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Interactions of insect pests, diseases, and Sub1 rice varieties across agro-climatic zones in Assam: insights for strengthening resilient rice cultivation

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This study investigates the prevalence and interaction of insect pests and diseases across the agro-climatic zones of Assam, which are deployed with submergence-tolerant (Sub1) rice varieties. Utilizing data collected from farmers' fields over 2 years (2020 and 2022), the research provides novel insights into how host genotype and climatic zones influence insect pests and disease prevalence under real-world conditions. The results reveal significant variability in insect and disease incidence across different agro-climatic zones and among rice varieties. The Central Brahmaputra Valley (CBV) zone exhibited a higher prevalence of insect pests such as the *L. acuta*, *S. incertulas*, and *C. medinalis*, while the Lower Brahmaputra Valley (LBV) zone demonstrated increased disease incidence, particularly of *M. oryzae* and *B. oryzae*. Similarly, varietal responses varied across agro-climatic zones; Bahadur-Sub1 exhibited comparatively lower insect and disease incidence, whereas Bina dhan 11 showed higher *L. acuta* and *C. medinalis* incidence across zones. Principal component analysis underscored zone-specific associations between insect pests and diseases, emphasizing the complex interactions among host plants, agro-climatic conditions, and insect-pest population buildup. Temporal variation was also observed, with differences in insect pests and disease prevalence between the 2 years, highlighting the impact of macro and micro-climatic factors. These findings suggest continuous monitoring and development of adaptive, zone-specific insect and disease management strategies that can minimize insect-pest adaptation and enhance the resilience and productivity of rainfed rice ecosystems in Assam.

KEYWORDS

host plant interaction, rice ecosystem, pest incidence, submergence, climatic variability

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1 Introduction

Rice is a critical staple food crop for more than half of the world's population and is grown under diverse agroecological zones across the world. Rice crop is affected by many biotic and abiotic stress factors, of which water lodging/flooding is a major abiotic constraint in rain-fed low-lying and deep-water rice growing regions, affecting crop growth, production, and yield. In recent years, stress-tolerant rice varieties (STRVs), introgressed with the submergence-tolerant *Sub1* gene, have been developed and promoted in several flood-prone regions of South and South-East Asia (Ismail et al., 2013). Sub1 introgressed rice varieties are capable of withstanding flooding conditions for periods ranging from 7 to 14 days, exhibiting higher yields than the popular local varieties and do not incur yield penalties under normal conditions (Dar et al., 2018).

Assam, a North-Eastern state of India, is situated south of the Eastern Himalayas, bordered by the fertile valleys of the Brahmaputra river in the north and the Barak river in the southern part of the state. The landscape of Assam can be categorized into three distinct geographic regions: The Brahmaputra River valley, the Barak River valley, and the hilly region. The Brahmaputra River valley is further divided into four zones: The North Bank Plain Zone (NBPZ), Upper Brahmaputra Valley Zone (UBVZ), Central Brahmaputra Valley Zone (CBVZ), and Lower Brahmaputra Valley Zone (LBVZ). The Barak River valley encompasses the Barak Valley Zone (BVZ), while the hilly regions comprise the hill zone. Rice serves as the most important staple food crop in the state, with rice cultivation occurring across various agro-climatic zones, ranging from the hill slopes to the low-lying, deep-watered regions of Assam (Konjengbam et al., 2021). Rice cultivation in Assam is adversely affected each year by severe flooding, which significantly impacts rice production. Approximately 0.5 million hectares (Mha) of land in Assam is chronically prone to flooding, with flash floods occurring at varying intensities, during different crop stages, for varying durations, and at different standing water depths (Kannan et al., 2017; Peramaiyan et al., 2024). Submergent tolerant rice varieties developed by introgressing the *Sub1* locus into high yielding local varieties, namely, Bahadur Sub1, Bina dhan 11, Ranjit Sub1, and Swarna Sub1 have been promoted across the diverse agro-climatic zones of Assam to mitigate the adverse effects of flooding (Sinha et al., 2019). The gene locus associated with submergence (i.e., *Sub1A*) modulates phytohormonal pathways including suppression of ethylene-mediated shoot elongation, chlorophyll breakdown, conserves carbohydrate metabolism, and activates alternative energy pathways (Hussain et al., 2024). This metabolic change enhances survival under submergence but may have an impact on other insect pests within the agroecosystem. Studies comparing the Sub1-tolerant and non-tolerant genotypes for their effects on other biotic stress factors remain limited. Although Sub1 rice varieties have significantly improved the resilience to submergence tolerance, their widespread cultivation across diverse agroecological zones may alter local insect and disease dynamics, leading to new pest management challenges.

The rice ecosystem is highly complex and diverse, encompassing a variety of flora and fauna, including weeds, amphibians, birds, and rodents which coexist and interact continuously (Horgan, 2017). The equilibrium of this ecosystem is predominantly determined by the interaction forces among its various components. Host plant resistance is one of the critical interaction components that can influence ecosystem function by regulating the prevalence and dynamics of pests, diseases, and weeds (Pelletier et al., 2013; Horgan, 2017). The dynamics of pests and diseases primarily depend on the plant species or variety (plant genome) in question, as well as the specific environmental conditions under which these interactions occur (Denno et al., 1995; Moran and Whitham, 1990). Given that host genotype is expected to play a central role in these interactions, and considering the sustained focus among crop breeders on developing crop varieties resistant to biotic and abiotic stresses (Pelletier et al., 2013; Fujita et al., 2013), changes in the composition of herbivore populations and in the outcomes of interactions among herbivore species on crops are anticipated to occur over time (years to decades) (Srinivasan et al., 2015). For example, large-scale adoption of hybrid rice varieties among Chinese farmers has been linked to increases in the abundance of stemborers, *Chilo* spp. and *Scirpophaga* spp., as well as planthoppers (Cheng, 2009; Horgan and Crisol, 2013; Sogawa, 2015). Therefore, a comprehensive understanding of the interactive relationships among specific crop genotypes, insect pests, and climatic zones is essential for developing varietal-specific pest models and management strategies tailored to agro-climatic zones.

The present study investigates insect pests and disease incidence in four agro-climatic zones of Assam characterized by rice varieties introgressed with the *Sub1* gene. We hypothesize that the prevalence of insect pests and disease incidence is significantly influenced by the interaction between host plant genotype and the associated agro-climatic zone. In this study, data on insect pest damage collected over two consecutive years (2020 and 2022) from the four agro-climatic zones of Assam, which are dominated by stress-tolerant rice varieties (Bahadur-Sub1, Bina dhan 11, Ranjit-Sub1 and Swarna-Sub1), were analyzed for their interaction effects.

2 Materials and methods

2.1 Study locations, genotypes, and sampling

Agro-climatic zone refers to geographic regions with similar climatic conditions, soil type, cropping intensity, and production (FAO). Assam state of India has six agro-climatic zones (Konjengbam et al., 2021), of which the present study covers four major agro-climatic zones, i.e., CBV, LBV, UBV, and NBP zone (Figure 1), and their major distinct features are mentioned in Table 1. The CBV has moderate rainfall with warm climate, whereas LBV is the wettest zone, and highly flood-prone; UBV features cooler temperatures and excessive rainfall, whereas NBP is characterized by erratic rainfall, flash floods, and drought.

There were 16 districts under the study (Supplementary Table S1), which were categorized into the above four agro-climatic zones (Figure 1). Each district had at least a minimum of four to a maximum of six data collection plots (ensuring the entire district is covered). The insect and disease incidence data were collected from integrated crop management demonstration (ICMD) plots of farmers' fields adapted with best management practices (BMP) of rice (Supplementary Table S2). The data were collected for 2 years (2020 and 2022) during *Sali* (June/July to Oct/Nov) season from the ICMD plots. The plots were random across districts, and no fixed sampling locations were maintained between the 2 years. The

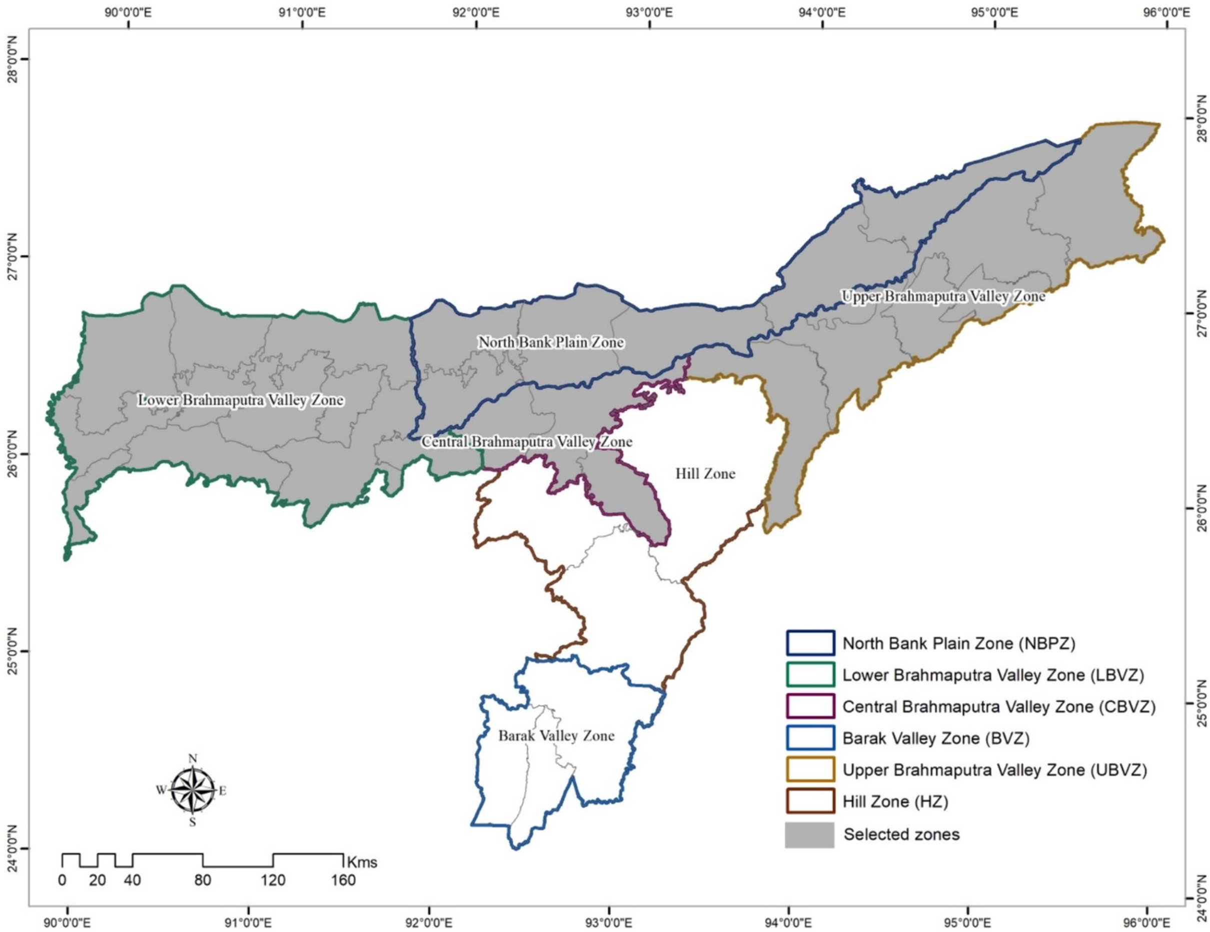

FIGURE 1
Selected agro-climatic zones of Assam for the study.

TABLE 1 Four major agro-climatic zones of Assam (CBV, LBV, UBV, and NBP) and their characteristics.

Parameter	CBV (Central Brahmaputra Valley)	LBV (Lower Brahmaputra Valley)	UBV (Upper Brahmaputra Valley)	NBP (North Bank Plain)
Annual mean temperature (°C)	23–27 °C	24–28 °C	22–26 °C	23–27 °C
Annual rainfall (mm)	1800–2,500 mm^2	2000–2,800 mm^2	2,200–3,000 mm^2	1,500–2,300 mm^2
Relative Humidity (%)	75–85%	75–90%	80–95%	70–85%
Vegetation type	Rice fields, wetlands	Rice fields, banana, jute	Tea gardens, rice, forest	Mustard, pulses, rice
Major cropping seasons	Sali (June–Oct/Nov), Boro (Nov/Dec–May), Ahu (March/April–June)	Sali (June–Oct/Nov), Boro (Nov/Dec–May), Ahu (March/April–June)	Sali (June–Oct/Nov), Boro (Nov/Dec–May), Ahu (March/April–June)	Sali (June–Oct/Nov), Boro (Nov/Dec–May), Ahu (March/April–June)
Soil type	Alluvial, sandy loam	Loamy and clayey alluvium	Acidic alluvial, lateritic	Sandy to loamy soils
Soil pH	5.5–6.8; slightly acidic to near neutral	6.0–7.0; ideal for rice cultivation	4.8–6.0; strongly acidic; lime required	5.0–6.5; moderately acidic
Flood/drought incidence	Moderate flood-prone	Highly flood-prone	Frequent waterlogging	Flash floods and drought

The table is based on the data from Assam State Action Plan on Climate Change (Government of Assam, 2020), IMD Assam Climate Summary Reports (2020–2022), Directorate of Agriculture, Assam—Agro-Climatic Zone Reports, Forest Survey of India and NBSS&LUP, ICAR, Assam Agricultural University Extension Bulletins and NBSS&LUP Soil Maps and Reports, ICAR.

demonstration plots were in 0.3 ha land area each and were owned by farmers; therefore, staggered sowing dates were observed across climatic zones.

The ICMD plots were grown with any one of the four stress-tolerant rice varieties (STRVs) (Table 2), and each district included all four STRVs, with at least one sampling point per variety per

TABLE 2 Stress-tolerant rice varieties (STRVs) grown under integrated crop management demonstration (ICMD) plots across various agro-climatic zones of Assam.

Genotype	Parentage	Year of notification	Duration	Tolerance to abiotic stress conditions	Tolerance to biotic stress conditions
Bahadur *Sub1*	Bahadur/Swarna *Sub1*// Bahadur	2018	150–155 days	Flooding tolerance up to 2 weeks	Not known
Ranjit *Sub1*	Ranjit/Swarna *Sub1*// Ranjit	2018	150–155 days	Flooding tolerance up to 2 weeks	Not known
Swarna *Sub1*	Swarna*3/IR 49830-7-1-2-2	2009	140–145 days	Flooding tolerance up to 2 weeks	Not known
Bina dhan11	IRRI149 and Ciherang	2015	115–120 days	Flooding tolerance up to 2 weeks	Not known

year (Supplementary Table S3). To maintain uniformity in data collection, insect and disease symptoms were recorded across all districts during panicle the initiation stage of the rice crop, except for leaf folder and swarming caterpillar during the active tillering stage. Observations were recorded by walking in zigzag direction across the field. Ten random hills were selected from each demonstration plot (0.3 ha) and observations (n = 10/plot) on the numbers of damaged leaves, tillers, and panicles were recorded. The major insects and diseases of rice and their damage symptom and stage of occurrence are mentioned in Supplementary Table S4. In case of insects, the count was avoided and plant damage was mainly recorded as the insect larvae/adults can easily fly or fall on ground during observation except brown planthopper (BPH). In case of BPH (*Nilaparvata lugens*, Delphacidae: Hemiptera), populations were counted near the base of the hill and recorded as number of plant hoppers per hill. For swarming caterpillar [*Spodoptera mauritia* (Boisduval), Noctuidae: Lepidoptera] and leaf folder (LF) [*Cnaphalocrocis medinalis* (Guenee), Pyralidae: Lepidoptera], a number of damaged leaves/hill were observed, and for gundhi bug [*Leptocorisa acuta* (Thunberg), Alydidae: Hemiptera]—the number of damaged panicles/hill, and for stem borer [*Scirpophaga incertulas* (Walker), Pyralidae: Lepidoptera], number of white earhead/hill were recorded as per cent insect incidence.

For all rice diseases, including both systemic (bacterial blight—*Xanthomonas oryzae* pv. *oryzae*; sheath blight—*Rhizoctonia solani* Kühn; sheath rot—*Sarocladium oryzae;* and false smut—*Ustilaginoidea virens*) and local infection (blast—*Magnaporthe oryzae*; brown spot—*Bipolaris oryzae*), observations were recorded as percent disease incidence by counting the number of infected hills and the total number of hills per plot. The disease observations represented the incidence, whereas disease severity (e.g., lesion size, affected area, or rating scales) and intensity were not recorded. The data collected on incidence provides us an estimate on the proportion of insect/disease occurrence and does not provide indication on the severity of the disease or insect attack. Future field-based studies should aim to include intensity of plant damage, by incorporating quantitative parameters to allow a more comprehensive evaluation of insect-disease impact and dynamics.

Weather data, including average temperature 2 m above Earth's surface (°C), average relative humidity (%), and average monthly precipitation (mm) were obtained from the NASA POWER (Prediction of Worldwide Energy Resource) database[1] for the years 2020 and 2022, specifically for the months July–November (Supplementary Table S5). Data were extracted for the representative coordinates of each agro-climatic zone (CBV, LBV, UBV, and NBP), and monthly averages were computed for the specific climatic factor (Supplementary Table S5). The NASA POWER dataset was used due to the unavailability of site-specific meteorological records across all sampling locations. Furthermore, the dataset was used only for the description of agro-climatic conditions across zones and years, and was not included in the statistical analysis of insect-pest and disease incidence, due to their consistent and coarse spatial resolution and lack of site-specificity.

Rice Doctor (Assamese), a mobile-based application developed by the International Rice Research Institute, Philippines, and built on the Lucid/ Identic platform, comprises all rice insects and diseases and their damage symptom specific to Assam climatic conditions. Rice Doctor was used to identify the insect pest and disease damage accurately under field conditions. It is an insect pests and disease diagnostic mobile-based app available free of cost for download at Google play store. The app enables farmers to access global knowledge and information for timely decisions on pest management.

2.2 Data analyses

The percentage of incidence for insect pests such as *L. acuta*, *S. incertulas*, and *C. medinalis*, and of diseases such as *B. oryzae* and *M. oryzae* were analyzed for each sampling climatic zone, rice variety and year. Each insect and disease incidence was checked for ANOVA assumptions (data normality, homogeneity of variance, and the independence of the observations), but the data were not normally distributed even after their transformations [log(x + 1), sqrt(x) and asin(x)]. Therefore, a non-parametric test (Kruskal–Wallis test) was used for the analysis. A significance level of p-value<0.05 was considered for all the analyses. When there were significant differences between climatic zones or rice varieties, the non-parametric Dunn's Test was used for multiple comparisons. Principal component analysis (PCA) was used to analyze variability in varieties among the evaluated insect and diseases across agro-climatic zones. The packages of "dplyr,"

1 https://power.larc.nasa.gov

"mice," and "FSA" (for the Dunn's Test) were used for the analyses, and "factoextra" for visualization. All data were analysed using the software R v4.0.2 (R Core Team, 2020).

3 Results

3.1 Prevalence and distribution of insect pests and diseases across agro-climatic zones of Assam

Insect pest incidence exceeded that of diseases especially for the CBV, LBV, and NBP zones (Figure 2). The most predominant insects found in each of the zones were *L. acuta*, *S. incertulas*, and *C. medinalis*, whereas *N. lugens* was present in low abundance in all zones except the UBV and *S. mauritia* was anecdotally present in NBP (Figure 2C). For this reason, the analyses of insects in this study have been conducted with the most representative insect pests such as the *L. acuta*, *S. incertulas*, and *C. medinalis*. The principal diseases found were *B. oryzae* and *M. oryzae,* as they were present in each of the evaluated zones with high incidences (these were selected for further statistical analyses). However, *R. solani* was observed at low incidence in all zones. Some other diseases, such as *X. oryzae*, *S. oryzae*, and *U. virens,* were encountered in some of the zones; for example, *X. oryzae* was found in all zones except CBV (Figure 2A), and *U. virens* was present in LBV and NBP zones only (Figures 2B,C).

It is worth noting that not all the recorded insects and diseases were equally prevalent across all zones of Assam. The evaluated zones are determinant for specific insect and disease occurrence over years (Table 3 and Supplementary Table S6), especially the CBV zone had significantly more incidence of insects and diseases compared to other zones (Figure 3), although for diseases, the LBV zone during the first year (2020) showed higher incidences compared to NBP and UBV zones (Figures 4A,C). However, the influence of variety is more pronounced for insect pests than for diseases, as this factor is highly significant in these cases (Table 3 and Supplementary Table S6). Similarly, the Sub1 varieties grown across various agro-climatic zones differed significantly in the incidences of insect-pests and diseases (Figures 3, 4). Bahadur-Sub1 and Swarna-Sub1 exhibited a higher incidence of *S. incertulas* and *L. acuta* in the CBV zone, whereas the insect-pest incidence in the varieties was comparatively lower in other zones. All four Sub1 varieties exhibited higher *L. acuta* incidence in the CBV zone compared to other zones, whereas Ranjit-Sub1 exhibited higher *B. oryzae* incidence across zones.

Furthermore, the insect and disease incidence are not consistent across years, with 2020 exhibiting a higher incidence compared to 2022. During 2022, the incidence of *C. medinalis* and *L. acuta* was significantly lower compared to 2020 (Figures 3A,B,E,F), whereas the incidence of *S. incertulas* and *B. oryzae* was similar in 2020 and 2022 (Table 3 and Supplementary Table S6; Figures 3C,D, 4C,D). Precipitation data from NASA POWER indicate that the year 2020 has experienced heavy rainfall compared to 2022 (Supplementary Table S5 and Supplementary Figure S2), suggesting that agro-ecological conditions, specifically rainfall, may have influenced the insect pest dynamics. However, the other meteorological variables, such as temperature and relative humidity across zones (Supplementary Table S5), exhibited only marginal variation between 2020 and 2022. This indicates that the differences in insect-pest and disease incidence are more likely influenced by localized agro-ecological factors, such as microclimatic variation, cropping intensity, soil properties, and genotype × environment interactions. Moreover, the non-availability of site-specific meteorological data limited our ability to correlate insect and disease incidence with weather parameters.

3.2 Interaction of rice varieties and insect/disease incidence across agro-climatic zones of Assam

The principal component analysis (PCA) biplots (Figure 5) illustrate the interaction between four Sub1 rice varieties (Bahadur-Sub1, Ranjit-Sub1, Swarna-Sub1, Bina Dhan 11) and major insect-pests (*S. incertulas*, *L. acuta,* and *C. medinalis*) and diseases (*B. oryzae* and *M. oryzae*) across agro-climatic zones of Assam. The position of vectors (insects/diseases) and the clustering of rice varieties reveal associations and shared pest pressures in a specific agro-climatic zone.

In general, all insect-pests and diseases contribute to the first principal component (dim1), except *M. oryzae* in the NBP study zone (Figure 5C) and *S. incertulas* in the CBV zone (Figure 5A) that contributed to the second principal component (dim2).

3.2.1 Central Brahmaputra Valley (CBV) zone

The biplot explains 63.6% of the total variability within the data set (dim1 37.8% and dim2 25.8%). In the CBV zone, PCA results indicate weak positive correlation between the *L. acuta* and *M. oryzae,* as well as between *B. oryzae* and *C. medinalis*; however, there are strong negative correlations between *L. acuta* and *B. oryzae* as well as between *S. incertulas* and *C. medinalis*. Rice varieties exhibited variability within groups, whereas Bahadur-Sub1 has a positive association with *S. incertulas,* suggesting susceptibility, whereas negative association with *B. oryzae* and *C. medinalis*. Bina dhan 11 is aligned along positive dim1 and associated with *M. oryzae* and *L. acuta* (Figure 5A).

3.2.2 Lower Brahmaputra Valley (LBV) zone

The biplot explains 80.3% of the total variance in the data set (dim1 64.8% and dim2 15.5%). All the insect-pests and diseases were positively correlated, except *M. oryzae* disease with *C. medinalis,* which was not correlated. All rice varieties exhibited minimum variability compared to other study zones. Ranjit-Sub1 and Swarna-Sub1 aligned more along negative dim1, exhibiting weak association with insects and diseases (Figure 5B).

3.2.3 North Bank Plain (NBP) zone

PCA biplot on NBP explains variance of 63.1% in dim1 and 24.3% in dim2 (contributing to 87.4% of the data variability). All the insect-pests and diseases were positively correlated, except *M. oryzae* disease with *C. medinalis* and *L. acuta,* that were not correlated. All the tested rice varieties exhibited variation within group, Swarna-Sub1 has higher variability, whereas Ranjit-Sub1 exhibits association with *C. medinalis* and *L. acuta* (Figure 5C).

3.2.4 Upper Brahmaputra Valley (UBV) zone

PCA biplot on UBV, dim1 explains 32% and dim2 explains 27.4% of the variance, and a total of 59.4% variability of the data set has been captured. In the UBV zone, the evaluated diseases (*M. oryzae* and *B. oryzae*) are strongly positively correlated, as well as all the insect-pests (*C. medinalis*, *S. incertulas,* and *L. acuta*) were positively correlated; however, insect-pests are nearly perpendicular to diseases, suggesting no correlation (Figure 5D).

Ranjit-Sub1 has low variation within the group and is not associated with insects and diseases, whereas Swarna-Sub1 has a moderate, narrow spread exhibiting some variation within the group and is not associated with insects and diseases (Figure 5D).

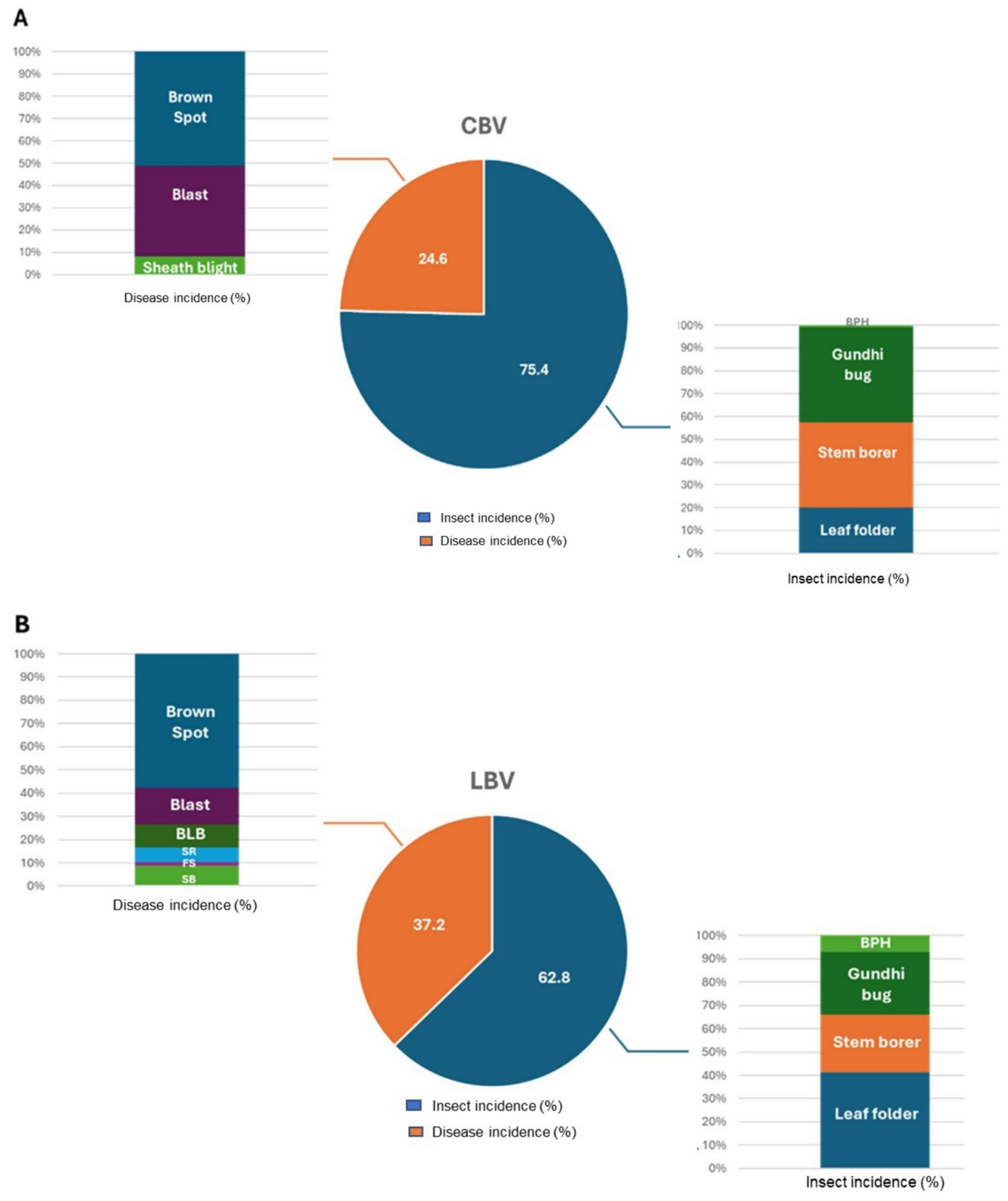

FIGURE 2 (Continued)

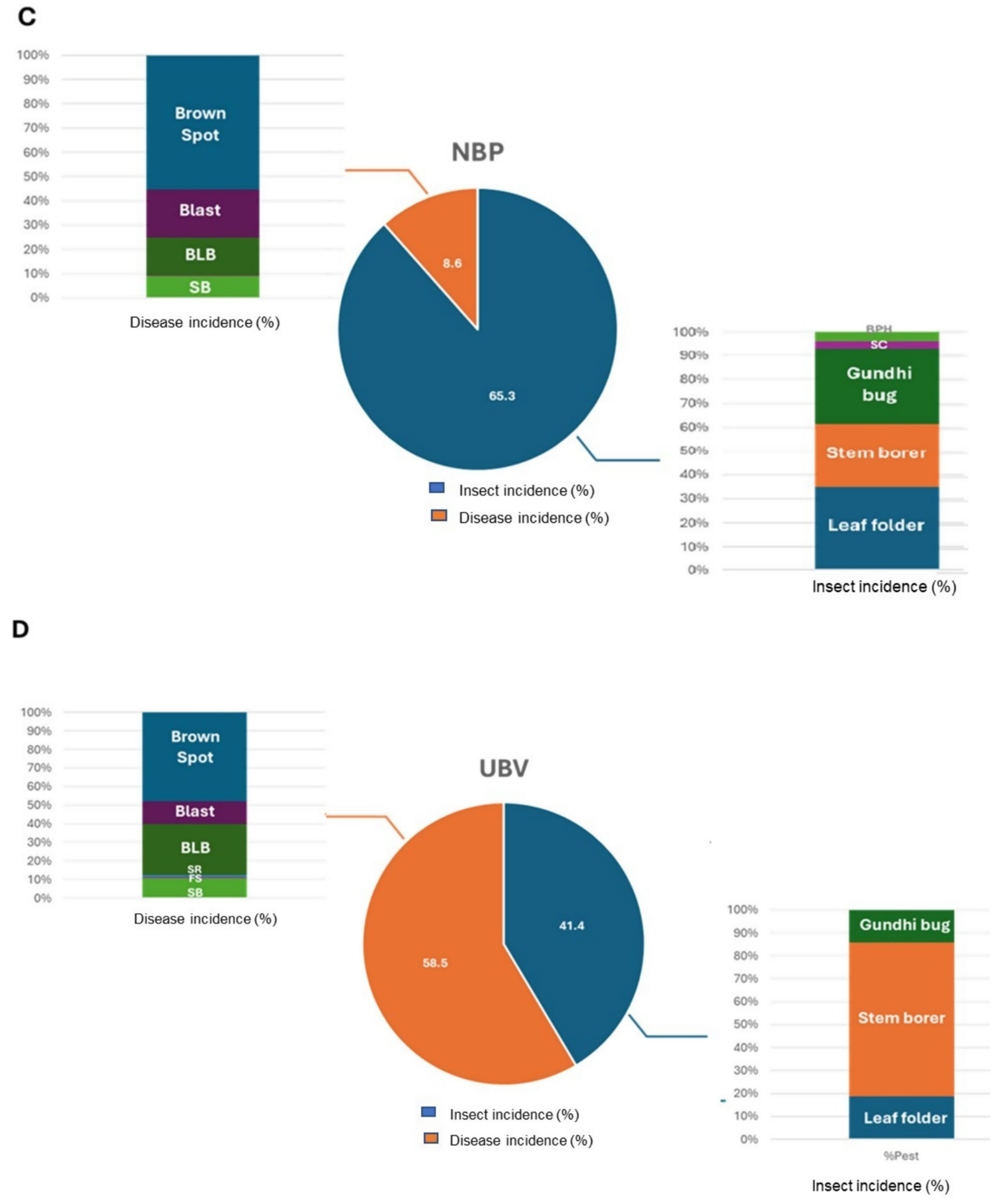

FIGURE 2 (Continued)
Percent incidence of each insect and disease that were observed in the studied agro-climatic zones of Assam [**(A)** CBV, **(B)** LBV, **(C)** NBP, and **(D)** UBV]. The main insect pests were the gundhi bug—*Leptocorisa acuta*; stem borer—*Scirpophaga incertulas* and leaf folder—*Cnaphalocrocis medinalis* and the secondary pests with lower incidence were the BPH (brown plant hopper—*Nilaparvata lugens*) and SC (swarming caterpillar—*Spodoptera mauritia*). Among diseases, the most abundant were brown spot—*Bipolaris oryzae* and blast—*Magnaporthe oryzae,* whereas lower incidence diseases—BLB (bacterial leaf blight—*Xanthomonas oryzae*), SB (sheath blight—*Rhizoctonia solani*), SR (sheath rot—*Sarocladium oryzae*), and FS (false smut—*Ustilaginoidea virens*) were reported in a few agro-climatic zones.

TABLE 3 Statistical analyses for each of the evaluated insect and disease incidence that was observed across four agro-climatic zones of Assam (CBV, LBV, NBP, and UBV) cultivated with four Sub1 rice varieties (Bahadur-Sub1, Bina Dhan 11, Ranjit-Sub1, and Swarna-Sub1) and recorded for 2 years (2020 and 2022).

Insect/disease	Parameter	Chi-Squared	df	*p*-value
Stem borer	Zone	144.88	3	<0.001***
	Year	1.75	1	0.186 ns
	Variety	53.73	3	<0.001***
Gundhi bug	Zone	430.83	3	<0.001***
	Year	19.79	1	<0.001***
	Variety	11.75	3	0.008**
Leaf folder	Zone	374.22	3	<0.001***
	Year	16.14	1	<0.001***
	Variety	22.63	3	<0.001***
Brown spot	Zone	104.37	3	<0.001***
	Year	3.62	1	0.057 ns
	Variety	8	3	0.046*
Blast	Zone	229.34	3	<0.001***
	Year	35.3	1	<0.001***
	Variety	9.19	3	0.027*

Factors that significantly affected insects/diseases are presented with significance levels as ***$p < 0.001$, **$p < 0.01$, *$p < 0.05$, and ns = $p > 0.05$.

4 Discussion

The present study indicates the predominance of insect pests over diseases in the evaluated agro-climatic zones of Assam, particularly in CBV, LBV, and NBP zones. Among the insect-pests, *C. medinalis*, *S. incertulas,* and *L. acuta* were frequently observed, while the diseases included *M. oryzae* and *B. oryzae*. The widespread incidence of these insects and diseases on Sub1 rice varieties cultivated across the agro-climatic zones of Assam can be attributed to several factors, including broad host adaptability, the prevalence of vulnerable cropping systems, prevailing agronomic practices, and specific environmental conditions that warrant further investigation. Additionally, the resistance or tolerance of Sub1 rice varieties across diverse agro-climatic zones and their influence on insect-pest dynamics have received limited attention.

The evaluated zones significantly influence the incidence of specific insect-pests and diseases, as evidenced by the highly significant chi-squared values for zone (Table 3). The CBV zone exhibited a higher incidence of insect-pests and diseases, particularly concerning *L. acuta* and *S. incertulas,* compared to other study zones. The population proliferation of *L. acuta* and *S. incertulas* was favored by warm weather combined with humid conditions during the reproductive stage of rice (Vivek et al., 2020). The climate of the CBV zone is warm and humid with >70% relative humidity (RH) during the sampling period of the *Sali* season (KVK Nagaon), which is highly conducive to the population increase of insect-pests. Similarly, fungal pathogens such as *M. oryzae* and *B. oryzae* were more prevalent in the LBV zone, indicating that the combination of warm temperature and high humidity (during July–October, *Sali* season) along with intermittent rainy days in LBV (Hussain, 2021) favored higher incidence of disease compared to the NBP and UBV zones (Figure 4). Furthermore, temporal variation, specifically, the year effect, was more pronounced for *L. acuta*, *C. medinalis*, and *M. oryzae* (Figures 3, 4), suggesting that these insects and diseases are sensitive to seasonal changes, including fluctuations in rainfall patterns and temperature.

Although weather data retrieved from NASA POWER[2] for the years 2020 and 2022 (Supplementary Table S5), along with long-term weather variables (1991 to 2020) (Supplementary Table S5) was used to describe the climatic zones, the data comparisons revealed only minor variation in temperature, and RH across the four study zones (Supplementary Table S5). These broad weather patterns suggest that the observed differences in insect and disease incidence are more likely shaped by localized agro-ecological factors like microclimatic variation, cropping intensity and pattern, and genotype × environment interaction, along with macro-weather parameters. Nevertheless, the lack of site-specific, high-frequency meteorological data limited our ability to correlate pest and disease incidence with weather parameters. Despite the constraints, the incidence of insects like *L. acuta* and *S. incertulas* across years, particularly in the CBV and LBV zones, underscores the importance of microclimate-sensitive pest monitoring and management strategies.

However, the insect-pests and disease incidence varied significantly among Sub1 rice varieties (Table 3 and Supplementary Table S6). Bina dhan 11 exhibited lower *S. incertulas* incidence, while Bahadur-Sub1 showed reduced incidence of *L. acuta.* Both Bahadur-Sub1 and Swarna-Sub1 exhibited lower levels of *C. medinalis* incidence. In the case of diseases, Bahadur-Sub1 exhibited lower *M. oryzae* incidence (Supplementary Figure S1). However, in this study, the effect of agro-climatic zones on host-plant response and pest incidence was more profound, thereby confounding varietal resistance (Figures 3, 4). For example, Bahadur-Sub1 exhibited overall lower *C. medinalis* incidence (Supplementary Figure S1), but in the LBV zone, it was anecdotally higher. Similarly, Bahadur-Sub1 exhibited higher *S. incertulas* incidence in the CBV zone, whereas in other zones it was less

2 https://power.larc.nasa.gov/data-access-viewer/index.html

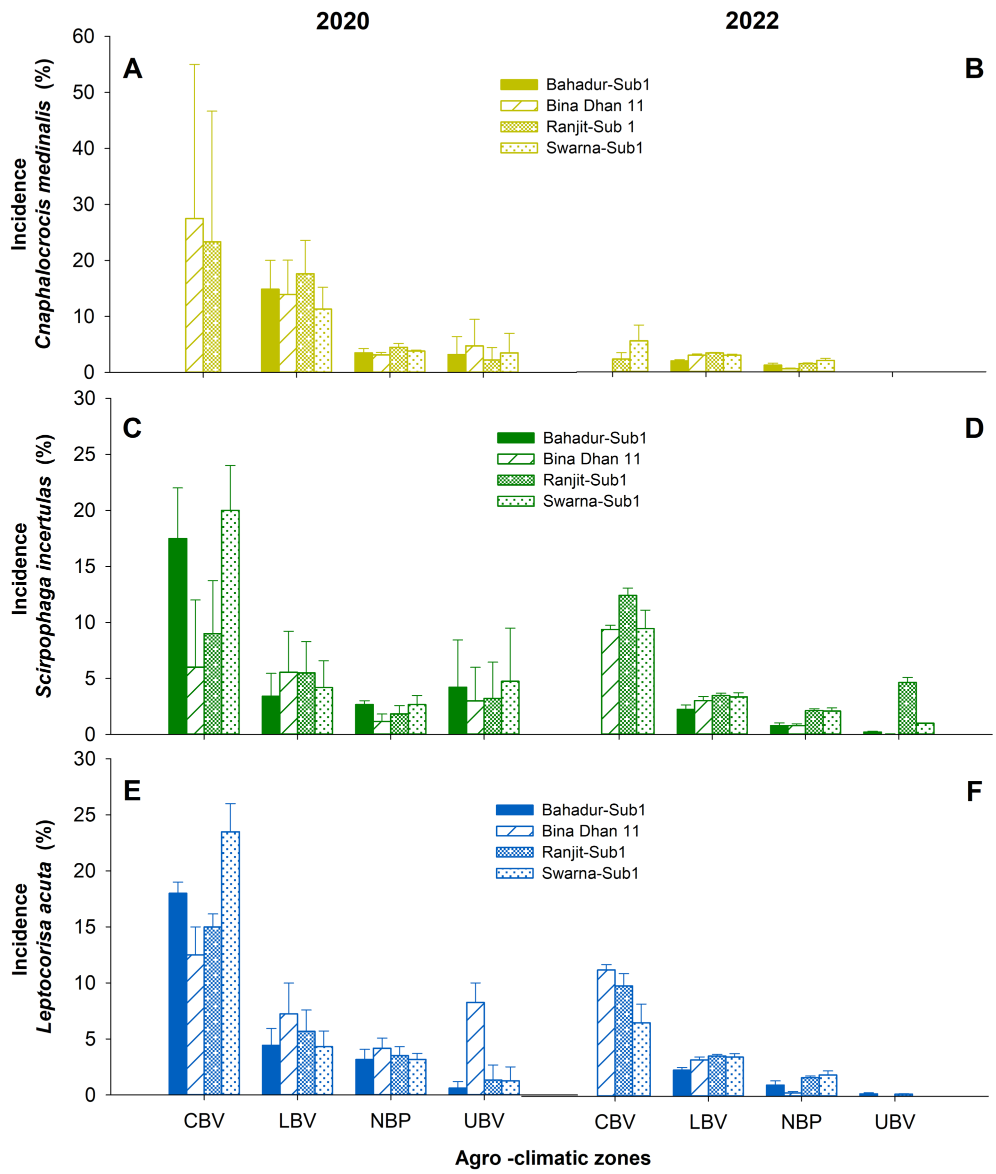

FIGURE 3
Results (mean ± SE) of the incidence of the predominant rice insect pest [**(A,B)** *Cnaphalocrocis medinalis*, **(C,D)** *Scirpophaga incertulas*, and **(E,F)** *Leptocorisa acuta*] from four agro-climatic zones of Assam (CBV, LBV, NBP, and UBV). Samplings were performed during the *Sali* season of 2020 **(A,C,E)** and 2022 **(B,D,F)**.

prevalent (Figure 3C). Rice genotypes grown under diverse agro-climatic conditions exhibit significant variation in their morphological, physiological, and molecular attributes, which subsequently determines their adaptability to varying environmental conditions (Haq et al., 2021). The present study reveals that distinct environmental and ecological conditions of agro-climatic zones have influenced the varietal response of Sub1 rice varieties, as well as the prevalence of insect-pests and diseases (Figures 3–5). This indicates the interactive effect of host genotype × climatic zone on pest occurrence, which further determines the spectrum of host resistance and durability. Ristaino et al. (2021) emphasized the possibility of the pest/pathogen to modify their host range, undergo shifts in geographical distribution, and alter their pathogenesis due to the continuous interplay among host, pathogen, and climatic conditions.

As highly evolving organisms, insects and diseases can extend their host and geographic ranges, increase fecundity and survival rates, exhibit increased risk of invasion, with changes in host phenology, climatic conditions, cropping systems and other ecological factors (Skendžić et al., 2021). Furthermore, few insect-pests and disease pathogens exhibited limited geographic distribution during the study period. This includes the lower abundance of *N. lugens* and sporadic occurrence of *S. mauritia*, along with the lower incidence of *R. solani* and sporadic occurrence of *X. oryzae*, *S. oryzae,* and *U. virens* in the study zones. These observations underscore the necessity of continuous monitoring and the implementation of effective insect and disease management strategies to prevent the potential outbreaks of insect pests and diseases in the context of changing climatic conditions, host genotypes, and cropping systems in Assam.

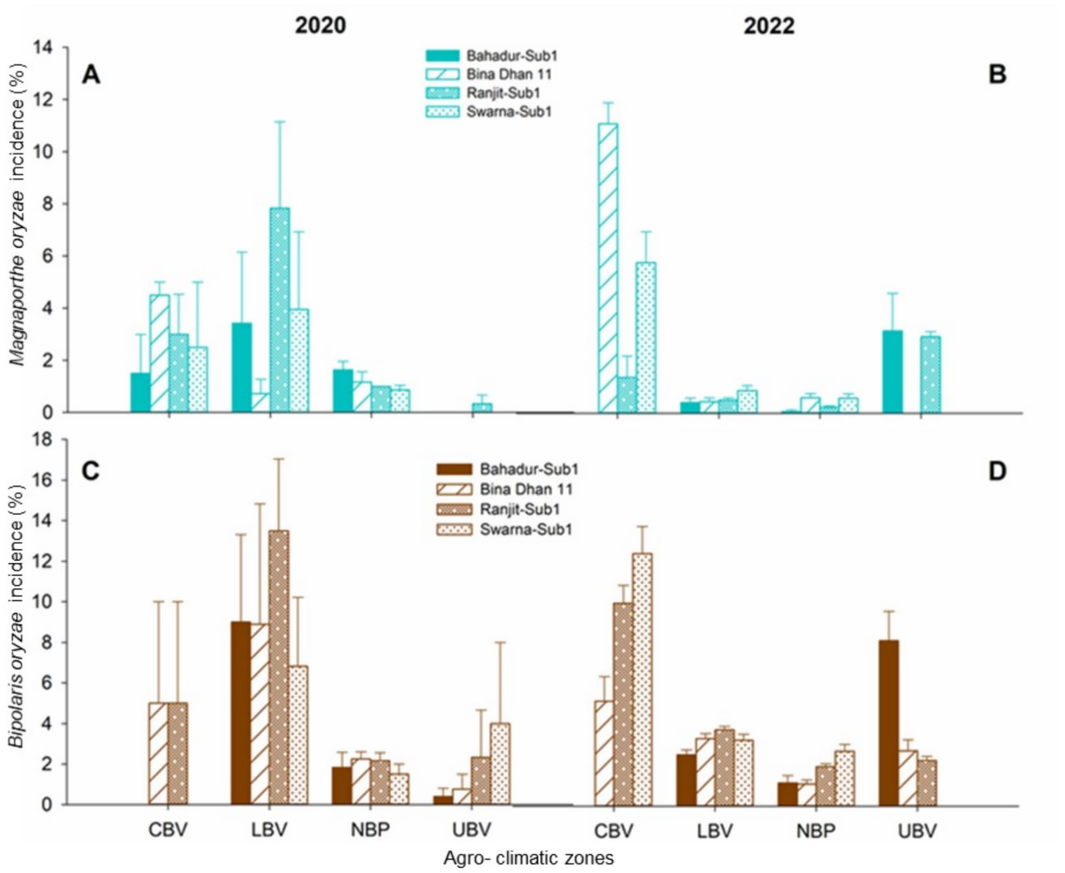

FIGURE 4
Results (mean ± SE) of the incidence of the predominant rice disease causing pathogens [**(A,B)** *Magnaporthe oryzae* and **(C,D)** *Bipolaris oryzae*] from four agro-climatic zones of Assam (CBV, LBV, NBP, and UBV). Samplings were performed during the *Sali* season of 2020 **(A,C)** and 2022 **(B,D)**.

Evidence further supports the regional-scale association among insects and diseases in accordance with host phenology, soil conditions, cropping patterns, and ecological conditions (Logan et al., 1979; Allara et al., 2012; Srinivasan et al., 2015; Lawton et al., 2022). In the present study, climatic zone-specific associations between insect populations and disease occurrences were observed. The NBP, LBV, and CBV zones exhibited positive association for insect damage (*C. medinalis*/*S. incertulas*) and disease occurrence, specifically *B. oryzae* (Figures 5B–D), suggesting that leaf damage inflicts mechanical harm that facilitates pathogen entry. *Cnaphalocrocis medinalis* and *S. incertulas* feeding involves scraping the green mesophyll tissue, resulting in reduced photosynthetic efficiency and diminished plant vigor (Chintalapati et al., 2019), rendering the plant more vulnerable to subsequent pathogen attacks. This positive association reflects the heightened vulnerability of the specific zone × host genotype interaction to concurrent pest populations, leading to increased crop stress, pest population adaptation, and ultimately, yield loss. Srinivasan et al. (2016) reported positive interspecific interactions among plant hoppers of rice, facilitating adaptation to resistant rice varieties. However, the reason behind the positive association of insect damage and fungal attack requires further investigation.

Despite variation among Sub1 varieties grown across various climatic zones, Bahadur-Sub1 showcased moderate levels of insect-pest and disease incidence compared to other Sub1 varieties, propounding it as a more suitable variety with moderate levels of insect-pest and disease tolerance for diverse agro-climatic zones of Assam (Figures 3–5). The Swarna-Sub1 variety displayed a lower disease incidence in the NBP and UBV zones, suggesting it may be a more suitable disease-tolerant variety for those areas (Figures 4, 5C,D). Conversely, Ranjit-Sub1 was more prone to *S. incertulas* and *L. acuta* in the CBV zone (Figures 3, 5A), and Bina dhan 11 exhibited higher incidences of *C. medinalis* and *L. acuta* across the study zones (Figures 3, 5). Continuous monoculturing of rice varieties such as Bina dhan 11 in vulnerable agro-climatic zones, such as the CBV zone, may favor faster adaptation of subsequent insect-pest populations. Furthermore, the recording of heavy rainfall across zones during 2020 (Supplementary Table S5) may have influenced pest and disease patterns compared to years with normal rainfall. While we acknowledge the limitations of our study regarding its correlation with typical flood and non-flood years. However, it is important to note that the frequency of flooding has increased in the study areas over the past decades (Supplementary Table S5), making these conditions more representative of the current climatic reality. Future research studies focusing on integrated datasets, including weather data, cropping systems, crop management practices, soil properties, fertilizer, and pesticide application patterns, can provide deeper insights into the complex interactions among macro and micro-climatic factors, agronomic practices, and host genotypes on insect disease dynamics.

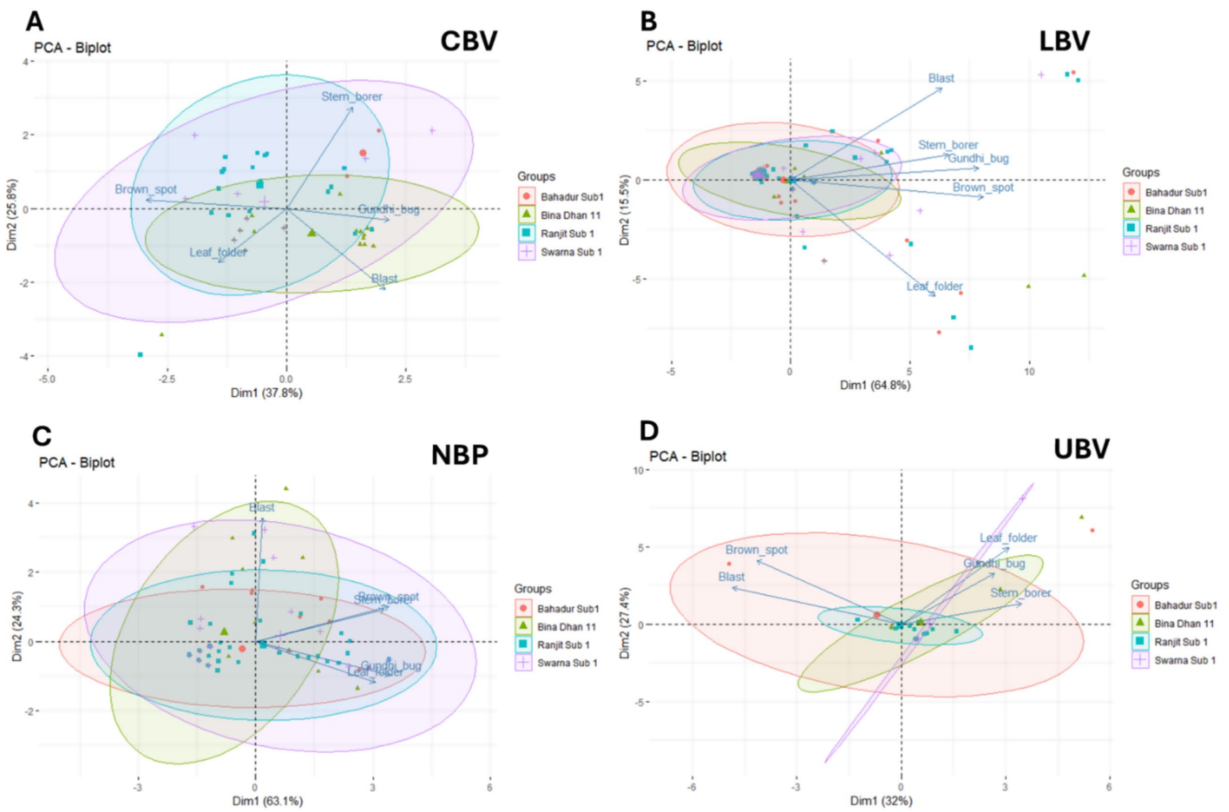

FIGURE 5
Results of the principal component analyses (PCA) for each of the agro-climatic zones of Assam [**(A)** CBV; **(B)** LBV; **(C)** NBP; **(D)** UBV] that indicate similarities and dissimilarities between observations of the rice varieties (Bahadur-Sub1, Bina Dhan 11, Ranjit-Sub1, and Swarna-Sub1) with points and ellipses, and infer the relationship between insect-pests (*Scirpophaga incertulas*, *Leptocorisa acuta,* and *Cnaphalocrocis medinalis*) and diseases (*Bipolaris oryzae* and *Magnaporthe oryzae*) with arrows. The angle between arrows indicates the correlation between variables; thus, <90° = positive correlation, ±90° = no correlation, close to 180° = negative correlation (gundhi bug—*Leptocorisa acuta*; stem borer *Scirpophaga incertulas;* leaf folder—*Cnaphalocrocis medinalis;* blast—*Magnaporthe oryzae* brown spot—*Bipolaris oryzae*).

5 Conclusion

The study provides insights into the prevalence and incidence of insect pests and diseases of Sub1 rice varieties grown across the agro-climatic zones of Assam. The results indicate that insect and disease incidence are governed by the complex interactions between host genotypes and agro-climatic conditions. The CBV zone exhibited higher insect incidence, whereas the LBV zone exhibited higher disease incidence, emphasizing the influence of zone-specific effects. Similarly, varietal differences were evident where Bahadur-Sub1 exhibited comparatively lower insect and disease incidence across zones. However, these varietal effects were often confounded by agro-climatic conditions, emphasizing the intricate interplay between host genotype and agroecological conditions. The findings of the study emphasize the critical need for continuous, location-specific monitoring and the development of adaptive pest and disease management strategies that integrate host genotype, climatic variability, and pest dynamics.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors without undue reservation.

Author contributions

TS: Conceptualization, Data curation, Formal analysis, Methodology, Software, Validation, Writing – original draft, Writing – review & editing. PP: Writing – original draft, Writing – review & editing. AP: Formal analysis, Validation, Visualization, Writing – original draft. SK: Data curation, Supervision, Writing – review & editing. VipK: Data curation, Writing – review & editing. VivK: Data curation, Writing – review & editing. MS: Project administration, Writing – review & editing. KP: Project administration, Writing – review & editing. RB: Funding acquisition, Resources, Writing – review & editing. KS: Supervision, Writing – review & editing. SA: Data curation, Writing – review & editing. GG: Supervision, Writing – review & editing. JD: Data curation, Writing – review & editing. VirK: Project administration, Writing – review & editing. SS: Funding acquisition, Resources, Writing – review & editing. AB: Project administration, Writing – review & editing.

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Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2025.1581572/full#supplementary-material

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