73	47.0 (64.38)	26.0 (35.62)			
- JUN	78	49.0 (62.82)	29.0 (37.18)			
- JUL	76	40.0 (52.63)	36.0 (47.37)			
- AUG	57	50.0 (87.72)	7.0 (12.28)			
- SEP	159	147.0 (92.45)	12.0 (7.55)			
- OCT	149	119.0 (79.87)	30.0 (20.13)			
- NOV	116	86.0 (74.14)	30.0 (25.86)			
- DEC	123	91.0 (73.98)	32.0 (26.02)			

Multivariate Risk Factor Analysis of *Enterocytozoon hepatopenaei* (EHP) Infection

Table 2 presents the results of the multivariate logistic regression analysis evaluating risk factors associated with *Enterocytozoon hepatopenaei* (EHP) infection (N = 990). The model shows an overall statistically significant fit ($\chi^2 = 147.837$, $p < 0.001$), with a Nagelkerke R^2 of 0.2013 and an AIC of 1,020.405. In the sample matrix, using shrimp as the reference category, water samples show a highly significant decrease in the odds of EHP detection (OR = 0.170, 95% CI: 0.121 - 0.240, $p < 0.001$), indicating a substantially lower likelihood of infection than shrimp. In terms of geographical location, with Banyuwangi as the reference group, Jember (OR = 0.161, 95% CI: 0.069 - 0.373, $p < 0.001$), Madura (OR = 0.415, 95% CI: 0.229 - 0.751, $p = 0.004$), and Situbondo (OR = 0.470, 95% CI: 0.295 - 0.750, $p = 0.002$) show statistically significant lower odds of EHP infection, whereas Probolinggo displays no significant difference ($p = 0.859$).

Furthermore, time-based analysis using April as the reference month shows substantial variation across specific periods. July shows significantly higher odds of infection (OR = 2.890, 95% CI: 1.190 - 7.022, $p = 0.019$). Conversely, significantly lower odds of EHP infection are observed in August (OR = 0.252, 95% CI: 0.087 - 0.727, $p = 0.011$), September (OR = 0.084, 95% CI: 0.035 - 0.202, $p < 0.001$), and October (OR = 0.296, 95% CI: 0.138 - 0.634, $p = 0.002$), while remaining months show no statistically significant deviation from the reference period.

Table 2. Multivariate Logistic Regression Analysis of Risk Factors Associated with *Enterocytozoon hepatopenaei* (EHP) Infection (N = 990)

Independent Variables	Coefficient (β)	Standard Error (SE)	Wald Statistic	p-value	Odds Ratio (OR)	95% Confidence Interval
(Intercept)	0.012	0.160	0.006	0.938	1.013	0.740 – 1.386
Kind of Sample (Ref: Shrimp)						
- Water	-1.772	0.175	102.0	< 0.001**	0.170	0.121 – 0.240
Location (Ref: Banyuwangi)						
- Jember	-1.829	0.430	18.08	< 0.001**	0.161	0.069 – 0.373

Independent Variables	Coefficient (β)	Standard Error (SE)	Wald Statistic	p-value	Odds Ratio (OR)	95% Confidence Interval
- Madura	-0.881	0.303	8.437	0.004	0.415	0.229 – 0.751
- Probolinggo	-0.034	0.190	0.032	0.859	0.967	0.666 – 1.404
- Situbondo	-0.754	0.238	10.06	0.002	0.470	0.295 – 0.750
Months (Ref: April)						
- January	0.411	0.565	0.530	0.467	1.509	0.499 – 4.565
- February	0.856	0.540	2.512	0.113	2.353	0.817 – 6.778
- March	0.450	0.444	1.026	0.311	1.568	0.657 – 3.744
- May	-0.291	0.407	0.510	0.475	0.748	0.337 – 1.661
- June	-0.340	0.406	0.705	0.401	0.712	0.321 – 1.575
- July	1.061	0.453	5.493	0.019	2.890	1.190 – 7.022
- August	-1.380	0.541	6.495	0.011	0.252	0.087 – 0.727
- September	-2.475	0.447	30.690	< 0.001	0.084	0.035 – 0.202
- October	-1.218	0.389	9.791	0.002	0.296	0.138 – 0.634
- November	-0.325	0.394	0.681	0.409	0.723	0.334 – 1.563
- December	-0.424	0.392	1.170	0.279	0.655	0.304 – 1.411

Note: N = 990, Model $X^2 = 147.837$ ($p < 0.001$), Nagelkerke $R^2 = 0.2013$, AIC = 1,020.405. EHP level 'POSITIVE' coded as class 1.

DISCUSSION

This study shows significant stratification in the prevalence of *Enterocytozoon hepatopenaei* (EHP) across sample matrices, with detection levels in shrimp tissues (40.54%) substantially higher than in water samples (11.99%). Multivariate logistic regression analysis confirms this pattern, indicating that aquatic matrices have a significantly lower probability of EHP detection than shrimp matrices (OR = 0.170, $p < 0.001^{**}$). The biological characteristics of EHP fundamentally drive the elevated detection rate in shrimp as an obligate intracellular parasite (Thepmanee *et al.*, 2023) that specifically targets and replicates within the epithelial cells of the host's hepatopancreatic (HP) tubules (Ayuzar *et al.*, 2026; Kumar *et al.*, 2022; López-Carvallo *et al.*, 2022; Utami *et al.*, 2025). Lacking mitochondria, EHP relies energetically

on the host by utilising nucleotide transporters to hijack ATP for proliferation (Thepmanee *et al.*, 2023; Yang, 2021), a process that induces severe histological damage, including epithelial degeneration, vacuolization, and cellular hypertrophy (Ayuzar *et al.*, 2026; Duan *et al.*, 2021). Consequently, the shrimp body serves as a biological reservoir where the pathogen is amplified, making it a reliable matrix for molecular diagnostics (Kumar *et al.*, 2022; Utami *et al.*, 2025). Conversely, the lower detection frequency in water matrices is attributed to environmental dilution and methodological constraints, as the free pathogen load in open water is frequently below the detection limit of standard PCR without extensive concentration protocols (Krishnan *et al.*, 2024). In aquatic habitats, spore distribution is additionally influenced by sedimentation, which acts as a reservoir for long-term horizontal transmission (Krishnan *et al.*, 2024; Tanpichai *et al.*, 2025), and the movement of mechanical vectors such as mud crabs (Tanpichai *et al.*, 2025). Structural equation modelling further confirms that the shrimp gut microbiome exhibits a relatively distinct composition from the bacterioplankton communities in the rearing water (Xu *et al.*, 2025; Yang *et al.*, 2025), suggesting that EHP presence in the host is driven more by specific cumulative exposure rather than the mere abundance of the pathogen in the water column (Sha *et al.*, 2025; Xu *et al.*, 2025).

Spatially, EHP distribution shows substantial regional variability, reflecting a heterogeneous disease burden. The Banyuwangi region recorded the highest infection prevalence at 32.50%. When used as the reference category in the regression analysis, it indicates that other regions have a substantially lower probability of infection, including Jember (OR = 0.161, $p < 0.001^{**}$), Madura (OR = 0.415, $p = 0.004$), and Situbondo (OR = 0.470, $p = 0.002$). This geographical heterogeneity in infection burden is mainly driven by the ecological and epidemiological conditions inherent to aquaculture intensification (Le *et al.*, 2026), such as high stocking densities that facilitate pathogen transmission and increase host physiological stress (Han *et al.*, 2025; Kumar *et al.*, 2026; Utami *et al.*, 2025). The horizontal transmission of spores across farming areas is also accelerated by connectivity through shared irrigation channels (Kumar *et al.*, 2026; Le *et al.*, 2026; Satkar *et al.*, 2024) and by macrofauna carriers, such as local crustacean and molluscan species (Sajiri *et al.*, 2023). Deficiencies in regional biosecurity governance—such as the transfer of infected seed stock and shared equipment—additionally transform productivity gains into long-term epidemiological vulnerabilities (Kumar *et al.*, 2026; Le *et al.*, 2026). In contrast, regions with a lower probability of infection likely benefit from implementing superior management practices, including systematic pond preparation, formal biosecurity training, and timely removal of shrimp mortalities (Kumar *et al.*, 2026). Furthermore, operators must strictly control environmental parameters such as pH, nitrite, and alkalinity to prevent microbial instability that predisposes shrimp to hepatopancreatic microsporidiosis (HPM) (Utami *et al.*, 2025). Given that EHP depletes host energy and causes chronic growth retardation (Cao *et al.*, 2023; Qiao *et al.*, 2025; Thepmanee *et al.*, 2023), managing the infection burden in these regions calls for rigorous pond governance that couples molecular surveillance with holistic biosecurity protocols (Le *et al.*, 2026; Tare *et al.*, 2023; Wang *et al.*, 2023).

Enterocytozoon hepatopenaei (EHP) infection shows clear temporal trends, peaking in July (OR = 2.890, $p = 0.019$) due to dry-season environmental stressors in Indonesian intensive aquaculture, including hypersalinity (>30 ppt) and degraded water quality, before declining significantly in September (OR = 0.084, $p < 0.001^{**}$) and October (OR = 0.296, $p = 0.002$) (Utami *et al.*, 2025). These environmental stressors compromise host homeostasis and immunity, enabling EHP to utilise nucleotide transporters (EhNTTs) to hijack host ATP (Thepmanee *et al.*, 2023; Utami *et al.*, 2025). The metabolic exploitation triggers severe oxidative stress, resulting

in hepatopancreatic necrosis, permanent growth retardation, and major economic losses (Zhang *et al.*, 2023; Cao *et al.*, 2023; Jaroenlak *et al.*, 2025; Utami *et al.*, 2025; Chang *et al.*, 2026). The reduced infection risk in Q3 reflects less conducive environmental conditions for EHP proliferation combined with successful management interventions (Utami *et al.*, 2025). Modifiable practices—specifically structured pond preparation, dedicated water reservoirs, specific pathogen-free (SPF) stock, and strict biosecurity protocols—are critical determinants of reduced EHP prevalence and enhanced host protection from seasonal outbreaks (Kumar *et al.*, 2026).

The multivariate logistic regression model applied in this study demonstrated a Nagelkerke R^2 value of 0.2013. This coefficient indicates that the independent variables in the model—sample matrix, geographical location, and monthly period—collectively explain about 20.1% of the total variance in the risk of *Enterocytozoon hepatopenaei* (EHP) infection. Thus, critical external and unmeasured variables likely drive a substantial portion of infection risk, accounting for nearly 80% of the variance. Existing literature identifies several high-impact factors not quantified in the current model but fundamental to EHP epidemiology. Higher stocking densities have been consistently identified as an important risk factor, as overcrowding increases host stress and aids rapid pathogen transmission (Kumar *et al.*, 2026; Utami *et al.*, 2025; Jithendran *et al.*, 2021). Post-larvae (PL) quality is another decisive variable, as infected seed stock or non-SPF (Specific Pathogen Free) larvae can serve as a primary entry point for EHP into intensive culture systems (Ayuzar *et al.*, 2026; Kumar *et al.*, 2026). Besides, the accumulation of organic matter and excessive loading in pond sediments provide a reservoir for resilient EHP spores, facilitating long-term persistence and horizontal transmission between culture cycles (Krishnan *et al.*, 2024; Tanpichai *et al.*, 2025). Gut microbiome dynamics along with the stability of intestinal microbial communities are also vital to host health, indicating that management strategies require a more specific approach to EHP control. Monitoring efforts ought to prioritize direct testing of shrimp tissues, such as the hepatopancreas, rather than relying solely on water samples, due to the higher pathogen concentration and detectability within the host (Uma *et al.*, 2025; Le *et al.*, 2026). Rigorous biosecurity and enhanced surveillance should be concentrated in key regional centers such as Banyuwangi, which demonstrates elevated infection odds compared to surrounding districts. Preventive protocols should be intensified before mid-year, particularly in July, identified as a peak month for EHP infection risk. To support durable sustainability and reduce environmental risks, farm management systems should consider adopting the integrated multi-trophic aquaculture (IMTA) model as a strategic alternative to conventional shrimp farming, providing improved environmental compatibility and economic security (Uddin *et al.*, 2025).

CONCLUSION

The prevalence of *Enterocytozoon hepatopenaei* (EHP) is mainly governed by matrix biology, spatial variation, and seasonal environmental stressors. As an obligate intracellular parasite, EHP amplifies within the hepatopancreas, making host tissue a significantly more reliable diagnostic matrix than environmentally diluted water. Epidemiologically, intensive farming regions such as Banyuwangi sustain the highest infection burden due to horizontal transmission and biosecurity deficits. Temporally, disease risk peaks in July, as dry-season extremes, notably hypersalinity and deteriorating water quality, induce host physiological stress. Since the modelled variables account for only 20.1% of the infection variance, unquantified farm management factors, including stocking density, specific pathogen-free

(SPF) seed quality, and host microbiome stability, continue to be crucial determinants of disease dynamics. Therefore, successful mitigation requires prioritising host-tissue molecular surveillance, applying strict biosecurity protocols in high-risk epicentres, and executing preemptive actions before mid-year climatic events.

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