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Proceedings of the National Institute of Ecology of the Republic of Korea (PNIE) is an open access and online journal aimed at promoting outcomes of basic ecological researches carried out in Korea and abroad. The journal focuses on not only basic ecological research on terrestrial and aquatic populations, communities, ecosystems and landscapes but also applied issues such as data science and climate change based on ecological research.

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Original Article

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Elevated CO_2 Enhances the Proliferation of *Pseudomonas syringae* in *Arabidopsis thaliana*

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ABSTRACT

Atmospheric carbon dioxide (CO_2) levels are rapidly increasing owing to anthropogenic activities, posing a significant threat to global ecosystems. This study examined the effects of elevated CO_2 on plant-pathogen interactions using *Arabidopsis thaliana* and *Pseudomonas syringae* pv. *tomato* DC3000. Plants were grown under four CO_2 concentrations (350 [control], 700, 1,000, and 4,000 ppm) in climate-controlled growth chambers. After inoculation, bacterial growth and disease symptoms were analyzed. Elevated CO_2 levels intensified the disease symptoms, with increased chlorosis observed as the CO_2 concentration increased. Plants grown under a CO_2 concentration of 4,000 ppm exhibited severe chlorosis. Bacterial growth increased approximately 5.3-fold at 700 and 1,000 ppm compared to the control (350 ppm) and further increased by 7.3-fold at 4,000 ppm relative to 1,000 ppm. These results indicate that elevated CO_2 enhances pathogen proliferation and disease severity in *Arabidopsis thaliana*, suggesting that rising atmospheric CO_2 may increase plant susceptibility to bacterial infections under future climatic conditions.

Keywords: *Arabidopsis thaliana*, Chlorosis, Climate change, Plant-pathogen interaction, *Pseudomonas syringae* pv. *tomato* DC3000

Introduction

The release of greenhouse gases, which trap heat in the atmosphere and increase temperatures, has substantially altered the global climate and has had devastating impacts on various ecosystems (Thomas *et al*., 2004). Climate change threatens biodiversity by disrupting weather patterns, causing extreme temperatures, rising sea levels, and shifting ecosystems (Bellard *et al*., 2012). It causes biological and ecological changes and reduces the genetic diversity of populations through directional selection and rapid migration, potentially affecting ecosystem functionality and resilience (Hughes, 2000; Davis *et al*., 2005; Hickling *et al*., 2006; Botkin *et al*., 2007; Bellard *et al*., 2012). Ecosystems play a vital role in mitigating and adapting to climate change (Malhi *et al*., 2020). Therefore, it is essential to investigate the interactions between plants and pathogens in response to increasing atmospheric CO_2 levels.

Elevated atmospheric CO_2 can affect plant physiology, including photosynthesis, growth, and resource allocation, while also modulating interactions with biotic stressors, such as pathogens (Ainsworth & Long, 2005; Zavala *et al*., 2008). Increased carbon availability can alter plant defense systems, including secondary metabolite production and resistance-related signaling pathways (Matros *et al*., 2006; Mikkelsen *et al*., 2008). However, the effects of el-

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evated CO_2 on plant susceptibility are variable and depend on the specific host-pathogen system and environmental conditions (Chakraborty *et al*., 2000; Eastburn *et al*., 2011). For instance, elevated CO_2 may promote pathogen infection by increasing leaf biomass and modifying leaf chemistry, thereby enhancing the conditions for pathogen colonization (Pangga *et al*., 2011), whereas changes in stomatal conductance may further influence pathogen entry and infection efficiency (Lake & Wade, 2009). In addition, rising CO_2 levels are expected to alter pathogen virulence, reproduction, and distribution, complicating plant-pathogen dynamics and potentially affecting ecosystem stability and agricultural productivity (Garrett *et al*., 2006; Bebber *et al*., 2013). Despite these findings, the underlying mechanisms remain poorly understood, highlighting the need for studies using model systems such as *Arabidopsis thaliana* and *Pseudomonas syringae* to better understand plant-pathogen interactions under future climate conditions.

Vulnerable ecosystems, characterized by low resilience and high sensitivity to environmental change, are increasingly threatened by the combined effects of climate change and emerging pathogens (Pecl *et al*., 2017; Legg, 2021). These systems often harbor specialized species with narrow ecological tolerances, making them particularly susceptible to disturbances and disease outbreaks (Thuiller *et al*., 2005). Pathogens play a key role in regulating community structure and ecosystem processes, and their impact may intensify under changing environmental conditions (Harvell *et al*., 2002; Fisher *et al*., 2012). Climate-driven changes in temperature, moisture, and atmospheric CO_2 can alter host susceptibility, pathogen virulence, and transmission dynamics, leading to changes in disease prevalence and severity (Garrett *et al*., 2006; Bebber *et al*., 2013). Even slight increases in pathogen pressure can result in substantial ecological consequences, including biodiversity loss and disrupting ecosystem functions, particularly when genetic diversity and adaptive capacity are limited (Daszak *et al*., 2000; Hughes *et al*., 2008; Keesing *et al*., 2010). Moreover, elevated CO_2 may further exacerbate plant-pathogen interactions by modifying plant physiology and weakening defense responses (Eastburn *et al*., 2011; Pangga *et al*., 2011). Therefore, understanding these interactions is essential for predicting ecosystem responses to global change and to develop effective conservation and management strategies.

As the climate crisis intensifies, ecosystem vulnerability and the expansion of at-risk ecosystems are becoming increasingly evident due to anthropogenic environmental changes (Pecl *et al*., 2017; Legg, 2021; Park *et al*., 2024). In this study, we investigated the effects of elevated CO_2 on plant-pathogen interactions under simulated vulnerable ecosystem conditions using *Arabidopsis thaliana* and the bacterial pathogen *Pseudomonas syringae* pv. *tomato* DC3000 under controlled CO_2 concentrations to analyze both phenotypic responses and quantitative bacterial proliferation.

Materials and Methods

Sowing and germination of *Arabidopsis thaliana*

Arabidopsis thaliana ecotype Columbia-0 (*Col-0*) was used in this study. Autoclaved commercial potting soil (Bio Potting Mix No. 2, Heungnong Seed Co., Pyeongtaek, Korea) was prepared and thoroughly mixed with water to achieve an appropriate moisture content (approximately 15 L of soil per 10 L of water). The prepared soil was then filled into 2×5 cell trays. Seeds of *A. thaliana* were evenly sown on the soil surface. To promote uniform germination, the sown trays were subjected to cold stratification by placing them in complete darkness at 4°C for 4 days. Following stratification, the trays were transferred to a controlled growth chamber with a CO_2 concentration of 350 ppm, photosynthetic photon flux density of 120 μmol m^{-2} s^{-1}, temperature of 24°C, relative humidity of 60%, and a photoperiod of 16 hours light/8 hours dark. Germination proceeded for 4-5 days under these conditions.

Treatment of *Arabidopsis thaliana* under various CO_2 concentrations

At 10 days post-germination, seedlings exhibiting uniform morphology and vigorous growth were selected for transplantation. Individual seedlings were transplanted into 4×9 cell trays (36 cells per tray) containing an autoclaved commercial potting substrate (Bio Potting Mix No. 2, Heungnong Seed Co.) with one plant per cell. Immediately following transplantation, a measured volume of water was applied to reduce air pockets between the root system and the surrounding substrate, thereby promoting root-soil contact and enhancing settlement. Transplanted seedlings were subsequently acclimated in a controlled-environment growth chamber for 48 hours under the following conditions: CO_2 concentration of 350 ppm, photosynthetic photon flux density of 120 μmol m^{-2} s^{-1}, temperature of 24°C, relative humidity of 60%, and a 16 hours light/8 hours dark photoperiod. After acclimating, plants were randomly assigned to four CO_2 treatment groups: 350 (control), 700, 1,000, and 4,000 ppm. Each treatment group was transferred to an independent growth chamber to maintain precise CO_2 concentrations. All other environmental parameters were held constant across treatments, with the temperature maintained at 24°C and relative humidity at 60%. Treatments were imposed for 7 days. Throughout the experimental period, plants were irrigated every 4 to 5 days using a sub-irrigation (bottom-watering) method, whereby trays were briefly immersed in water to ensure a uniform moisture

supply while minimizing potential confounding effects on aboveground tissues.

Culture and inoculation of pathogen

Pseudomonas syringae pv. *tomato* DC3000 (*Pst*DC3000) was cultured in nutrient yeast extract glucose (NYG) liquid medium (peptone 5 g/L, yeast extract 3 g/L, glycerol 20 g/L) supplemented with rifampicin (50 mg/L) in a rotary shaker for 24 hours prior to inoculation. The bacterial suspension was adjusted to a final concentration of 1×10 CFU/mL. Plants were inoculated by infiltrating the bacterial suspension onto the abaxial side of leaves using a needleless syringe. After inoculation, the plants were returned to the chambers with the respective CO_2 concentrations and maintained for an additional 3 days.

Quantification of bacterial population in *Arabidopsis* plant tissues

Immediately after inoculation, leaf discs (5 mm in diameter) were collected from four individual plants using a cork borer, and their fresh weights were recorded. Each sample was placed in a tube containing metal beads and 1 mL of sterile distilled water was added. Tissues were homogenized using a bead-beating system (Retsch MM400; Retsch GmbH, Haan, Germany). The homogenates were plated onto NYG agar medium supplemented with rifampicin (50 mg/L) and incubated at 28°C for 2 days, after which colony-forming units (CFUs) were counted. Similarly, at 3 day post-inoculation (3 dpi), leaf samples were collected from plants maintained under different CO_2 concentrations. The samples were processed as described above, with serial dilutions performed prior to plating. The plates were incubated at 28°C for 2 days, and the CFUs were quantified. Bacterial population data are expressed as mean values per treatment, and statistical analysis was performed using one-way analysis of variance with IBM SPSS Statistics software ver. 25.0 (IBM Co., Armonk, NY, USA).

Results and Discussion

Analyzing plant-pathogen interactions under various CO_2 concentrations

In addition to the direct interactions between plants and pathogens, environmental factors play a critical role in determining plant disease outcomes. Among these factors, increasing atmospheric CO_2 concentration are expected to significantly influence plant susceptibility to pathogens. This study investigated how elevated CO_2 levels affect plant defense responses against pathogens. We established a series of controlled growth chambers capable of maintaining different CO_2 concentrations, including the control (350 ppm) and elevated levels of 700, 1,000, and 4,000 ppm (Fig. 1A). These chambers enabled precise regulation of CO_2 conditions (Fig. 1B) and allowed us to examine plant-pathogen interactions under progressively increasing CO_2 concentrations, simulating future climate scenarios. As a model system, *Arabidopsis thaliana* (Col-0) plants were grown under various CO_2 conditions and inoculated with *Pseudomonas syringae* pv. *tomato* DC3000 (*Pst*DC3000), a well-characterized bacterial pathogen widely used in mechanistic studies. Disease symptoms were subsequently monitored to analyze changes in plant resistance across CO_2 treatments. The established chamber system provided a robust platform for studying plant responses to pathogens under varying CO_2 levels and is a

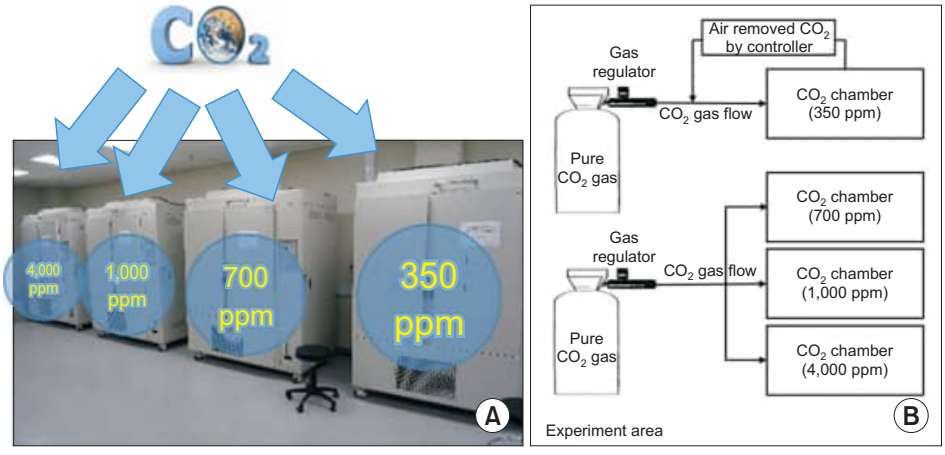

Fig. 1. Growth chambers for plant cultivation under varying CO_2 concentrations. (A) Photograph of the constructed plant growth chamber. (B) Schematic diagram of CO_2 supply according to different concentration treatments. Plants were cultivated in controlled-environment growth chambers under different CO_2 concentrations. Temperature, humidity, light intensity, and photoperiod were uniformly regulated, with only CO_2 levels varied to analyze their effects on plant growth and physiological responses.

valuable tool for understanding plant-microbe interactions in the context of climate change.

Inoculation of plant leaves with a bacterial pathogen under different CO_2 concentrations

Arabidopsis thaliana plants grown for approximately two weeks were exposed to four different CO_2 concentrations (350 ppm [control], 700 ppm, 1,000 ppm, and 4,000 ppm) in controlled growth chambers for seven days. After the CO_2 treatments, the leaves were inoculated on the abaxial surface with a standardized suspension of the pathogenic bacterium *Pst*DC3000. Following inoculation, the plants were returned to their respective CO_2 chambers and maintained for an additional three days. All environmental conditions, except for CO_2 concentration, were kept constant across treatments, and the pathogen was applied uniformly to all samples. Disease symptoms were monitored over time by analyzing symptom development, lesion formation, and bacterial proliferation. For the quantitative analysis of bacterial growth, the inoculated leaves were harvested, weighed, and homogenized. The resulting extracts were serially diluted and plated onto agar media. Plates were incubated at 28°C for 48 hours, after which CFUs were counted (Fig. 2). This method enables quantitative analysis of pathogenic bacterial growth in plants under varying environmental conditions.

Elevated CO_2 enhances the susceptibility of bacterial pathogen in *Arabidopsis* plants

To investigate the effect of elevated atmospheric CO_2 on plant-pathogen interactions, *Arabidopsis thaliana* plants were exposed to four different CO_2 concentrations (350 ppm [control], 700 ppm, 1,000 ppm, and 4,000 ppm) for one week prior to pathogen inoculation. Following this pretreatment, the plants were inoculated with the bacterial pathogen *Pst*DC3000 and maintained under the same CO_2 conditions throughout the experimental period. Disease symptoms were visually analyzed after inoculation. Plants grown under elevated CO_2 conditions exhibited more pronounced disease symptoms, including chlorosis and necrosis, at 3 dpi than the controls (Fig. 3A). The severity of these symptoms increased progressively with rising CO_2 concentrations, suggesting that elevated CO_2 enhanced host susceptibility to bacterial infection. To quantitatively analyze bacterial proliferation, bacterial population densities in leaf tissues were measured immediately after inoculation (0 dpi) and at 3 dpi. At 0 dpi, no significant differences in the bacterial population size (log scale) were observed among the treatments, confirming that equal amounts of inoculum were applied across all CO_2 conditions. In contrast, at 3 dpi, bacterial populations increased markedly with increasing CO_2 concentrations. Specifically, bacterial growth in plants exposed to 700 ppm and 1,000 ppm CO_2 increased approximately 5.3-fold relative to control (350 ppm). Furthermore, plants grown under 4,000 ppm CO_2 exhibited an approximately 7.3-fold higher bacterial population compared to those grown at 1,000 ppm (Fig. 3B). These findings are consistent with the observed disease symptoms and indicate that elevated CO_2 promotes bacterial proliferation within host tissues. In conclusion, these results demonstrate that increasing atmospheric CO_2 concentrations enhance the susceptibility of *Arabidopsis thaliana* to the bacterial pathogen *Pst*DC3000, as evidenced by both intensified disease symptoms and increased pathogen growth.

Author Contributions

Conceptualization: HCP. Data curation: HCP. Formal analysis: HCP, YJK. Funding acquisition: HCP. Investigation: HCP, YJK. Methodology: HCP, YJK. Project administration: HCP. Resources: HCP. Software: HCP, YJK. Supervision: HCP. Validation: HCP. Visualization: HCP. Writing – original draft: HCP. Writing – review & editing: HCP.

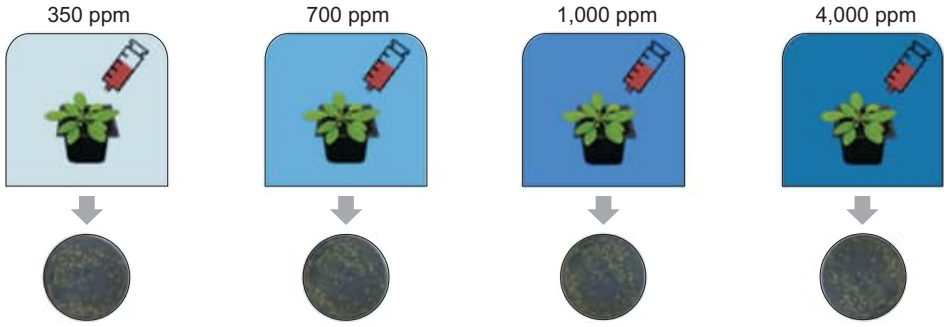

Fig. 2. Schematic diagram of plant pathogen (*Pst*DC3000) treatments under varying CO_2 concentrations. Plants were exposed to controlled CO_2 levels, and pathogen infection was evaluated under uniform environmental conditions to enable reliable comparisons among treatments. Each circle denotes an individual culture dish of *Pst*DC3000 following infection, corresponding to the respective CO_2 treatment conditions.

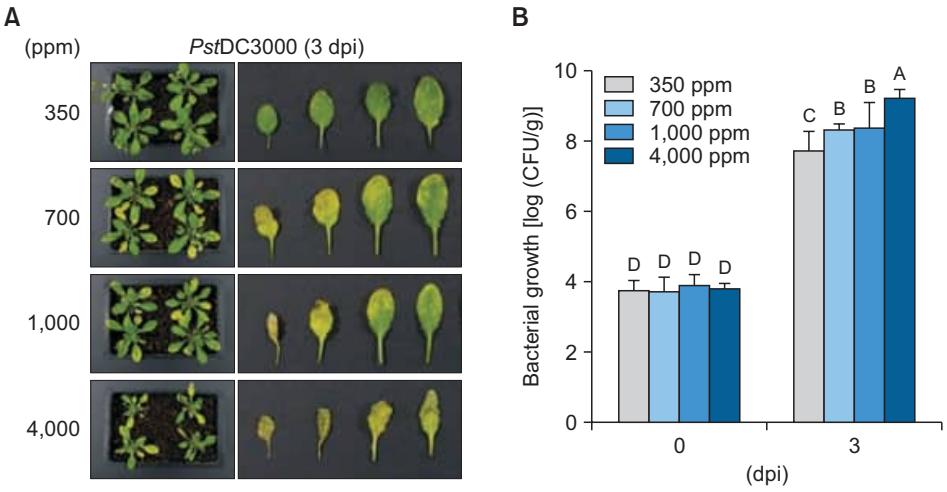

Fig. 3. Effects of different CO_2 concentrations on disease symptoms and bacterial growth of *Pst*DC3000. (A) Representative disease symptoms in plants at 3 day post-inoculation (dpi) under different CO_2 concentrations (350, 700, 1,000, and 4,000 ppm). Whole-plant phenotypes (left) and detached leaves (right) illustrate variations in symptom severity across treatments. (B) Bacterial population dynamics in infected leaves at 0 and 3 dpi, expressed as log (CFU g^{-1}). The results are representative of three independent experiments. Data represent mean±standard error. Different letters indicate statistically significant differences among CO_2 treatments (P<0.05). CFU, colony-forming unit.

Conflict of Interest

The authors declare that they have no competing interests.

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Effects of Thermal Effluents on the Species Diversity and Community Structures of Benthic Macroinvertebrates and Fish in the Jukdangcheon Basin, South Korea

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ABSTRACT

This study assessed how thermal effluents from semiconductor manufacturing influence stream water temperature and the community structure of benthic macroinvertebrates and fish in two Korean streams. Jukdangcheon receives continuous warm wastewater, whereas nearby Bokhacheon receives no such inflow. Five sites were surveyed: three along Jukdangcheon and two on Bokhacheon, located upstream and downstream of the confluence. Benthic macroinvertebrates and fish were collected and identified in field surveys, and water temperature was measured on five occasions. Welch's two-sample t-tests compared temperatures among sites. Venn diagrams described shared and unique species, while β-diversity and local contributions to β-diversity (LCBD) quantified spatial heterogeneity in both assemblages. Results showed that Jukdangcheon was significantly warmer than Bokhacheon during winter (P<0.001), but summer differences were not significant, demonstrating that thermal-effluent effects are strongly seasonal. Jukdangcheon also had relatively high frequencies and proportions of invasive non-native taxa. Heat-tolerant invasive benthic macroinvertebrates and ornamental fish were concentrated in the upper reaches, indicating that warmed habitats can favor establishment and aggregation of non-native species. Several upstream sites exhibited high LCBD values for both communities, suggesting that localized environmental conditions and invasive species jointly increased community heterogeneity. Overall, the study concludes that wintertime warming driven by thermal effluents can be a key driver of biological community change in receiving streams. It recommends year-round temperature monitoring and β-diversity-based assessment as baseline tools for ecological risk evaluation and for developing conservation and management strategies for impacted streams. These approaches can guide mitigation, detect future invasions early, and prioritize restoration actions effectively.

Keywords: β-diversity, Benthic macroinvertebrates, Fish assemblage, Invasive alien species, LCBD, Thermal effluent

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Introduction

With the acceleration of industrial activity and urbanization, anthropogenic heat sources entering streams are increasing worldwide. Thermal effluent discharged from power plants, industrial complexes, and sewage treatment

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facilities is identified as a major factor disrupting the temperature dynamics of stream water systems. Stream water temperature is a pivotal environmental factor that influences the physiology, growth, reproduction, and species distribution of aquatic organisms. Artificial increases in water temperature can have short- and long-term impacts on the structure and function of stream ecosystems (Han *et al.*, 2017; West *et al*., 2021).

In South Korea, the summer season is characterized by elevated natural water temperatures, which reduce the effect of relative temperature increase from thermal effluents. Conversely, during winter, under conditions of low air temperature, thermal effluents lead to the formation of localized high-temperature environments, resulting in a considerable increase in water temperature heterogeneity. In some areas, they can function as thermal refugia for certain biota (Worthington *et al*., 2015; Johnson *et al*., 2024). Such environments may act as limiting factors for native aquatic organisms; conversely, they may provide favorable conditions for the establishment and spread of highly heat-tolerant, invasive non-native species.

Benthic macroinvertebrates and fish constitute representative biological indicator groups reflecting the structure and function of stream ecosystems and exhibit heightened sensitivity to changes in water temperatures and disturbances in their habitat environment. A body of research has reported that thermal effluents can result in alterations, including a decline in species richness, a simplification of community structure, and an escalation in the population of non-native species (Madden *et al*., 2013; Johnson *et al*., 2024). However, there is a paucity of comprehensive analyses on the effects of thermal effluents on spatial community structure and β-diversity in South Korean streams. In particular, research comparing thermal effluent-affected streams and adjacent natural streams based on year-round survey data, including winter, is limited.

β-diversity has been identified as a pivotal metric for evaluating spatial heterogeneity and alterations in ecosystem structure, as evidenced by disparities in species composition among distinct locations. Local contributions to β-diversity (LCBD) analyses, which help quantify the contributions of individual sites to overall β-diversity, have been utilized to evaluate stream ecosystems and establish conservation priorities (Legendre & De Cáceres, 2013; Heino & Grönroos, 2017). LCBD analyses are considered a suitable tool for assessing the impact of thermal effluents and can be used to effectively detect the ecological distinctiveness of specific sites, the impact of invasive species, or community differentiation based on local environmental conditions.

In this study, we evaluated the impact of thermal effluents on stream ecosystems by analyzing water temperatures, benthic macroinvertebrate and fish communities, and β-diversity and LCBD in the Jukdangcheon and Bokhacheon streams, receiving continuous or no effluent, respectively, from semiconductor manufacturing. We specifically aimed to analyze any differences in the effects of thermal effluents in response to seasonal changes in water temperatures, identify invasive non-native species and community heterogeneity, assess ecological risks, and ensure the management and conservation of streams receiving thermal effluent. Our findings provide foundational data for evaluating the ecosystems of streams affected by thermal effluents and for establishing long-term monitoring strategies.

Materials and Methods

Data collection and field survey

In this study, we selected a total of five sampling sites: three sites along the Jukdangcheon Stream affected by thermal effluents (JD1-JD3) and one site each upstream and downstream of the Bokhacheon Stream where the Jukdangcheon Stream converges (BH1 and BH2) (Fig. 1).

The latitude and longitude of each site, as well as the stream order, were calculated using the stream network constructed based on the digital elevation model, following the criteria proposed by Strahler (1952). Stream and water widths were measured in the field using a distance measuring device (FineCaddie UPL300; FINEDIGITAL Inc., Seongnam, South Korea). Water temperatures were also measured on March 19, June 20, July 6, and September 11, 2024 and January 20, 2025 (five occasions in total) using a thermometer (Foronemillion Foldable Thermometer, FS100; Foronemillion Co., Ltd., Seoul, South Korea)

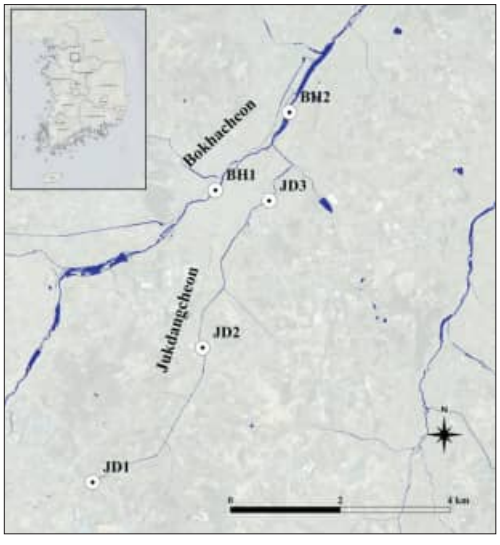

Fig. 1. The geographic location of survey sites in the Jukdangcheon basin. JD, Jukdangcheon; BH, Bokhacheon.

(Table 1). A comparative analysis of temperature variations in the water bodies of the Jukdangcheon and Bokhacheon Streams was conducted. The water temperature measurements obtained from both streams were categorized into winter (January and March) and summer (July and September) periods. For testing the mean difference between the groups, the two-sample t-tests proposed by Welch (1947), which did not require the assumption of equal variances, considering the possibility of differing sample sizes and variances, were used.

Surveys of benthic macroinvertebrates were conducted on April 11-12, June 20, October 21-22, 2024 and January 21 and February 25, 2025 (five occasions in total). Survey sections were set to lengths of 50-100 m; quantitative (three samples per site) and qualitative (focusing on microhabitats) sampling was performed using a D-frame net (frame size: 30 cm width×25 cm height; mesh size: 500 μm) and a scoop net (frame size: 30 cm width×10 cm height; mesh size: 1 mm). The sampling surveys included various microhabitats, such as riffles, pools, edge stillwater zones, aquatic vegetation beds, leaf litter, and organic matter deposits (Table 2). The collected samples were fixed on-site (in 95% ethanol) and transported to the laboratory. Following their sorting in the laboratory, the specimens were identified under a stereomicroscope (Olympus SZX-TR30; Olympus, Tokyo, Japan). Taxonomic groups that proved challenging to identify at the species level were classified at the genus or family level. Fish surveys were conducted on April 28-29, July 14-15, and October 13-14, 2024 and January 26-27, 2025 (four times in total). Sampling was conducted using a scoop net (frame size: 30 cm width×10 cm height; mesh size: 1 mm) and a cast net (radius: 2.1 m; mesh size: 7 mm). The surveys were meticulously designed to include as many different habitats as possible at each site, while considering the flow velocity, water depth, and streambed structure of the streams. Sampling efforts were standardized based on the number of cast net throws (10 times per site) and scoop net duration (60 minutes per site) to ensure the comparability of data collected across different sites (Table 2). All collected fish specimens were identified on-site. In cases where specimen identification in the field proved challenging, they were photographed and subsequently reconfirmed in the laboratory. The reconfirmation process involved using domestic fish identification guides and taxonomic literature to verify the species. The final species list was prepared according to the national species list framework (NIBR, 2023).

Comparative analysis of species composition

To compare any differences in the species composition of benthic macroinvertebrates and fish between the survey sites, presence and absence data were compiled based on the species lists identified at each site. Venn diagram analysis was performed to identify species unique to each site and those common to all sites, which revealed the

Table 1. Survey site location information in the Jukdangcheon basin

ID	Latitude	Longitude	Locality	Stream name	Stream order	Altitude (m)	Stream width (m)	Water width (m)
JD1	37.258545	127.48319	Sinha-ri, Bubal-eup, Icheon-si	Jukdangcheon	3	64	20	8
JD2	37.280448	127.505774	Jukdang-ri, Bubal-eup, Icheon-si	Jukdangcheon	3	48	35	15
JD3	37.304342	127.51947	Gobaek-ri, Bubal-eup, Icheon-si	Jukdangcheon	4	41	40	10
BH1	37.306052	127.508407	Muchon-ri, Bubal-eup, Icheon-si	Bokhacheon	6	38	240	45
BH2	37.318723	127.523631	Daegwan-ri, Bubal-eup, Icheon-si	Bokhacheon	6	36	240	50

JD, Jukdangcheon; BH, Bokhacheon.

Table 2. Standardized sampling effort at each site (benthic macroinvertebrates and fish)

Taxa	Gear	Unit effort definition	Total surveys	Methods
Benthic macroinvertebrates	D-frame net (30×25 cm, 500 μm)	3 times×point	5	Quantitative
	Scoop net (30×10 cm, 1 mm)	10 min×2 people	5	Qualitative
Fish	Cast net (2.1 m, 7 mm)	10 times×point	4	Quantitative
	Scoop net (30×25 cm, 500 μm)	60 min×2 people	4	Qualitative

commonalities and differences in community structure based on the presence/absence of thermal effluent inflow and differences in habitat conditions. The Venn diagram was created using the "VennDiagram" package in R (Chen & Boutros, 2026; Dray *et al*., 2026; The R Core Team, 2026).

β-diversity analysis of benthic macroinvertebrates and fish using the LCBD approach

β-diversity is a key indicator revealing structural differences in ecosystems, the impact of disturbances, and conservation value by examining spatial variations in species composition between sites. The species composition data for each survey site were organized into a cluster matrix with survey sites in the rows and species in the columns, which was then converted to Hellinger distance for application. Next, β-diversity was calculated using the Bray–Curtis distance coefficient based on transformed cluster data and then decomposed into variance components to determine the contribution of each survey point to the overall β-diversity, which was expressed as the LCBD value (Legendre & Cáceres, 2013; Heino & Grönroos, 2017; Xia *et al*., 2022). This scale can ultimately be divided by the contribution of the region or species to the overall β-diversity (Legendre & Cáceres, 2013). LCBD output was generated using the "adespatial" package in the R software (Dray *et al*., 2026; The R Core Team, 2026). The calculated LCBD results were mapped using QGIS (version 3.40.9-Bratislava) (QGIS Development Team, 2024).

Results and Discussion

Jukdangcheon Stream with thermal effluents

Water temperatures measured at three points on the Jukdangcheon Stream and two points on the Bokhacheon Stream averaged 25.2±7.0°C and 19.8±10.4°C, respectively, with the Jukdangcheon Stream generally showing higher temperatures than the Bokhacheon Stream. The average temperature difference was significant during winter (January and March), with that of the Jukdangcheon Stream at 17.9±5.2°C and that of the Bokhacheon Stream at 7.8±1.9°C (approximately 10.1°C) (Table 3), based on Welch's two-sample t-tests (P<0.001). Conversely, during the summer months of July and September, the average temperature difference between Jukdangcheon (30.2±1.9°C) and Bokhacheon (28.0±1.3°C) was relatively small (approximately 2.2°C) and not statistically significant (P=0.056), suggesting that the impact of thermal effluents is more pronounced in winter than during the annual average temperature increase owing to the formation of thermal refugia. Changes in community structure and the potential of non-native species to become established may be more sensitive to winter conditions than to summer conditions.

Previous studies have also reported that water temperature modeling considering wastewater treatment plant effluent showed a rapid increase in water temperature near the discharge point, with its impact diminishing downstream. The impact of effluents on winter water temperatures was found to be statistically significant. However, the relative effects of changes in air temperatures were found to be limited (Adams *et al*., 2023). The results obtained in this study corroborated a pattern of rapid increases in water temperatures near the discharge points of the semiconductor factory. Furthermore, the differences in water temperatures between the streams was greater in winter than in summer, aligning with the results of previous studies (Adams *et al*., 2023).

The rise in water temperatures in winter owing to thermal effluent inflow has the potential to transform the affected section into a relatively stable thermal refugia compared with the surrounding streams. This phenomenon may serve as an important factor in altering the distribution of species whose survival and activity are restricted during low-temperature periods (Fig. 2). In particular, species with high water-temperature tolerance or invasive non-native species may exhibit elevated overwintering success rates and population maintenance potential under these conditions, leading to a concentrated occurrence pattern centered around thermal effluent inflow sections (Park *et al*., 2025a; Yoğurtçuoğlu *et al*., 2025). Consequently, even within the same stream, differences in

Table 3. Water temperature (°C) conditions at each survey site

Date \ Site	Jukdangcheon			Bokhacheon	
	JD1	JD2	JD3	BH1	BH2
March 19, 2024	21.9	18.9	8.0	8.0	10.4
June 20, 2024	30.1	30.1	29.8	26.4	28.9
July 6, 2024	31.7	31.4	31.5	28.7	29.2
September 11, 2024	30.9	28.9	26.9	26.3	27.6
January 20, 2025	22.2	19.0	17.3	5.9	7.0

JD, Jukdangcheon; BH, Bokhacheon.

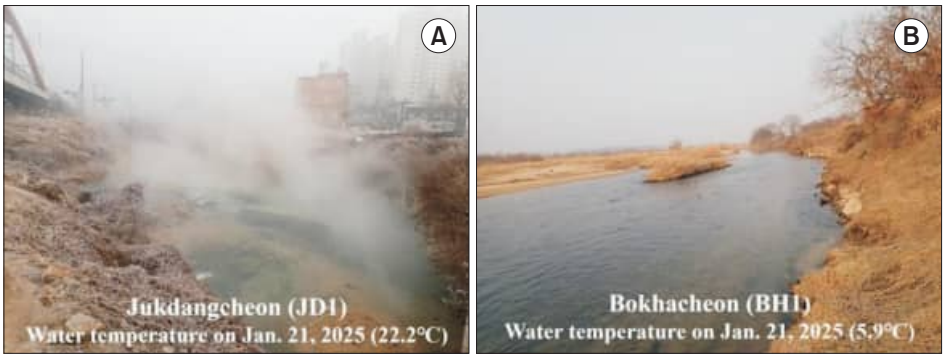

Fig. 2. Site photographs of (A) Jukdangcheon (JD1) and (B) Bokhacheon (BH1), January 21, 2025.

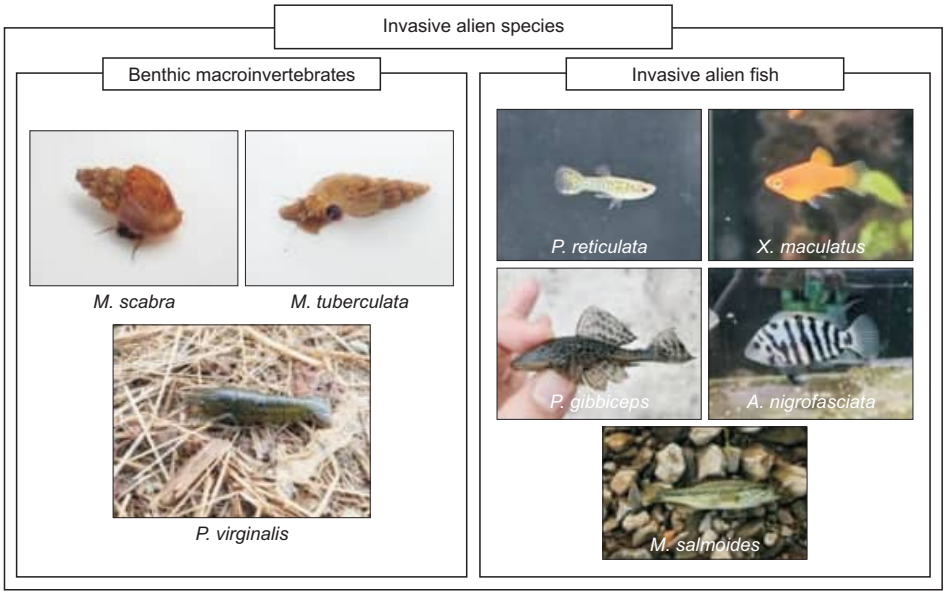

Fig. 3. Alien invasive fish and benthic macroinvertebrates observed in Jukdangcheon.

species composition between points may widen, potentially increasing the spatial heterogeneity (β-diversity) of the community. Therefore, in this study, we focused on examining the species compositions and patterns of non-native species identified in Jukdangcheon (thermal effluent impact zone) and Bokhacheon (control stream) and on investigating the connection, derived through LCBD analysis, of "specific sites" to water temperature characteristics.

Species composition in thermally affected streams

A total of 44 species of benthic macroinvertebrates were surveyed, comprising 35 in the Jukdangcheon Stream and 32 in the Bokhacheon Stream (Supplementary Table 1). Among these, three non-native invasive species were identified: *Mieniplotia scabra*, *Melanoides tuberculata*, and *Procambarus virginalis* (Fig. 3) (Park *et al*., 2024; 2025a). A total of nine species were identified in the Jukdangcheon Stream and twelve in the Bokhacheon Stream. These findings indicate substantial differences in species composition between the two streams. When Jukdangcheon was divided into upper (JD1), middle (JD2), and lower (JD3) reaches, the number of recorded species was 20, 23, and 24, respectively, showing an increasing trend toward the lower reaches. In contrast, the presence of invasive non-native species was identified in the upper reaches (JD1; three species [15.0%]) and in the middle reaches (JD2; two species [8.7%]); no such observations were recorded in the lower reaches (JD3). This finding suggests that the occurrence of non-native species is predominantly concentrated in the upper and middle reaches (Table 4, Fig. 4). The higher prevalence of non-native species in the upper reaches (JD1) is presumably attributable to the relatively warm winter water temperatures, which engender optimal conditions for overwintering and population maintenance (Rahel & Olden, 2008).

A total of 18 distinct fish species were documented within the two streams, with 13 species being surveyed across both the Jukdangcheon and Bokhacheon Streams (Supplementary Table 2). There were five confirmed invasive fish species: *Pterygoplichthys gibbiceps*, *Micropterus salmoides*, *Poecilia reticulata*, *Xiphophorus maculatus*, and

Table 4. Species number, invasive alien species number, and proportion (%) by survey site (fish and benthic macroinvertebrates)

Site	Taxa	Benthic macroinvertebrates			Fish		
		Number of species	Number of alien species	Ratio of alien species (%)	Number of species	Number of alien species	Ratio of alien species (%)
Jukdangcheon	JD1	20	3	15.0	9	4	44.4
	JD2	23	2	8.7	6	0	0
	JD3	24	0	0	7	0	0
Bokhacheon	BH1	25	0	0	11	1	9.1
	BH2	23	0	0	7	1	14.3

JD, Jukdangcheon; BH, Bokhacheon.

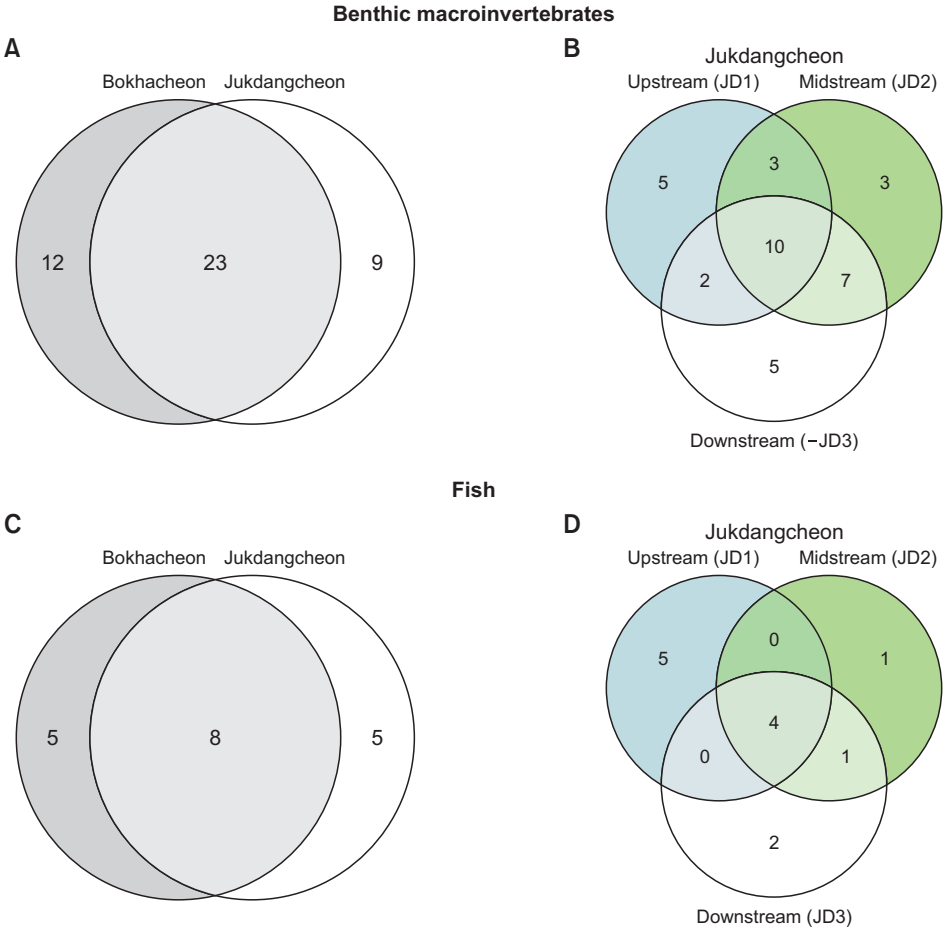

Fig. 4. Comparison of species richness between benthic macroinvertebrate and fish among survey sites. (A) Species richness of benthic macroinvertebrates for each stream, (B) benthic macroinvertebrate species richness at each survey site in Jukdangcheon, (C) species richness of fish for each stream, (D) fish species richness at each survey site in Jukdangcheon.

Amatitlania nigrofasciata (Fig. 3). Four of these species (*P. gibbiceps*, *P. reticulata*, *X. maculatus*, and *A. nigrofasciata*) were observed in the Jukdangcheon Stream, whereas one species (*M. salmoides*) was observed in the Bokhacheon Stream, indicating a greater burden of non-native species in Jukdangcheon than in Bokhacheon. Additionally, five fish species were observed exclusively in Jukdangcheon and five exclusively in Bokhacheon. The number of species recorded in the upper (JD1), middle (JD2), and lower reaches (JD3) of the Jukdangcheon Stream was nine, six, and seven, respectively. Four species (44.4%) of invasive non-native fish were identified in the upper reaches (JD1), whereas none were observed in the middle (JD2) or lower reaches (JD3), indicating a distinct concentration of non-native species occurrence in the upper reaches (Table 4, Fig. 4).

This pattern suggests that thermal disturbances in streams receiving thermal effluent can influence the structure of biological communities. The inflow amounts of thermal effluent have been observed to exceed the tolerance range of aquatic ecosystems, likely resulting in adverse effects on fish and large benthic invertebrates (Madden *et al*., 2013). Moreover, considering that the Jukdangcheon Stream bed is predominantly composed of sand, the diversity of species present within such a stream may be constrained owing to their rudimentary habitat. Concurrently, the thermal effluent inflow section functions as a winter thermal refugia, thereby increasing the potential for species with high water-temperature tolerance, particularly invasive non-native species, to overwinter and establish themselves, which creates a favorable environment for population maintenance. The localized concentration of invasive species, in conjunction with an increase in heterogeneity within community structure, may consequently result in long-term alterations in food web structure and ecosystem function.

The gastropods *M. scabra* and *M. tuberculata* identified in this study are highly popular in the ornamental trade as "clean-up crews" for controlling algae and organic matter. They are likely to have been introduced unintentionally by attaching to aquatic plants or released after being reared for ornamental purposes (Park *et al*., 2025b; 2026). These species are spreading globally through the aquarium trade, and their presence in Jukdangcheon Stream is believed to be the result of introduction along with ornamental fish by local residents or hobbyists. The fish species *P. reticulata* and *P. gibbiceps* are also commonly traded in the ornamental fish market. Given that Jukdangcheon Stream is locally referred to as "Guppy Stream," intentional release appears to be the primary source of their introduction (Park *et al*., 2025a). The identified gastropods (*M. scabra* and *M. tuberculata*) possess strong reproductive capabilities, including parthenogenesis, which allows them to rapidly increase their population size. Once established, they may outcompete native species and suppress their populations (Park *et al*., 2024; 2025a). Although these species generally prefer tropical and subtropical climates (18-31°C), environments like Jukdangcheon Stream, where heated effluent maintains warm water temperatures year-round, serve as "thermal refugia," enabling their survival and reproduction even during winter. While their immediate spread to adjacent natural streams with low winter temperatures may be limited at present, these species have the potential to spread throughout domestic aquatic ecosystems in the event of rising water temperatures due to climate change or anthropogenic translocation to other streams receiving thermal effluent (Park *et al*., 2025a; 2026).

LCBD-based habitat analysis of macroinvertebrates and fish

The inter-site β-diversity of benthic macroinvertebrate communities (β-diversity [BD] total=9.1, sum of squares [SS] total=36.4) was found to be relatively high, confirming distinct spatial heterogeneity in species composition among survey sites. The site-specific LCBD values were calculated as JD1=0.267, JD2=0.152, JD3=0.168, BH1=0.295, and BH2=0.119. Notably, BH1 (LCBD=0.295) and JD1 (LCBD=0.267) were identified as "unique sites" with notable contributions to the overall β-diversity. This finding suggests that, relative to other data points, the composition of the clusters at these particular instances is comparatively distinctive (Fig. 5A). BH1 exhibited characteristics that distinguished it from other sites, including the distribution of fine gravel on the streambed and formation of riffles influenced by submerged weirs. These characteristics suggest that BH1 inhabits a distinct physical habitat. JD1 was identified as a site where the appearance of invasive non-native species was concentrated. In contrast, BH2 (LCBD=0.119) exhibits a cluster composition that closely resembles the overall mean, suggesting that it functions as a "representative" site.

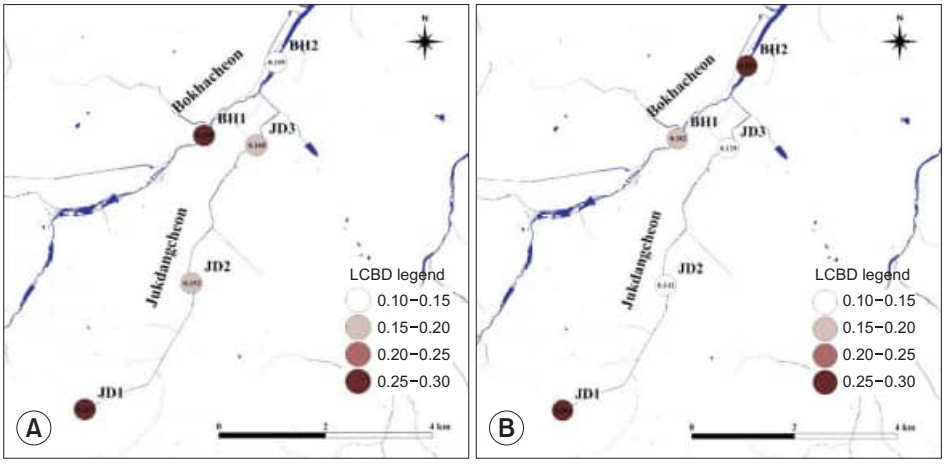

Fig. 5. Local contribution to beta diversity (LCBD) of benthic macroinvertebrates (A) and fish (B) across survey sites in the Jukdangcheon basin. JD, Jukdangcheon; BH, Bokhacheon.

Fish communities exhibited variations in species composition between the sites, as demonstrated by β-diversity (BD total=3.8, SS total=15.2) (Fig. 5B). The location of the large underwater dam at BH2 may have induced variations in fish community composition due to alterations in flow velocity, water depth, and habitat structure. JD1 is a primary nexus for the proliferation of invasive non-native species, indicating that factors contributing to the emergence of non-native species may have intensified the distinctiveness of the community structure. In contrast, JD2 and JD3 exhibited relatively stable cluster composition with low LCBD values, showing patterns similar to the overall average.

A high LCBD value does not mean that the thermal effluent is the cause, but rather that the community composition is unique compared with other sites. Therefore, the specificity of JD1 can be explained based on the combination of two biological factors: (i) high water temperatures in winter (thermal effluents) and (ii) emergence of non-native species. In contrast, the specificity of BH1/BH2 in Bokhacheon is likely due to physical habitat factors, such as submerged weirs, riffle formation, and bed sediment size (Legendre & Cáceres, 2013).

The impact of thermal effluents has been shown to cause more pronounced thermal disturbances in winter than in summer. Furthermore, the upper reaches of the Jukdangcheon Stream (JD1) have been found to contain a high concentration of invasive species and a high LCBD, indicating that it is considered an invasion risk hotspot. Moreover, LCBD can also increase in comparable streams depending on structural/bed conditions. Consequently, the design of management and monitoring systems should prioritize efficiency, encompassing not only "thermal effluent sections" but also points exhibiting high community specificity (upper LCBD points). The probability of invasive species overwintering in water bodies increases with increasing water temperatures in winter. Therefore, streams receiving thermal effluents should be subjected to prioritized intensive monitoring in winter (early detection) and management of upstream sources (discharges, leaks, and ornamental fish releases) responsible for the introduction of invasive species.

Author Contributions

Conceptualization: SJK. Data curation: SJK, YP. Formal analysis: SJK. Funding acquisition: YP. Investigation: SJK, ICH, YJ, HY. Supervision: YP. Visualization: SJK. Writing – original draft: SJK, YP. Writing – review & editing: SJK, YP.

Conflict of Interest

The authors declare that they have no competing interests.

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Distribution of Invasive Alien Plants and Park-Type–Specific Management Strategies in National Parks of Korea

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ABSTRACT

Invasion by alien species is a major driver of global biodiversity loss and ecosystem degradation, posing significant threats to protected areas. Despite the importance of national parks as core conservation areas in Korea, nationwide analyses of invasive alien plant distributions and management strategies remain limited. This study analyzed the distribution patterns of invasive alien plants across 23 national parks in Korea using the National Park Species List (2023) and proposed park-type–specific management strategies. Among 3,636 vascular plant taxa, 14 of the 18 designated invasive alien plant species were recorded in at least one national park. Although the number of invasive taxa varied among parks, no significant differences were found among park types (Kruskal–Wallis test, P=0.141). Ambrosia artemisiifolia and Humulus japonicus occurred in all parks, mainly in disturbed habitats such as trails and roadsides. National parks were classified into three types—mountainous, coastal–marine, and urban-adjacent—based on their characteristics. Distinct invasion patterns were identified among park types. Mountainous parks showed relatively high resistance but vulnerability at localized disturbance sites. Coastal–marine parks were characterized by habitat-specialist species requiring long-term habitat-based management. Urban-adjacent parks acted as invasion gateways due to continuous propagule input, highlighting the need for ongoing monitoring and cooperative management. This study provides the first nationwide assessment of invasive alien plants in Korean national parks and suggests practical, park-type–specific management strategies.

Keywords: Conservation of natural resources, Ecosystem management, Invasive species, National parks, Plant invasions

Introduction

With the expansion of globalization and international trade, the increased movement of people and goods among countries has intensified the introduction of alien species that threaten ecosystems, leading to growing ecological instability and economic losses worldwide (Bang *et al*., 2004). Invasive alien species are characterized by rapid and often explosive spread, allowing them to colonize wide areas. Consequently, they have increasingly invaded protected areas, which are recognized as one of the most effective tools for biodiversity conservation and for protecting species, habitats, and ecosystems at the national level (Woodley *et al*., 2012), thereby expanding their distribution and causing ecological degradation.

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Among protected areas, national parks represent core conservation areas in Korea, harboring approximately 50% of the nation's estimated 100,000 biological species and approximately 60% of the 246 endangered wildlife species designated by the Ministry of Climate, Energy, and Environment (Lee, 2013). Due to their diverse habitat characteristics, national parks are widely regarded as key refugia and the last strongholds for biodiversity conservation (Kang & Jeong, 2017). Nevertheless, alien plant species have been introduced into national parks, both intentionally and unintentionally, and studies on alien plant invasions and invasive alien plants in national parks have been actively conducted for several decades.

Leem *et al*. (2020) reported a total of 79 alien plant taxa in Byeonsanbando National Park, among which seven invasive alien plant species were identified: *Lactuca serriola*, *Ambrosia artemisiifolia*, *Aster pilosus*, *Hypochaeris radicata*, *Solidago altissima*, *Rumex acetosella*, and *Humulus japonicus*. Myeong *et al*. (2015) recorded 56 taxa (19 families, 19 genera, 55 species, and one variety) in Gyeryongsan National Park, including four invasive alien plant species: *A. artemisiifolia*, *Ambrosia trifida*, *A. pilosus*, and *L. serriola*. Similarly, a floristic study of Juwangsan National Park by Jang *et al*. (2019) identified 55 alien plant taxa, with invasive alien plants comprising *L. serriola*, *A. artemisiifolia*, and *A. pilosus*. Lee *et al*. (2021) reported 45 alien species in the Damyang area of Mudeungsan National Park, among which four invasive alien plant species, *A. artemisiifolia*, *R. acetosella*, *Solanum carolinense*, and *S. altissima*, were confirmed.

Although studies on alien and invasive alien plants in national parks have been actively conducted, most have focused on individual parks and have primarily reported indices, such as naturalization rates and urbanization indices, derived from local floristic surveys. Comprehensive nationwide analyses of invasive alien plant distributions across all national parks in Korea, as well as studies addressing direct removal and management strategies, remain limited. Although national parks are designated to conserve the country's most intact natural ecosystems, the introduction of alien plants can weaken the competitive position of native species and disrupt ecosystem structure and function (Lim & Hwang, 2006). Furthermore, invasive alien plants have a strong capacity for rapid establishment and spreading to new habitats, resulting in negative impacts on biodiversity, ecosystem functioning, and human activities (Pyšek *et al*., 2020).

Therefore, this study aimed to analyze the distribution of invasive alien plants across national parks in Korea and to propose park-type–specific management strategies, including effective species-specific control measures, to provide a scientific basis for improving invasive plant management and establishing fundamental management frameworks within national parks.

Materials and Methods

This study covered 23 national parks in Korea (Fig. 1) based on the National Park Species List published by the National Park Research Institute (2024). This dataset compiled biological records derived from multiple sources, including the Korea National Park Service's in-house programs, such as Natural Resource Monitoring and New Species Discovery by Park Offices, research projects conducted by the National Park Research Institute, and biodiversity surveys carried out by national research institutions within national park areas. The National Park Species List (2023) was developed from long-term monitoring programs, biodiversity surveys, and research projects conducted by the National Park Research Institute and the Korea National Park Service, and integrates field observations collected over multiple years using standardized survey protocols.

Among the compiled species records, 3,636 vascular plant taxa were identified. These taxa were cross-referenced with 18 invasive alien plant species officially designated by the Ministry of Climate, Energy, and Environment, and the invasive alien plant species occurring in each national park were extracted (Table 1).

Furthermore, the distribution of invasive alien plants was analyzed by classifying national parks into three types (mountainous, Coastal, marine, and urban-adjacent) and comparing differences in species occurrence among park types. This classification was based on the designa-

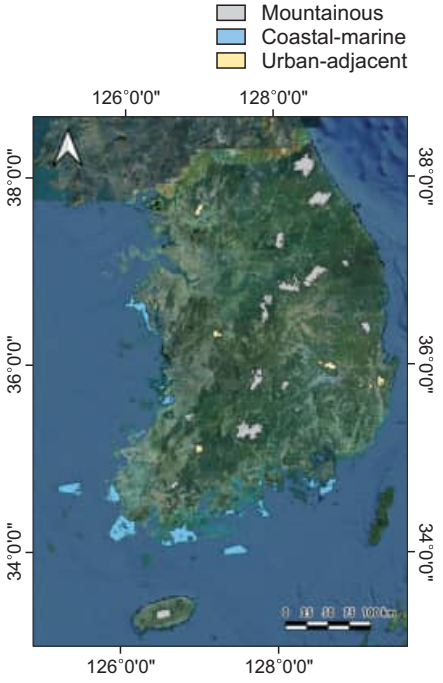

Fig. 1. National parks of Korea by park type.

tion criteria presented in the Second Natural Park Master Plan (2013-2022) established by the Korea National Park Service (2012), which categorizes parks into urban, mountainous, coastal–marine, historical, and geopark types. These categories were further reclassified into three broad categories. Geoparks were included in the mountainous category because of their similar ecological characteristics, whereas historical parks were incorporated into the urban-adjacent category, reflecting their spatial and functional similarities to parks located near urban areas. This reclassification was conducted to facilitate comparative analysis of invasion patterns and management strategies across park types. The number of parks of each type was as follows: mountainous (n=14), coastal–marine (n=4), and urban-adjacent (n=5).

To test for differences in invasive alien plant species richness among park types, the Kruskal–Wallis test was performed.

Results and Discussion

Distribution of invasive alien plants across national parks in Korea

An analysis of 3,636 vascular plant taxa recorded in national parks, cross-referenced with 18 invasive alien plant species designated by the Ministry of Climate, Energy, and Environment, revealed that 14 invasive alien plant taxa were confirmed in at least one of the 23 national parks nationwide (Table 2). This result indicates that a substantial proportion of the currently designated invasive plant species have already established populations within national parks, demonstrating that these protected areas are not entirely free from biological invasions.

Table 1. Invasive alien plants in Korea

Scientific name	Year of designation
Ambrosia artemisiifolia	1999
Ambrosia trifida	
Ageratina altissima	2002
Paspalum distichum var. *indutum*	
Paspalum distichum	
Solanum carolinense	
Rumex acetosella	2009
Sicyos angulatus	
Hypochaeris radicata	
Aster pilosus	
Solidago altissima	
Lactuca serriola	2013
Spartina alterniflora	2016
Spartina anglica	
Humulus japonicus	2019
Alliaria petiolata	2020
Parthenium hysterophorus	2022
Ludwigia peploides	2024

In contrast, *Alliaria petiolata*, *Spartina anglica*, *Parthenium hysterophorus*, and *Ludwigia peploides* are not included in the vascular plant species lists of any national park and, therefore, are not considered to have been introduced or established within national parks to date.

The number of invasive alien plant taxa recorded in each national park varied. Taean Haean National Park and Dadohae National Marine Park exhibited the highest richness, with ten invasive alien plant taxa each, whereas Songnisan National Park exhibited the lowest richness, with only three taxa. However, the Kruskal–Wallis test indicated that the differences in species richness among park types were not statistically significant (P=0.141).

Although the differences were not statistically significant, the observed patterns suggested ecologically meaningful trends related to park-specific factors such as geomorphological characteristics, land-use history, spatial connectivity with surrounding areas, and the intensity of anthropogenic disturbance. The relatively high richness of invasive alien plants in national parks, including coastal and island environments, suggests that coastal and aquatic systems may function as important pathways and vulnerable habitats for alien plant invasion and establishment (Bray *et al*., 2024).

Species-level distribution patterns showed that *A. artemisiifolia* and *H. japonicus* were present in all national parks, indicating that these species are the most widely distributed invasive alien plants across Korean national parks. Notably, *H. japonicus* exhibited the highest frequency of occurrence, with 1,176 recorded observations among the invasive alien plants analyzed. This finding is consistent with previous studies reporting that *H. japonicus* possesses high ecological adaptability across diverse environmental conditions and a strong capacity for spread, particularly in disturbed habitats, such as riparian zones and roadsides (Dumitrașcu *et al*., 2024). *A. artemisiifolia* also showed a high occurrence frequency, with 391 recorded observations, and a tendency to occur repeatedly across various areas within national parks owing to its strong adaptability to open and disturbed environments (Knolmajer *et al*., 2024).

Park-type–specific management strategies based on the distribution patterns of invasive alien plants

In this study, all 23 national parks in Korea were classified into three major types (mountainous national parks, coastal–marine national parks, and urban-adjacent national parks) to examine differences in the invasion mech-

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Table 2. Distribution of invasive alien plants in Korean national parks based on the National Park Species List (2023) (Korea National Park Service, 2024)

Scientific name	Recorded distribution number (number of occurrence records)																						
	Mountainous														Coastal–marine				Urban-adjacent				
	JR	GY	HL	SA	SN	NJ	DY	OD	JW	CA	WA	TB	SB	WC	TH	DD	HH	BB	BH	MD	PG	GJ	GR
Solanum carolinense						2								1	6			1		2		1	4
Ageratina altissima	1				3		4			7	1				1				12	3	2		4
Ambrosia artemisiifolia	22	13	2	13	13	14	18	27	43	23	9	9	26	11	16	27	10	22	30	4	14	17	8
Ambrosia trifida		2		2				6		3	3	6			3				20				
Aster pilosus	2			16		2	11	32	10	48	19	11	12	9	9	4		3	30	2	4	21	4
Hypochaeris radicata			2				3								13	7	1	3	6	2			
Lactuca serriola	1						2		2			1	3		10	1		8		1			
Solidago altissima						2										5		3		2			4
Rumex acetosella	16	6	2	10		4	14	30		6	1	3	2	5	9	15	1	6	13	8	8	4	2
Humulus japonicus	88	60	2	5	65	68	59	68	41	63	106	10	108	21	73	86	44	49	49	23	28	35	25
Sicyos angulatus		1									1		2		12								
Paspalum distichum							1							1		4			1				
Paspalum distichum var. indutum																9							
Spartina alterniflora																2							
Total	130	82	8	46	81	92	112	163	96	150	140	40	153	48	152	160	56	95	161	47	56	78	51
	6	5	4	5	3	6	8	5	4	6	7	6	6	6	10	10	4	8	8	9	5	5	7

Total (row 1): Total number of plant occurrence records per national park.
Total (row 2): Total number of invasive alien plant species recorded per national park.
JR, Jirisan National Park; GY, Gayasan National Park; HL, Hallasan National Park; SA, Seoraksan National Park; SN, Songnisan National Park; NJ, Naejangsan National Park; DY, Deogyusan National Park; OD, Odaesan National Park; JW, Juwangsan National Park; CA, Chiaksan National Park; WA, Woraksan National Park; TB, Taebaeksan National Park; SB, Sobaeksan National Park; WC, Wolchulsan National Park; TH, Taean Haean National Park; DD, Dadohae National Marine Park; HH, Hallyeo National Park; BB, Byeonsanbando National Park; BH, Bukhansan National Park; MD, Mudeungsan National Park; PG, Palgongsan National Park; GJ, Gyeongju National Park; GR, Gyeryongsan National Park.

anisms and distribution patterns of invasive alien plants.

Mountainous national parks are defined as those dominated by inland mountainous forest ecosystems, where forest vegetation accounts for the majority of the park area. This category excluded national parks primarily characterized by coastal or marine environments (Taean Haean, Dadohae, Hallyeo, and Byeonsanbando) and urban-adjacent national parks (Bukhansan, Gyeryongsan, Mudeungsan, Palgongsan, and Gyeongju). Mountainous national parks include Jirisan, Seoraksan, Odaesan, Chiaksan, Woraksan, Sobaeksan, Taebaeksan, Songnisan, Deogyusan, Juwangsan, Naejangsan, Gayasan, Wolchulsan, and Hallasan. Although Gyeongju National Park is the only historical (cultural heritage–oriented) national park in Korea that differs in its primary designation, it was classified as an urban-adjacent national park in the present study to examine forest-based plant invasion mechanisms.

Based on this classification, the distribution characteristics, invasion mechanisms, and management strategies of invasive alien plants were analyzed and discussed for each park type.

Mountainous national parks: high resistance to invasion due to closed forest structure reducing light availability for native herbaceous and shrub layers

Mountainous national parks are generally characterized by extensive and continuous forest cover, with forest interiors exhibiting closed-canopy structures that limit light availability to the understory (Ameztegui *et al*., 2021). These conditions contrast with the high-light and disturbance-prone environments preferred by many alien plant species. Consequently, forest interiors are considered relatively resistant to plant invasion because light limitation restricts the establishment of invasive alien plants. In contrast, previous studies have reported that increased canopy openness or the formation of canopy gaps can facilitate the establishment and growth of invasive species (Oshima & Takahashi, 2020). Thus, the structural contrast between closed-canopy forests, which suppress invasion, and open-canopy forests, which promote invasion, is a key determinant of the initial establishment potential of alien invasive plants in mountainous forest ecosystems.

Despite the inherently high resistance to invasion associated with closed forest structures and limited open areas, multiple invasive alien plant species have been recorded in mountainous national parks. This suggests that invasions in these parks do not occur uniformly across forest interiors. Rather, species with specific ecological traits are selectively established and spread by exploiting repeatedly disturbed and human-modified environments.

Species-specific control and management strategies in mountainous national parks

The most widely distributed invasive alien plant species in mountainous national parks were *H. japonicus* and *A. artemisiifolia*. Both species were recorded in all mountainous national parks and shared a common distribution pattern, occurring primarily in repeatedly disturbed habitats, such as bike trails, roadsides, slope restoration sites, and recreational areas along streams, rather than within undisturbed forest interiors.

H. japonicus, an annual climbing vine, exhibits a competitive strategy characterized by rapid growth and extensive horizontal and vertical coverage in open spaces adjacent to disturbed areas (Huang & Matthews, 2024). This species attains a particularly high cover in locations where canopy openness improves light availability, such as forest edges and trail margins, where it can rapidly and severely reduce light availability for native herbaceous and shrub layers (Shin *et al*., 2025). As a result, *H. japonicus* is considered a priority invader at disturbed sites within mountainous national parks, with a high potential for further expansion into adjacent forest edges if left unmanaged.

A. artemisiifolia, an annual herb characterized by high seed production, exhibits high establishment success in environments characterized by repeated soil disturbance and exposure (Ziska *et al*., 2007). In mountainous national parks, this species is commonly observed in slope-stabilization areas, recently maintained trail sections, and parking facilities. Owing to its prolific seed production and persistent soil seed bank, *A. artemisiifolia* is frequently reestablished after removal. In addition to its ecological impact, this species poses significant public health concerns as a major allergen, warranting its classification as a high-priority management target in national park settings.

Other disturbance-adapted alien plant species, such as *L. serriola* and *H. radicata*, did not exhibit widespread distribution across mountainous national parks, but were locally concentrated around visitor-use areas and disturbed sites. Although the potential for expansion into forest interiors appears limited, insufficient management of disturbed areas may allow these species to maintain stable local populations.

Taken together, these species-specific distribution patterns indicate that effective management of invasive alien plants in mountainous national parks requires differentiated strategies based on species ecological traits and invasion pathways. Species with rapid canopy-forming or smothering capabilities, such as *H. japonicus*, should be repeatedly removed before flowering to prevent seed production, with management efforts concentrated along the trails and forest edges. For *A. artemisiifolia*, early-stage population removal combined with follow-up monitoring for at least two–three years after disturbance events is es-

sential for addressing persistent seed banks.

In contrast, for disturbance-adapted species, such as *L. serriola* and *H. radicata*, management focused on eliminating disturbance drivers and stabilizing habitats is likely to be more effective than large-scale removal. Minimizing soil exposure and promoting the rapid establishment of vegetation restoration play critical roles in preventing reinvasion. Accordingly, the most effective management framework for mountainous national parks is a dual strategy that combines the conservation of invasion-resistant forest interiors with the disturbance-point-based, species-specific management of visitor use and disturbed areas.

The species-specific distribution characteristics and corresponding management strategies for major invasive alien plants in mountainous national parks are summarized in Table 3.

Coastal–marine national parks: collective expansion of habitat-specialist invasive species

Coastal–marine national parks comprise complex ecosystems that include coastal zones, islands, salt marshes, and estuaries. The results of this study indicate that this park type harbors the highest number of invasive alien plant taxa among all national park types. In particular, Taean Haean National Park and Dadohae National Marine Park showed notably high frequencies and distinct species compositions of habitat-specialist invasive plants adapted to wetland and salt marsh environments, including *Spartina alterniflora*, *Paspalum distichum*, and *Paspalum distichum* var. *indutum*.

These species share common traits, such as strong vegetative reproductive capacity and high tolerance to fluctuations in water level, salinity, and sedimentary conditions,

Table 3. Species-specific distribution characteristics and management strategies of major invasive alien plants identified in mountainous national parks

Scientific name	Growth form	Primary habitats	Invasion and spread characteristics	Major ecological impacts	Recommended management strategies
Humulus japonicus	Annual climbing vine	Trail edges, roadsides, slope restoration sites, forest edges	Rapid horizontal and vertical cover expansion in open areas adjacent to disturbed sites, Repeated regeneration	Increased light competition leading to reduced understory vegetation cover and species diversity	Repeated removal prior to flowering to prevent seed production, combined with focused management of disturbed sites and long-term monitoring
Ambrosia artemisiifolia	Annual herb	Roadsides, areas around parking lots, exposed soil areas, slope stabilization areas	High seed production, repeated occurrence following disturbance	Suppression of native herbaceous vegetation through stand formation, along with social impacts such as allergenic effects	Early removal at the initial population stage, followed by 2-3 years of post-removal follow-up management to prevent reoccurrence
Lactuca serriola	Annual herb	Trail-adjacent areas, bare ground, areas adjacent to visitor facilities	Disturbance-adapted, localized low-density distribution	Limited spatial competition, visual landscape degradation	Early detection followed by immediate removal, combined with soil stabilization and minimization of disturbance
Hypochaeris radicata	Perennial herb	Open areas adjacent to trails, forest edges	Persistent low-density distribution, slow rate of spread	Potential for long-term vegetation simplification	Surveillance-based management with selective removal as needed
Solidago altissima	Perennial clonal herb	Localized disturbed areas, slopes, and open sites in certain parks	Potential for clonal expansion via rhizomes	Replacement of native vegetation through stand formation	Removal at the early stand stage, combined with repeated removal to suppress further spread

which enable their rapid establishment and expansion in coastal and estuarine ecosystems. Notably, *S. alterniflora* promotes sediment accretion through both aboveground and belowground growth, thereby altering the geomorphology and hydrological structure of salt marshes (Li *et al*., 2009). These characteristics suggest that *S. alterniflora* functions not only as a competitor of native vegetation but also as a driver of habitat modification, with long-term implications for species composition and spatial structure of native halophytic plant communities.

P. distichum and *P. distichum* var. *indutum* also form dense stands through rhizomatous and stoloniferous vegetative reproduction, rapidly replacing native vegetation in riparian zones and shallow-water habitats (Lee *et al*., 2015). The spread of these species in coastal–marine national parks is characterized by collective, stand-level expansion rather than by the gradual invasion of individual plants. Such collective expansion substantially increases management difficulties and costs when early removal opportunities are missed.

Consequently, the management of invasive alien plants in coastal–marine national parks cannot rely solely on short-term removal-focused interventions. Without concurrent natural recovery or assisted restoration of native halophytic vegetation following its removal, the likelihood of reinvasion under similar habitat conditions remains high. Therefore, long-term habitat-based management strategies are required to integrate the removal of invasive species with sediment management and native vegetation restoration.

Furthermore, coastal and island environments are ecologically connected to adjacent coastal and estuarine ecosystems beyond national park boundaries, limiting the effectiveness of park-scale management. Accordingly, the establishment of broad-scale, coordinated management frameworks involving local governments and marine and coastal management authorities is essential to prevent reinvasion and ensure sustained management effectiveness in national coasta–marine parks.

Species-specific removal and management strategies in coastal–marine national parks

Invasive alien plants identified in coastal–marine national parks exhibited a tendency to form dense stands and undergo collective expansion, showing strong specialization to particular habitat types, in contrast to the invasion patterns observed in mountainous national parks. This indicates that invasive plant management in coastal–marine national parks cannot be effectively addressed through a single, uniform removal approach, and instead requires tailored management strategies that account for species-specific ecological traits and expansion mechanisms.

S. alterniflora is regarded as the highest-priority invasive species for management in coastal–marine national parks. This species possesses strong vegetative reproductive capacity through both rhizomes and aboveground shoots and accelerates sediment trapping in salt marshes and estuarine environments, thereby altering geomorphological and hydrological structures. Due to these characteristics, *S. alterniflora* should be recognized not merely as a removal target but as a key invasive species capable of driving habitat structural modification. Accordingly, management of *S. alterniflora* is most effective when intensive removal is implemented at the early stage of small stand formation. Where extensive stands have already developed, partial removal should be combined with restoration of native halophytic vegetation and hydrological management to mitigate further habitat alteration.

P. distichum and *P. distichum* var. *indutum* rapidly form dense stands in riparian zones and shallow-water habitats and can readily regenerate following removal because of their strong vegetative reproduction. Consequently, a one-time removal effort is insufficient for effective control. Repeated removal, combined with stabilization of soil and hydrological conditions, is essential for long-term management. In areas subject to frequent water-level fluctuations, adjusting the timing and frequency of removal to prioritize conditions favorable for native vegetation reestablishment is particularly important.

Overall, effective management in coastal–marine national parks requires differentiation of strategies according to the growth and expansion characteristics of invasive species, including stand-forming species, vegetatively reproducing species, and disturbance-adapted species. This approach contrasts with the disturbance-point–based management strategies commonly applied in mountainous national parks and represents a species-specific management framework tailored to the ecological characteristics of coastal and marine national parks.

Species-specific distribution characteristics and management strategies for invasive alien plants in coastal and marine national parks are summarized in Table 4.

Urban-adjacent national parks: gateway-type invasion driven by continuous alien plant input

Urban-adjacent national parks are located near large cities and residential areas, and are characterized by high visitor use intensity and dense concentrations of anthropogenic infrastructure, including roads, parking lots, visitor facilities, and landscaped areas. These spatial characteristics increase the likelihood of initial introduction of alien plants. Accordingly, the results of this study indicate that urban-adjacent national parks exhibit a relatively high frequency of disturbance-adapted invasive alien plants compared to other park types. In particular, *A. artemisiifolia* and *H. japonicus* were recorded in all urban-adjacent national parks, whereas disturbance- and bare-

Table 4. Species-specific distribution characteristics and management strategies of major invasive alien plants identified in coastal-marine national parks

Scientific name	Growth form	Primary habitats	Invasion and spread characteristics	Major ecological impacts	Recommended management strategies
Spartina alterniflora	Perennial halophytic herb	Salt marshes, estuaries, intertidal zones	Strong vegetative reproduction via rhizomes and shoots; stand-level expansion	Accelerated sediment accumulation; alteration of salt-marsh geomorphology and hydrological structure	Intensive removal at early small-stand stages; in extensively invaded areas, partial removal combined with restoration of native halophytic vegetation and hydrological management
Paspalum distichum	Perennial stoloniferous herb	Riparian zones, shallow water bodies, wetland margins	Rapid stand formation via stolons; easy regeneration after removal	Replacement of native riparian vegetation; stand homogenization	Repeated removal-based management combined with stabilization of water level and soil conditions
Paspalum distichum var. *indutum*	Perennial stoloniferous herb	Salt marshes, moist grasslands	Dominant vegetative reproduction; high stand persistence	Competitive exclusion of halophytic and wetland vegetation	Regular repeated removal and facilitation of native vegetation re-establishment after removal
Ambrosia artemisiifolia	Annual herb	Coastal use areas, areas around management facilities, bare ground	High seed production; disturbance-adapted	Localized stand formation; allergenic effects	Early detection followed by immediate removal, with management prior to seed production
Lactuca serriola	Annual herb	Areas adjacent to ports and parking lots, open areas	Restricted distribution in disturbed sites; low dispersal ability	Limited spatial competition	Surveillance-based management with selective removal as needed

ground–adapted species such as *L. serriola* and *H. radicata* were also prominent.

These distribution patterns suggest that urban-adjacent national parks do not function as long-term establishment sites for invasive alien plants, but rather as invasion gateways that receive continuous propagule input from surrounding areas (Lozano *et al*., 2023). Even after individual species are removed, repeated reinvasion occurs through multiple pathways, including seed introduction via visitor movement, spread from adjacent urban green spaces and landscaped areas, and unintentional dispersal associated with road and infrastructure maintenance activities. This structural characteristic indicates that invasive plant management in adjacent urban national parks cannot be achieved effectively through one-time removal-focused interventions alone.

Although the major invasive alien plant species observed in urban-adjacent national parks appear similar to those recorded in mountainous national parks, leading to the assumption that management approaches for the two park types might also be similar, the invasion processes and ecological responses differ fundamentally despite their outward similarity as forest-dominated protected areas. These differences arise from contrasting site conditions, forest structures, disturbance regimes, and propagule input mechanisms from the surrounding landscapes.

Mountainous national parks are generally characterized by a steep topography, substantial elevational gradients, and extensive areas of continuous forest cover. Forest interiors in these parks are dominated by closed-canopy structures that limit light availability to the understory, and the frequency of anthropogenic disturbance is rela-

tively low. Under such conditions, high-light environments and repeated disturbances required for the establishment and spread of invasive alien plants are rarely encountered. Consequently, stable establishment and population expansion within forest interiors are unlikely even when alien plants are introduced from external sources. Therefore, in mountainous national parks, invasive plant occurrences are largely confined to localized areas such as forest edges, disturbed riparian zones, and areas adjacent to forest roads, and the park as a whole can be regarded as a structurally invasive system.

In contrast, urban-adjacent national parks are located near urban or peri-urban areas, where boundaries with surrounding land use are often indistinct and anthropogenic infrastructure, such as roads, bike trails, and visitor facilities, are densely distributed. This spatial configuration facilitated the linear expansion of canopy openings and soil disturbance in the forest interior. In particular, areas surrounding trails and facilities function as persistent disturbance nodes, where soil exposure and propagule input occur continuously because of frequent visitor use. As a result, urban-adjacent national parks function less as long-term establishment sites and more as invasion gateways, receiving continuous inputs of invasive alien plants from surrounding landscapes and enabling repeated reinvasion and redistribution.

These fundamental differences have important implications for the development of management strategies. In mountainous national parks, where invasions tend to be localized and episodic, early detection and rapid response can be effective management approaches. In contrast, in urban-adjacent national parks, the removal of individual species alone is insufficient to suppress invasion. Without concurrent management of invasion pathways, such as trails, roads, and facility areas, and coordinated measures addressing surrounding land use, sustained and effective long-term control of invasive alien plants is unlikely.

Species-specific removal and management strategies in urban-adjacent national parks

In urban-adjacent national parks, *H. japonicus* forms localized dominance through rapid canopy cover expansion around bike trails and visitor facilities, whereas *A. artemisiifolia* tends to recur repeatedly because of its high seed production and the formation of persistent soil seed banks. Other invasive alien plants, such as *L. serriola* and *H. radicata*, do not exhibit extensive spatial expansion, but occur persistently at low densities in areas adjacent to visitor-use zones, where insufficient management may allow the maintenance of stable local populations.

Given these invasion mechanisms, the effective management of invasive alien plants in urban-adjacent national parks requires a system centered on continuous surveillance and repeated management rather than a solely removal-focused approach. Regular monitoring and rapid early stage removal should be prioritized at locations with a high risk of invasion, including trail entrances, parking lots, and park boundary areas. Moreover, without cooperative management between national park authorities and adjacent local government jurisdictions, it is difficult to achieve substantial long-term control, highlighting the need for coordinated cross-jurisdictional management frameworks.

Furthermore, considering the high intensity of visitor use in urban-adjacent national parks, enhancing visitor awareness of invasive alien plant issues and introducing participatory management programs can substantially improve long-term management effectiveness. This perspective underscores that urban-adjacent national parks function not merely as sites for invasive plant removal, but also as frontline areas for preventive management aimed at blocking the further spread of invasive alien plants.

The species-specific distribution characteristics and management strategies of major invasive alien plants in urban-adjacent national parks are summarized in Table 5.

Conclusion and policy implications

This study comprehensively analyzed the distribution patterns of invasive alien plants across 23 national parks in Korea and proposed park-type–specific management strategies based on invasion mechanisms. The results showed that 14 of the 18 invasive alien plant species designated by the national authorities were recorded in at least one national park, clearly demonstrating that national parks are not exempt from biological invasion. Given that national parks represent core areas for biodiversity conservation in Korea, these findings indicate that the management of invasive alien plants should be regarded as a continuous and structural management task and not as an optional or ad hoc response.

The distribution of invasive alien plants varied among national parks, reflecting the combined influence of topographic characteristics, habitat structure, connectivity with surrounding land use, and intensity of anthropogenic disturbance. In particular, the high number of invasive alien plant taxa recorded in coastal and island-based parks, such as the Taean Haean and Dadohae National Marine Parks, reaffirms at the policy level that coastal and aquatic environments are structurally vulnerable to biological invasions. This finding underscores that invasive plant management in marine and coastal national parks is not merely a vegetation control issue but a core component of habitat conservation.

Species-level analyses identified *A. artemisiifolia* and *H. japonicus* as the most widespread invasive alien plants in all national parks. Therefore, these species should be considered top-priority targets for management across the national park system. Both species exhibit high adapt-

Table 5. Species-specific distribution characteristics and management strategies of major invasive alien plants identified in urban-adjacent national parks

Scientific name	Growth form	Primary habitats	Invasion and spread characteristics	Major ecological impacts	Recommended management strategies
Humulus japonicus	Annual climbing vine	Trail edges, forest margins adjacent to visitor facilities	Localized high-density occurrence, repeated reappearance	Increased canopy openness along trails and facilities, suppression of understory vegetation	Removal prior to flowering; intensive surveillance and control along trails and park boundaries
Ambrosia artemisiifolia	Annual herb	Roadsides, parking areas, park boundaries	Recurrent emergence, formation of local stands through soil seed banks	Seed dispersal via visitor movement, spread from adjacent urban green spaces and road maintenance	Early removal before seed set; continuous monitoring and follow-up management
Lactuca serriola	Annual herb	Bare ground, areas adjacent to visitor-use facilities	Persistent low-density distribution	Association with soil exposure and landscaped areas	Immediate removal upon early detection
Hypochaeris radicata	Perennial herb	Open areas adjacent to hiking trails	Local establishment with slow expansion	Soil disturbance caused by repeated visitor use	Surveillance-based management; selective removal when necessary
Solidago altissima	Perennial clonal herb	Open disturbed areas in some parks	Limited distribution but potential for clonal expansion	Influence from adjacent landscaped and agricultural areas	Management at early colony stage to prevent further expansion

ability to disturbed environments and occur repeatedly in areas associated with human use, such as trails, roadsides, and facility zones. This pattern highlights that effective invasive plant management in national parks should focus not only on the species themselves but also on disturbance hotspots and visitor-use structures that facilitate repeated invasions.

Management implications differ substantially among park types. Mountain-type national parks generally exhibit high structural resistance to invasion due to closed-canopy forest conditions; however, invasions are concentrated in localized disturbed areas, such as bike trails, slope restoration sites, and forest roads. Accordingly, for mountainous national parks, an Early Detection and Rapid Response strategy focusing on disturbance hotspots is the most efficient management approach. Importantly, this strategy is highly applicable at the park office level, because it can be implemented with relatively limited personnel and financial resources.

Habitat-specialized invasive species such as *S. alterniflora*, *P. distichum*, and *P. distichum* var. *indutum* exhibited clonal colony-based expansion. Owing to their strong vegetative reproduction, short-term removal efforts alone are insufficient to achieve lasting management outcomes. Therefore, management objectives in marine national parks should shift from complete eradication to containment of spread and restoration of habitat function. This requires long-term, integrated management plans linking invasive species removal with hydrological and sediment management and restoration of native halophytic vegetation. This approach necessarily presupposes coordinated governance frameworks involving national parks, coastal management authorities, and local governments.

Urban-adjacent national parks functioned as "invasion gateways," characterized by continuous propagule input from surrounding urban and suburban areas. Although the species composition was similar to that of mountain-type parks, invasion drivers and management priorities were fundamentally different. In these parks, the establishment of permanent surveillance systems and institutionalized repetitive management should be set as primary management goals. Particular attention should be paid to park boundaries and coordination with adjacent municipal management zones. Trail entrances, parking lots, and facility surroundings should be designated as priority surveillance and management areas, because they represent key nodes for invasive plant introduction.

Overall, the management of invasive alien plants in national parks must transition from a uniform, nationwide approach to a differentiated management framework

tailored to park type and species characteristics. From a policy perspective, this requires the following:

(1) the development of park-type–specific invasive alien plant management guidelines,

(2) field-oriented reorganization of priority invasive species lists, and

(3) explicit integration of invasive plant management measures into national park management plans.

In the long-term, the establishment of monitoring systems capable of evaluating management effectiveness and proactive strategies that account for increasing invasion risks under climate change will be essential.

The management framework proposed in this study provides a practical and immediately applicable foundation for on-site management in national parks, and serves as a critical reference for the future development and refinement of national invasive alien plant management policies.

Author Contributions

Conceptualization: KHP. Data curation: KHP, DEK. Formal analysis: KHP. Funding acquisition: KHP. Investigation: KHP. Methodology: KHP. Project administration: KHP. Resources: KHP. Software: DEK. Supervision: KHP. Validation: KHP. Visualization: KHP, DEK. Writing – original draft: KHP. Writing – review & editing: KHP.

Conflict of Interest

The authors declare that they have no competing interests.

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Case Report

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First Record of *Hippotiscus dorsalis* (Stål) (Hemiptera: Pentatomidae) from Korea

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ABSTRACT

In this study, the genus *Hippotiscus* Bergroth, 1906, and its constituent species *Hippotiscus dorsalis* (Stål, 1864) (Hemiptera: Pentatomidae) were reported for the first time in Korea. Specimens were collected from bamboo (*Phyllostachys* sp.) in Changwon-si, Gyeongsangnam-do. *H. dorsalis* is readily distinguished by its oblong oval body, laminate lateral margins on the head, and distinct yellowish longitudinal markings on the head and pronotum. Herein, we provide a morphological re-description of the species, including detailed illustrations of both the male and female genitalia. Additionally, mitochondrial cytochrome c oxidase subunit I DNA barcode sequences for the Korean specimens have been provided and deposited in GenBank under the accession numbers PX788675-PX788676.

Keywords: DNA barcoding, Hemiptera, *Hippotiscus dorsalis*, Korea, New record, Pentatomidae

Introduction

The family *Pentatomidae* (Hemiptera: Heteroptera) is one of the most diverse groups within the suborder Heteroptera, with approximately 5,000 species recorded worldwide (Schuh & Weirauch, 2020). Many species within this family are economically and ecologically important, acting either as agricultural pests that damage various crops or as natural enemies (Panizzi *et al.*, 2000). The genus *Hippotiscus* Bergroth, 1906, is a relatively small group distributed primarily across the East Palearctic and Oriental regions.

The target species of this study, *Hippotiscus dorsalis* (Stål, 1870), is a major pest of bamboo forests, including moso bamboo (*Phyllostachys edulis*), in southern China and its adjacent areas (Yang *et al.*, 2004). Both nymphs and adults of *H. dorsalis* feed by sucking sap from bamboo shoots and stems, which causes significant economic damage via the degradation of bamboo timber quality and reduction of shoot production (Zhao *et al.*, 2023). Despite its considerable economic importance in neighboring countries, there are no previous records of the genus *Hippotiscus* from the Korean Peninsula. Although another bamboo-feeding bug, *Brachymna tenuis* (Stål, 1864), was recently added to the Korean fauna in 2020 (Ahn *et al.*), *H. dorsalis* has not yet been recorded.

Recently, the cross-border movement of insects has increased because of the expansion of international

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trade and climate change, heightening the possibility of introducing and establishing exotic species in domestic ecosystems. Alien species often exist at low densities during their initial introduction phase, making their effects difficult to perceive. However, once established, they can disrupt ecosystems and reduce agricultural productivity. Therefore, early detection and accurate taxonomic reporting of insect species not yet recorded in Korea are crucial for building a baseline of biodiversity data and establishing future quarantine and management strategies.

This is the first study to report the confirmed distribution of *H. dorsalis* in Korea. We provided a morphological description and figures of key diagnostic characteristics, including male genitalia, along with information on the confirmed host plant and collection locality. To ensure the accuracy of species identification, we analyzed the cytochrome c oxidase subunit 1 (COI) gene of the mitochondrial DNA and verified its molecular phylogenetic validity by comparing its sequences with those of populations from neighboring countries deposited in GenBank. This report adds an unrecorded genus and species to the Korean Insect Fauna Checklist and provides foundational data for assessing the potential spread of this species in Korea, and for future management research on alien insects.

Materials and Methods

Sample collection

The specimens used in this study were collected on 29 June 2025, from near a neighborhood park in Jinhae-gu, Changwon-si, Gyeongsangnam-do, Republic of Korea (35°06′20.4″N, 128°48′07.0″E). Adult individuals were obtained by direct hand collection following visual inspection. In particular, an intensive survey was conducted on the stems and leaves of bamboo (*Phyllostachys* spp.), which are known to be the primary host plant of this species. Photographic records of individuals consistent with *H. dorsalis* were available from EcoBank (National Institute of Ecology, Korea) based on observations made in Busan, Korea, on 7 and 31 July 2024. However, no specimens were collected at that time, and the records were therefore excluded from the material examined.

Specimen preparation and preservation

The collected specimens were immediately immersed and fixed in 95% ethanol in the field, and subsequently transported to the laboratory. In the laboratory, dry specimens were prepared for morphological observations. All specimens used in this study were deposited in the insect collection of the Department of Horticulture at Gyeongsang National University.

Morphological examination and identification

Species identification was based on the original description by Stål (1870) and other relevant studies (Rider *et al.*, 2002). Habitus photographs were obtained using a digital single-lens reflex camera (Nikon D500; Nikon Corp., Tokyo, Japan) equipped with a Nikon 60 mm microlens. Botanical nomenclature followed the World Flora Online (WFO, 2026).

Molecular analysis

Genomic DNA was extracted from the leg tissues of *H. dorsalis* using the DNeasy Blood and Tissue Kit (QIAGEN, Hilden, Germany) according to the manufacturer's instructions. Polymerase chain reaction amplification of the mitochondrial COI gene was performed using universal primers (LCO1490 and HCO2198) and thermal cycling conditions described by Folmer *et al.* (1994).

Results and Discussion

Taxonomic accounts

Family Pentatomidae Leach, 1815
Genus *Hippotiscus* Bergroth, 1906
Hippotiscus dorsalis (Stål, 1864) (Hwang-jul-no-rin-jae)

Synonyms

Sciocoris dorsalis: Stål, 1864: 171.
Hippotiscus dorsalis: Bergroth, 1906: 4.

Material examined

4exx (2 males, 2 females), Korea: Gyeongsangnam-do, Changwon-si, Jinhae-gu, 35°06'20.4"N, 128°48'07.0"E, 29 June 2025, on bamboo (*Phyllostachys* sp.), coll. Soo Jeong Ahn & Sung Hwan Choi.

Diagnosis

Body length 12.5-14.0 mm. Body oblong, oval, and

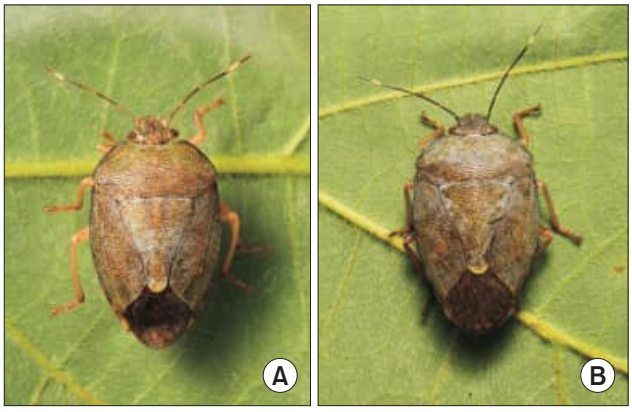

Fig. 1. Dorsal habitus of *Hippotiscus dorsalis*. (A) Male. (B) Female.

somewhat dorsally flattened (Fig. 1). Head broader than long, apically rounded, laminated, with a lateral margin. Pronotum more than twice as broad as long, with distinctly convex lateral margins and a finely punctate surface. The scutellum was elongated, extending beyond the middle of the abdomen, with a sub-rounded apex. This species is readily distinguished by the presence of distinct yellowish to pale longitudinal markings on its head and pronotum (Fig. 1). Metathoracic scent gland ostioles with large apertures and elongated anteriorly directed peritremes. The mesosternum is distinctly carinated. In the male genitalia, the pygophore was subquadrate with a deeply excavated ventral margin, and the parameters were slender and slightly curved apically (Fig. 2A, B). In the female genitalia, gonocoxite 8 was large and subquadrate, with slightly sinuating posterior margins. Laterotergite 8 was triangular, and laterotergite 9 was elongated, reaching or slightly surpassing the posterior margin of the fused laterotergite 8 (Fig. 2C).

Host plant

Phyllostachys spp. (Poaceae).

Distribution

Korea (new record: Changwon), China (southern and eastern regions), Taiwan, Japan, Vietnam, Thailand (Fig. 3).

Molecular analysis

Partial mitochondrial COI sequences (658 bp) were successfully obtained and deposited in GenBank under the accession numbers PX788675-PX788676. Basic local alignment search tool analysis revealed that these sequences shared a high similarity (99.7%) with the mitochondrial genome of *H. dorsalis* from China (GenBank accession no. NC_058969.1). The low barcoding gap between the Korean and Chinese sequences (0.3%) indicated a close genetic relationship between populations from the two regions.

This study reports the first confirmed record of *H. dorsalis* (Stål) in Korea based on voucher specimens, supported by morphological characteristics, male and female genital structures, and molecular evidence. Although photographs of suspected *H. dorsalis* individuals from Busan were recorded in the public biodiversity database (EcoBank) in July 2024, they were not recognized as official occurrences because of the lack of physical specimens. Thus, the specimens collected from Changwon in June 2025 constituted the first confirmed record of *H. dorsalis* in Korea.

The morphological characteristics of the Korean specimens closely matched the diagnostic features described in the original description and the subsequent taxonomic literature. In particular, the oblong oval body shape, distinct yellowish to pale longitudinal markings on the head and pronotum, the scutellum extending beyond the mid-



Fig. 2. Genitalia of *Hippotiscus dorsalis*. (A) Male pygophore (ventral view). (B) Male left paramere. (C) Female external genitalia (ventral view).

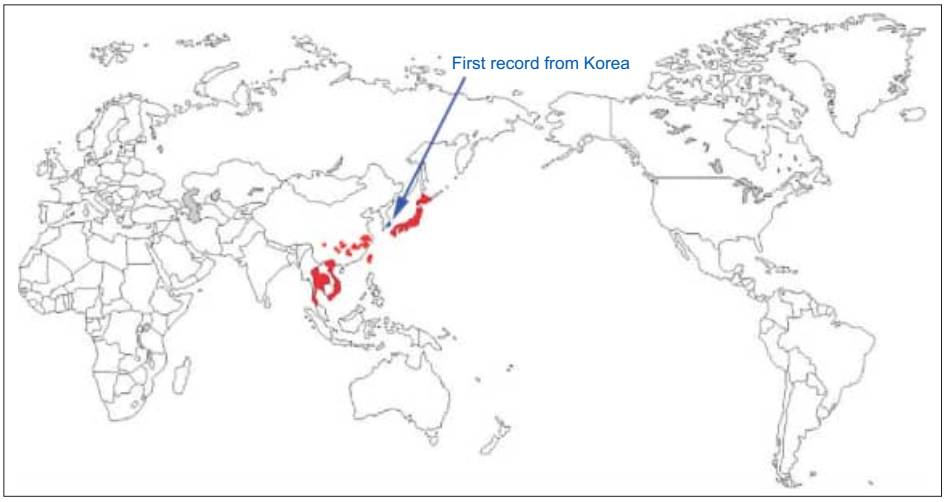

Fig. 3. Geographic distribution of *Hippotiscus dorsalis*. The blue arrow indicates the first confirmed record from Korea.

dle of the abdomen, and the characteristic structure of the metathoracic scent gland ostioles were consistent with the diagnostic traits of *H. dorsalis*. In addition, the male and female genital structures corresponded well with previously reported diagnostic characters of the species, and the COI sequence data provided independent molecular evidence supporting morphological identification.

Considering both the photographic record from Busan in 2024 and the specimen-based record from Changwon in 2025, *H. dorsalis* may have been present in southern Korea for at least one year prior to its formal confirmation. The observation and collection of this species in different localities over consecutive years suggest that its occurrence is unlikely to be the result of a single accidental introduction and instead indicates the possibility of a sustained presence, implying a relatively high potential for establishment. However, the currently available data are insufficient to conclusively determine the long-term establishment, and additional surveys and data accumulation are required. The potential for such an establishment is further supported by recent records of other bamboo-associated pests in Korea. For example, *B. tenuis* Stål, another specialist bamboo feeder, was first recorded in southern Korea in 2020 (Ahn *et al.*, 2020). The discovery of *H. dorsalis* following *B. tenuis* suggests a possible trend of increasing diversity or range expansion of exotic bamboo-feeding insects on the Korean Peninsula.

The specimens examined in this study were collected from bamboo stands (*Phyllostachys* sp.) within an urban park, demonstrating that *H. dorsalis* can utilize artificially created urban green spaces. Recently, the use of bamboo species as landscaping plants in single-family houses, public facilities, and commercial buildings has increased in South Korea. Such anthropogenic plantings may provide suitable habitats and potential dispersal pathways for bamboo-associated insects, such as *H. dorsalis*, thereby contributing to its potential range expansion. Accordingly, continuous monitoring of nonagricultural areas, including urban green spaces and landscaped sites, is necessary.

Currently, no information is available regarding the economic or ecological impacts of *H. dorsalis* in Korea. Nevertheless, continued field surveys and population-level studies are needed to evaluate the potential range expansion, host plant utilization, and interactions with native pentatomid species. Future research should contribute to a clearer understanding of the establishment and ecological significance of *H. dorsalis* in South Korea.

Remark

These specimens represent the first confirmed records of this species in South Korea. The Korean common name 'Hwang-jul-no-rin-jae' is proposed based on the distinct longitudinal stripes present on the pronotum and scutellum.

Author Contributions

Conceptualization: SJA. Data curation: SJA. Formal analysis: SJA, HWC. Funding acquisition: SJA. Investigation: SJA, SHC. Resources: EJH. Visualization: SJA. Writing – original draft: SJA. Writing – review & editing: SJA, HWC, EJH, SHC.

Conflict of Interest

The authors declare that they have no competing interests.

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Case Report

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Use of a Pre-Existing Wasp Nest by the Red-Rumped Swallow (*Cecropis daurica*): A Record Based on Citizen Science

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ABSTRACT

This study document the nest construction behavior of the Red-rumped Swallow (*Cecropis daurica*) observed through local biodiversity monitoring based on citizen science. This observation was made beneath a railway bridge in Samnangjin-eup, Miryang-si, Gyeongsangnam-do, South Korea, where the species built a mud nest using a pre-existing wasp nest as a supporting structure. Although the nest was complete, no evidence of breeding activity was observed, and the structure subsequently collapsed. This record provides an example of the use of biological structures in nest construction by *C. daurica* and contributes to our understanding of the range of nesting substrates utilized by this species. It also highlights the value of citizen science data in documenting avian behavioral observations.

Keywords: Biological structures, *Cecropis daurica*, Citizen science, Nest construction

Introduction

The Red-rumped Swallow (*Cecropis daurica*), a member of the family Hirundinidae, is widely distributed across Eurasia and is known to construct gourd-shaped mud nests beneath bridges, building eaves, and other artificial structures (Turner & Rose, 1989). Recent studies have reported that some swallow species that have historically been nested on natural cliffs have increasingly shifted to anthropogenic substrates as primary breeding sites. Additionally, swallows exhibit both intra- and interspecific nest occupation or reuse, which is interpreted as a flexible strategy for utilizing the available structural resources within breeding environments (Tella *et al*., 2024).

Studies of the nesting materials of mud-nesting swallows have demonstrated that these birds do not collect mud randomly; rather, they select materials with specific clay mineral compositions and particle size characteristics (Papoulis *et al*., 2018). Comparative analyses among species indicated that the physical stability of the nests was closely linked to the mineralogical properties of the materials used, suggesting a strong relationship between material characteristics and structural durability.

C. daurica typically builds nests on inorganic substrates such as concrete surfaces, masonry structures, and natural rock faces (Turner & Rose, 1989). However, the use of biologically derived insect structures as supporting substrates for nest construction has rarely been reported. Empirical evidence on whether biologically derived struc-

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tures fall within the nesting substrate range of *C. daurica* is limited.

This study reports a case in which *C. daurica* constructed a nest beneath a railway bridge, utilizing a pre-existing wasp nest as a supporting structure. Observations were made through citizen science-based local monitoring and provided baseline information for understanding the range of nesting substrates used by this species.

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Study site

The observations were conducted beneath a railway bridge in Songji-ri, Samnangjin-eup, Miryang-si, Gyeongsangnam-do, South Korea (35.39744°N, 128.83528°E). The site is situated adjacent to Mijeoncheon Stream and surrounded by a mosaic of agricultural land and residential areas (Fig. 1).

Field observations

In mid-May 2025, three to four adult *C. daurica* were first observed by citizen scientists repeatedly entering and exiting a pre-existing wasp nest located beneath a railway bridge (Fig. 2A). Nest construction behavior was not recorded throughout June. In early July, *C. daurica* began transporting mud and attaching it to the side of the wasp nest using the structure as a supportive base for nest construction (Fig. 2B). By mid-July, the external structure of the nest was largely complete (Fig. 2C); however, no further entry of adult swallows was observed. In early August, the central portion of the nest had collapsed (Fig. 2D). Throughout the observation period, no eggs or nestlings were detected, indicating that breeding did not occur.

Discussion

In general, wasp nests are considered annual structures used in a single breeding season (Spradbery, 1973; Jeanne, 1975). The wasp nests observed in the present study showed no signs of activity. Nests constructed by social wasps consist of papery materials with a porous structure and relatively rough surface texture (Jeanne, 1975). These surface characteristics might have influenced the initial attachment of mud during nest construction by *C. daurica*, as suggested by studies on the material properties of mud-nesting swallows (Papoulis *et al.*, 2018). In this case, the swallow nest was formed in close contact with the outer wall of the wasp nest, indicating that the wasp nest served as a physical substrate during nest construction.

Although the nest appeared structurally complete, it did not result in successful breeding, and eventually collapsed. The nest was located beneath a railway bridge, where frequent vibrations occurred because of passing trains. These physical conditions likely contributed to failure. Although the adhesion between the papery material and mud may be sufficient under static conditions, repeated vibrations can compromise the structural stability in such a dynamic environment.

This case was documented through citizen science-based monitoring. Citizen participation has contributed to

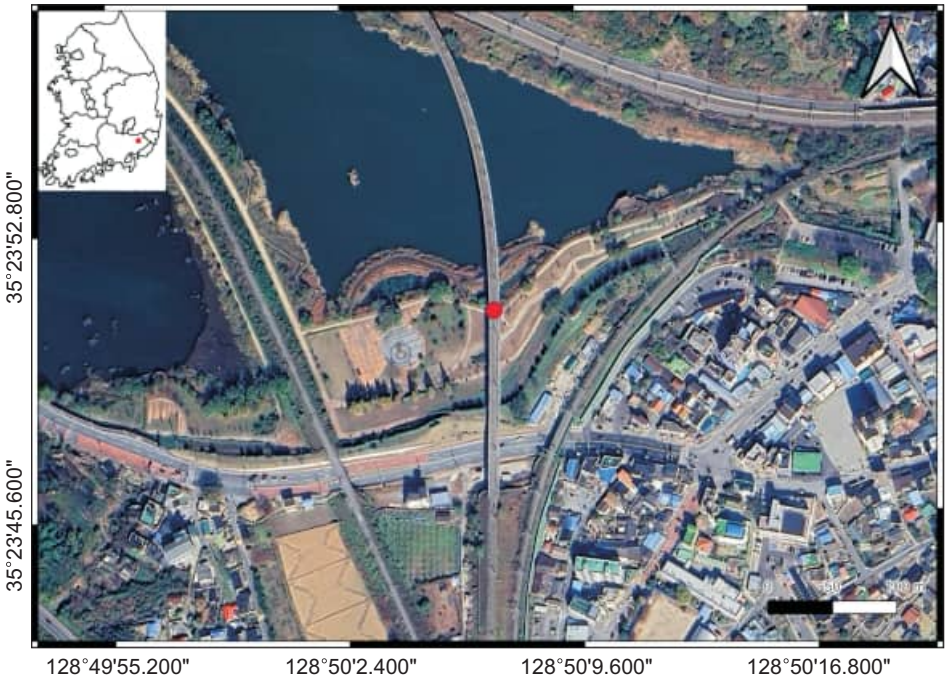

Fig. 1. Location of the study site in Miryang-si, Gyeongsangnam-do, South Korea, shown as a satellite image with a detailed view of the area.

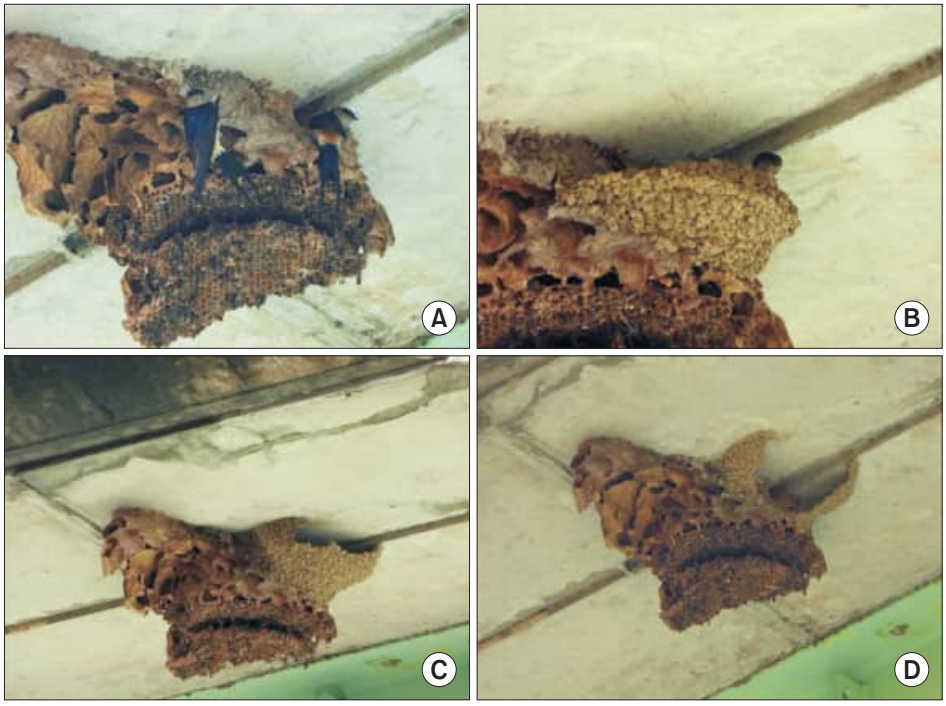

Fig. 2. Sequence of nest construction by *Cecropis daurica* using a pre-existing wasp nest beneath a railway bridge. (A) Adults repeatedly entering and exiting the wasp nest prior to nest construction. (B) Early stage of nest construction, with mud being attached to the side of the wasp nest. (C) Nest structure largely completed. (D) Collapsed nest observed.

the recording of behaviors occurring in locations that are not continuously accessible to researchers (Bonney *et al.*, 2009; Dickinson *et al.*, 2010) and has served as a complementary data source in studies of avian distribution and behavior (Cooper *et al.*, 2014; Sullivan *et al.*, 2014). This record provides additional empirical information on the range of nesting substrates used by *C. daurica.*

Author Contributions

Conceptualization: HJL, SYL. Funding acquisition: SYL. Investigation: HJL, JRK. Project administration: YL, AH. Writing – original draft: SYL. Writing – review & editing: All authors.

Conflict of Interest

The authors declare that they have no competing interests.

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Two Newly Recorded Species of *Nemophora* (Lepidoptera, Adelidae) from Korea, with a Checklist of Korean *Nemophora*

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ABSTRACT

Two newly recorded species from the genus *Nemophora*, *N. rubrofascia* (Christoph, 1882) and *N. hunanensis* Liao, Hirowatari & Huang, 2023, were reported in Korea for the first time. Illustrations of adults and genitalia are provided, along with the DNA barcoding data. Here, we also present the first comprehensive checklist of Korean *Nemophora* species.

Keywords: Adelinae, Longhorn moths, Palearctic region, Taxonomy

Introduction

Adelidae are commonly called long-horn moths because of their extremely long antennae. They are distributed worldwide, except in the polar regions (Liao *et al*., 2023). The genus *Nemophora* is the most species-rich genus within the Adelidae family and is well known for its colorful wing patterns and diverse markings (Kozlov, 2020; Ko *et al*., 2025).

The genus *Nemophora* comprises over 250 described species worldwide, with more than 220 occurring mainly in the Palearctic region and Southeast Asia (Sun *et al*., 2022; Ko *et al*., 2023). *Nemophora* has been actively studied in neighboring countries, such as China and Japan (Hirowatari, 2005a; Hirowatari *et al*., 2012; Liao *et al*., 2021; 2023; Sun *et al*., 2022; Sun & Li, 2023). In China, 91 species have been recorded (Liao *et al*., 2023), whereas 29 have been reported in Japan (Hirowatari, 2005b; 2013; 2023).

In Korea, 14 species of *Nemophora* are currently known (KSAE & ESK, 2021), including *N. lutea*, which was recently described as a new species by Ko *et al*. (2023). Here, we report two newly recorded species of *Nemophora* in Korea and provide the first checklist for this genus in the country. Photographs of adults and genitalia, along with DNA barcoding data, are provided to support future identification and species comparisons. With the addition of these two species, 16 species of *Nemophora* are now confirmed in Korea.

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Materials and methods

Specimens were collected using at night a light tent with a mercury vapor lamp (200V/200W), and bucket light trap with a black light UV lamp (12V/8W). The genitalia were dissected and examined under a Leica EZ4 stereomicroscope (Leica Microsystems Ltd., Wetzlar, Germany). Images of adults and their genitalia were captured using a Canon EOS 5Ds digital camera (Canon Inc., Tokyo, Japan) attached to a Canon MP-E 65 mm F2.8 Macro Photo lens (Canon Inc.) and a Leica DM 2500 microscope attached to a Leica ICC50 E microscope (Leica Microsystems Ltd.). The species examined in Korea were deposited at the DASARI Research Institute of BioResources, Daejeon, Korea and at the National Institute of Biological Resources (NIBR), Ministry of Climate, Energy and Environment, Korea. Here, we followed the concept of genitalia as suggested by Davis (1998) and Liao *et al*. (2023).

DNA analysis

Genomic DNA was extracted from the legs of the adult specimens. DNA extraction was performed using the DNeasy® Blood & Tissue Kit (Qiagen, Hilden, Germany), following the manufacturer's protocol. Polymerase chain reaction (PCR) amplification was carried out using Solg™ 2X Taq PCR Pre-mix (SolGent, Daejeon, Korea). The universal primer pair LCO1490 (forward, 5′-GGTCAACAAATCATAAAGATATTG-3′) and HCO2190 (reverse, 5′-TAAACTTCAGGGTGACCAAAAAATCA-3′) was used to amplify a 658 bp fragment of the cytochrome c oxidase subunit I (COI) gene (Folmer *et al*., 1994). The PCR conditions included an initial denaturation at 95°C for 2 minutes, followed by 40 cycles of denaturation at 95°C for 20 seconds, annealing at 52°C for 40 seconds, and extension at 72°C for 1 minute, with a final extension at 72°C for 5 minutes. The resulting sequences were deposited in the GenBank database.

Results

Family Adelidae Bruand, 1850
Subfamily Adelinae Bruand, 1850
Genus *Nemophora* Hoffmannsegg, 1798

***Nemophora rubrofascia* (Christoph, 1882)**

(Korean name: Bul-geun-jul-gin-su-yeom-na-bang)
(Figs. 1A, 2A, 2C, 3A, 4A)

Adela rubrofascia Christoph, 1882: 9. Type locality: Russia, Chingan and Wladiwostok.

Nemotois rubrofascia: Matsumura, 1931: 1112, Fig. 2339; Matsumura, 1932: 121, pl. 4, Fig. 2.

Nemophora rubrofascia: Hirowatari, 2005b: 8; Hirowatari, 2013: 106, Figs. 3-08-9,10; Umetsu, 2014: 5, Fig. 11; Fukuda & Kanai, 2016: 18.

Nemotois rubrifascia [sic!]: Meyrick, 1912a: 8; Meyrick, 1912b: 7; Meyrick, 1914: 61.

Diagnosis: Forewing length was 8 mm for males. This species is similar to *Nemophora lutea* Ko & Hirowatari, 2023 (Ko *et al*., 2023; Figs. 1-4), but can be distinguished by the following characteristics: the forewing is narrower than in *N. lutea*; the ground color of the forewing is darker than that in *N. lutea*; the basal area of the forewing is not metallic (metallic in *N. lutea*), and the medial band is deep orange (orange in *N. lutea*). In the male genitalia, the apex of the uncus is rather triangular (rounded in *N. lutea*); the valva is rather rectangular (triangular in *N. lutea*); the transtilla and vinculum are longer than in *N. lutea*; the arrow-shaped juxta is longer than in *N. lutea*; the aedeagus is nearly straight (curved in *N. lutea*); the apical part is straight (twisted in *N. lutea*).

Material examined: 1♂, Tongo MT, Geumgangsong-myeon, Uljin-gun, Gyeongsangbuk-do (GB), Korea, (N36°55′13″, E129°11′37.1″ Alt. 514 m), 03.VI.2017, (Park B.S., Na S.M., Lee D.J., Ko J.H.), Genitalia slide no. INU-7186; sample ID for DNA analysis: KJH-0004 (GenBank



Fig. 1. Adults. (A) *N. rubrofascia* (male, INU-7186). (B) *N. hunanensis* (male, INU-7185).

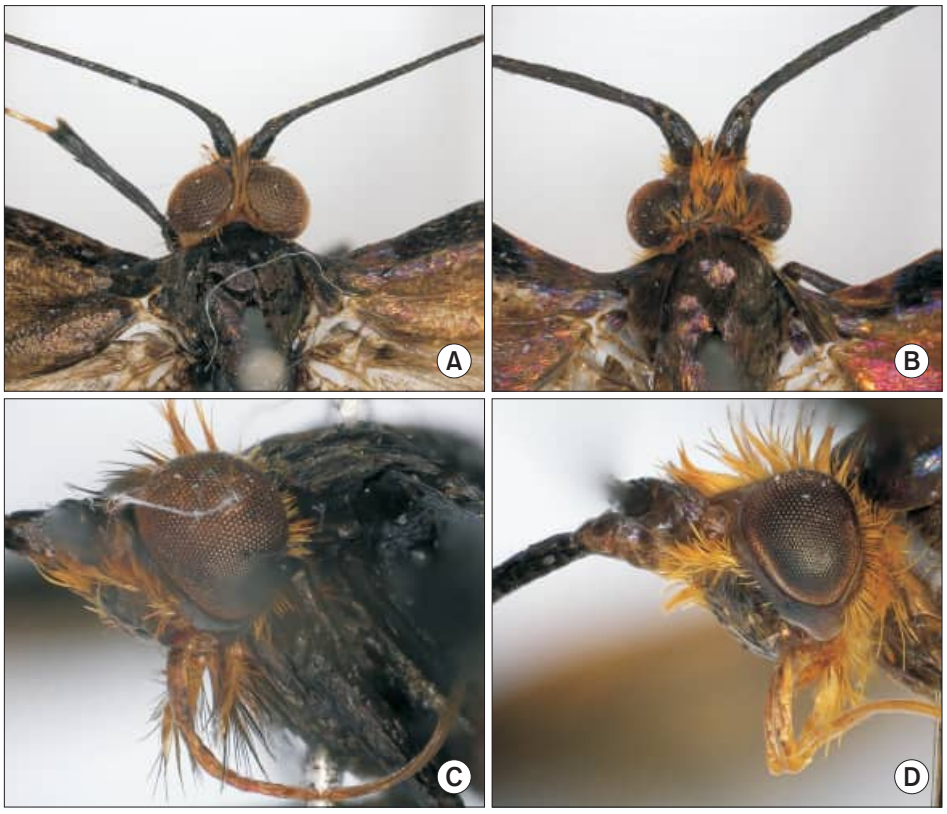

Fig. 2. Heads of adults. (A, C) *N. rubrofascia* (male, INU-7186). (B, D) *N. hunanensis* (male, INU-7185).

accession number: PZ193723).

Distribution: Korea (new record), China, Japan, and Russia.

DNA analysis: A basic local alignment search tool (BLAST) search of the COI barcode sequence of this species in the National Center for Biotechnology Information (NCBI) database showed 95.64% sequence similarity with *Nemophora rubrofascia* from Japan (sample ID: GenBank accession number: SaY541/ON256890). Although this level of divergence exceeds the 3% threshold suggested for Lepidoptera by Hebert *et al*. (2003), this value should be regarded as a general guideline rather than a strict diagnostic criterion. Species identification must be supported by morphological evidence. Therefore, the Korean specimen was herein identified as *N. rubrofascia* (sample ID: GenBank accession number: KJH0004/PZ193723), based on the limited number of available specimens and its strong morphological similarity.

Remarks: This species is reported from Korea for the first time in this study. It has occasionally been observed in several regions of Korea (Muju, Gwangju, and Uljin), where a few male individuals have been observed in photographs. Similar to other species of *Nemophora*, they appeared mainly from May to June. Here, specimens were collected during night surveys, and some individuals appeared to be attracted to light. The Korean specimens showed a narrower medial band on the forewing than *N. rubrofascia* specimens from Japan, and the COI sequence divergence was 4.36%. However, based on the strong similarities in external morphology and genital characteristics, the specimens were identified as *N. rubrofascia* in this study. Additional sampling and broader comparisons with related species from neighboring countries are needed in the future.

***Nemophora hunanensis* Liao, Hirowatari & Huang, 2023**

(Korean name: Geum-jul-gin-su-yeom-na-bang)

(Figs. 1B, 2B, 2D, 3B, 4B)

Nemophora hunanensis Liao, Hirowatari & Huang, 2023: 34, Plates III-5, XIV-5. Type locality: China (Hunan).

Diagnosis: Forewing length was 7 mm in male. This species is similar to *Nemophora smaragdaspis* (Meyrick, 1924), which has been recorded in Korea (Ji *et al*., 2018; Figs. 1E, 2D), but can be distinguished by the following characteristics: the length of the forewing is 7 mm (10 mm in *N. smaragdaspis*), the medial band is orange (yellow in *N. smaragdaspis*), and metallic gray lines on both sides of the medial band are absent (present in *N. smaragdaspis*). In the male genitalia, the valva is nearly rectangular (ovoid in *N. smaragdaspis*), and the arrow-shaped juxta has a head and tail of similar length (tail shorter than head in *N. smaragdaspis*); the apex of the aedeagus is spatulate (twisted in *N. smaragdaspis*)

Material examined: 1♂, Seonheul-ri, Jocheon-eup,

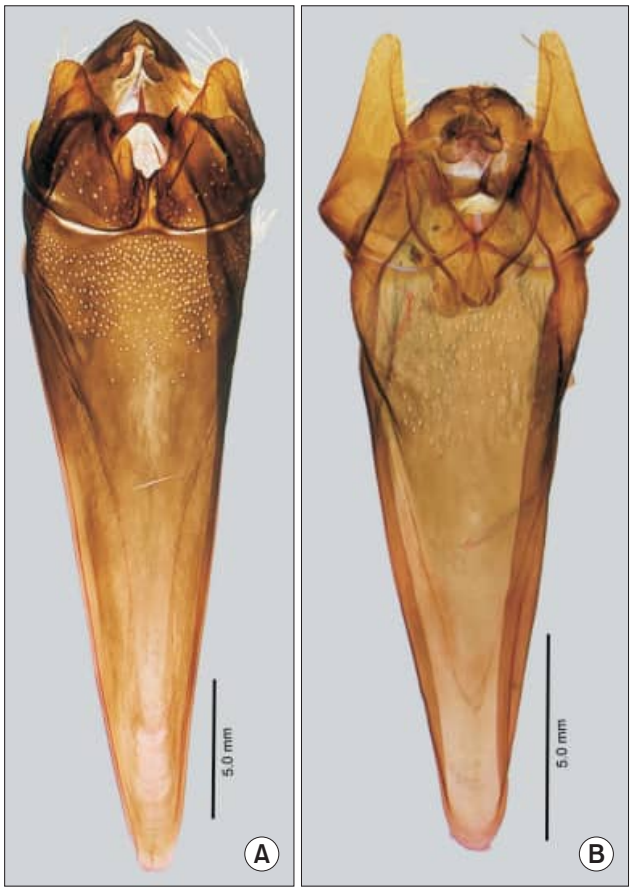

Fig. 3. Male genitalia. (A) *N. rubrofascia* (male, INU-7186). (B) *N. hunanensis* (male, INU-7185).

Jeju-si, Jeju-do (JJ), Korea, (N33°28′29.8″, E126°38′14.8″ Alt. 276 m), 08.VII.2015 (Bae *et al.*), Genitalia Slide no. INU-7185; sample ID for DNA analysis: KJH-0003 (GenBank accession number: PZ193722).

Distribution: Korea (new record), China.

DNA analysis: A BLAST search of the COI barcode sequence of this species in the NCBI database showed 99.24% sequence similarity with *Nemophora hunanensis* from China (sample ID: GenBank accession number: LCQ773/PP065984). The Korean specimen also showed extremely high morphological similarity to the Chinese *N. hunanensis*. The COI sequence divergence was extremely low (0.76%). Therefore, the Korean specimen was identified as *N. hunanensis* (GenBank accession number: KJH0003/PZ193722).

Remarks: This species is reported from Korea for the first time in this study. To date, it has been isolated only from Jeju Island, South Korea. Here, specimens were collected during the night surveys, and some individuals appeared to be attracted to light. The Korean specimen showed a wider medial band on the forewing than *N. hunanensis* from China, but the COI sequence divergence



Fig. 4. Juxta and aedeagus of male genitalia. (A) *N. rubrofascia* (male, INU-7186). (B) *N. hunanensis* (male, INU-7185).

was extremely low (0.76%). Based on these morphological similarities and minimal genetic divergence, the specimen was identified as *N. hunanensis*.

Discussion

In this study, we report *Nemophora rubrofascia* and *N. hunanensis* for the first time from Korea.

Regarding *N. rubrofascia*, a comparison of its external morphology with the type specimen (Liao *et al.*, 2023: Plate X, 10) and Japanese specimens (Hirowatari, 2013: p.19, Figs. 3-08-9, 10) suggests that the deep orange band on the wings exhibits considerable variation. Despite this chromatic variability, the male genitalia were found to be identical to those of the Japanese populations. Furthermore, our molecular phylogenetic analysis using COI sequences showed that the Korean specimens cluster strongly with the Japanese *N. rubrofascia* (UFBoot=100). Based on the morphological consistency of the genitalia and the robust genetic evidence, we identified this species as *N. rubrofascia*.

As for *N. hunanensis*, which was recently described by Liao *et al.* (2023), the Korean specimens exhibit wing patterns identical to those of the Chinese populations. Our molecular analysis further supported this, as the Korean specimens clustered with the Chinese *N. hunanensis* with strong support (UFBoot=100). Although slight differences

Table 1. Checklist of the known species of the genus *Nemophora* from Korea

No.	Species	Species group	Distribution
1	*Nemophora albiantennella* (Issiki, 1930)	*albiantennella*	Korea, Japan, China, Russia
2	*Nemophora askoldella* (Milliére, 1879)	*askoldella*	Korea, Japan, China, Russia
3	*Nemophora aurifera* (Butler, 1881)	*aurifera*	Korea, Japan, China
4	*Nemophora tyriochrysa* (Meyrick, 1935)	*aurifera*	Korea, Japan, China
5	*Nemophora hunanensis* (Liao, Hirowatari & Huang, 2023)	*sakaii*	Korea, China
6	*Nemophora decisella* (Walker, 1863)	*decisella*	Korea, China, Russia, Southeast Asia
7	*Nemophora lutea* (Ko & Hirowatari, 2023)	*decisella*	Korea
8	*Nemophora smaragdaspis* (Meyrick, 1924)	*decisella*	Korea, Japan, China, India, Nepal
9	*Nemophora rubrofascia* (Christoph, 1881)	*rubrofascia*	Korea, Japan, China, Russia
10	*Nemophora amatella* (Staudinger, 1892)	*degeerella*	Northern Europe–Asia
11	*Nemophora chalybeella* (Bremer, 1864)	*degeerella*	Korea, Japan, China, Russia
12	*Nemophora karafutonis* (Matsumura, 1932)	*degeerella*	Korea, Japan, China, Russia
13	*Nemophora lapikella* (Kozlov, 1997)	*degeerella*	Korea, Japan, China, Russia
14	*Nemophora staudingerella* (Christoph, 1881)	*degeerella*	Korea, Japan, China, Russia
15	*Nemophora wakayamensis* (Matsumura, 1931)	*degeerella*	Korea, Japan, Russia
16	*Nemophora raddei* (Rebel, 1901)	*Incertae sedis*	Korea, Japan, Russia

were observed in the shape of the valva compared to the original description, these are likely attributable to intraspecific variation or morphological distortion caused by the compression of the genital slide during preparation. Consequently, we identify these specimens as *N. hunanensis* based on the integrated evidence.

As noted above, research on Adelidae in Korea is still limited compared to neighboring Japan and China, and it is highly likely that many species, including new and unrecorded ones, remain to be discovered. To provide a foundation for future research, we have compiled an updated checklist of the genus *Nemophora* recorded in Korea (Table 1). In conclusion, further comprehensive studies on the family Adelidae, including the two species reported in this study, are necessary to understand the biodiversity of this group in Korea.

Author Contributions

Conceptualization: JHK. Data curation: SC, JHK. Formal analysis: JHK, SC. Funding acquisition: JHK. Investigation: JHK. Methodology: JHK, SC. Resources: EJH. Visualization: JHK. Writing – original draft: JHK. Writing – review & editing: UB, JHK.

Conflict of Interest

The authors declare that they have no competing interests.

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Case Report

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Pimpla spuria, a Darwin Wasp of the Genus *Pimpla* (Hymenoptera, Ichneumonidae, Pimplinae) New from Dokdo Island, South Korea

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ABSTRACT

The subfamily Pimplinae is well-studied subfamily of moderately large and cosmopolitan Darwin wasps, that comprises more than 1,730 valid species across 77 genera in three tribes. The most well-known species of this subfamily are the endo- and ectoparasitoids of the orders Coleoptera, Diptera, Hymenoptera, Lepidoptera, and Araneae. In this study, the first record of the species *Pimpla spuria* in South Korea is reported and photographs its morphological features are presented.

Keywords: Ichneumonids, Parasitoids, Pimplini, Taxonomy, Unrecorded species

Introduction

The genus *Pimpla* (Pimplinae: Pimplini), which is the second largest group of the tribe Pimplini, comprises more than 205 species worldwide (Yu *et al.*, 2016). Twelve species have been recorded in South Korea and 39 species is represented in the Eastern Palaearctic region. A taxonomic study of *Pimpla* was initiated by Fabricius in 1804, with *Ichneumon instigator* being the type species. This genus can be distinguished by the following charaters: a clypeus separated from the face by a suture, with a distinct transverse basal ridge; a fore wing with a closed areolet; and a usually stout first metasomal tergite.

Pimpla spuria was discovered in Dokdo Island in 2024 by Malaise trapping and is recorded for the first time from South Korea in this study. This species has been recognized as an important pest control agent for *Archips rosana* (Lepidoptera: Ceratopiidae) in organic cherry orchards and *Garella musculana*, a walnut tree pest (Yurtcan & Beyarslan, 2005; Aydoğdu, 2014; Yildiz & Ayberk, 2019). In this study, the diagnosis and illustrated characteristics of this species are provided.

Materials and Methods

The morphological terminology used in the present study follows that of Broad *et al*. (2018). The specimens used in this study were collected by Malaise trapping on Dokdo Island. The examined material is preserved in the Insect Inquiry · Education Institute of the Daegu National University of Education (DNUE-IIEI, Daegu, Korea). Images of the specimen were taken using a Leica MC190 HD camera attached to a Leica M125 microscope (Leica Microsystems, Wetzlar, Germany) and processed using Leica LAS X software.

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Taxonomy

Family Ichneumonidae Latreille, 1802 Maep-si-beol-gwa

Subfamily Pimplinae Wesmael, 1845 Nap-jak-maep-si-beol-a-gwa

Genus *Pimpla* Fabricius, 1804 Ho-kka-i-do-o-nap-jak-maep-si-beol-sok

Pimpla spuria Gravenhorst, 1829 No-rang-da-ri-nap-jak-maep-si-beol

Pimpla spuria Gravenhorst, 1829: 1-1097. Lectotype:

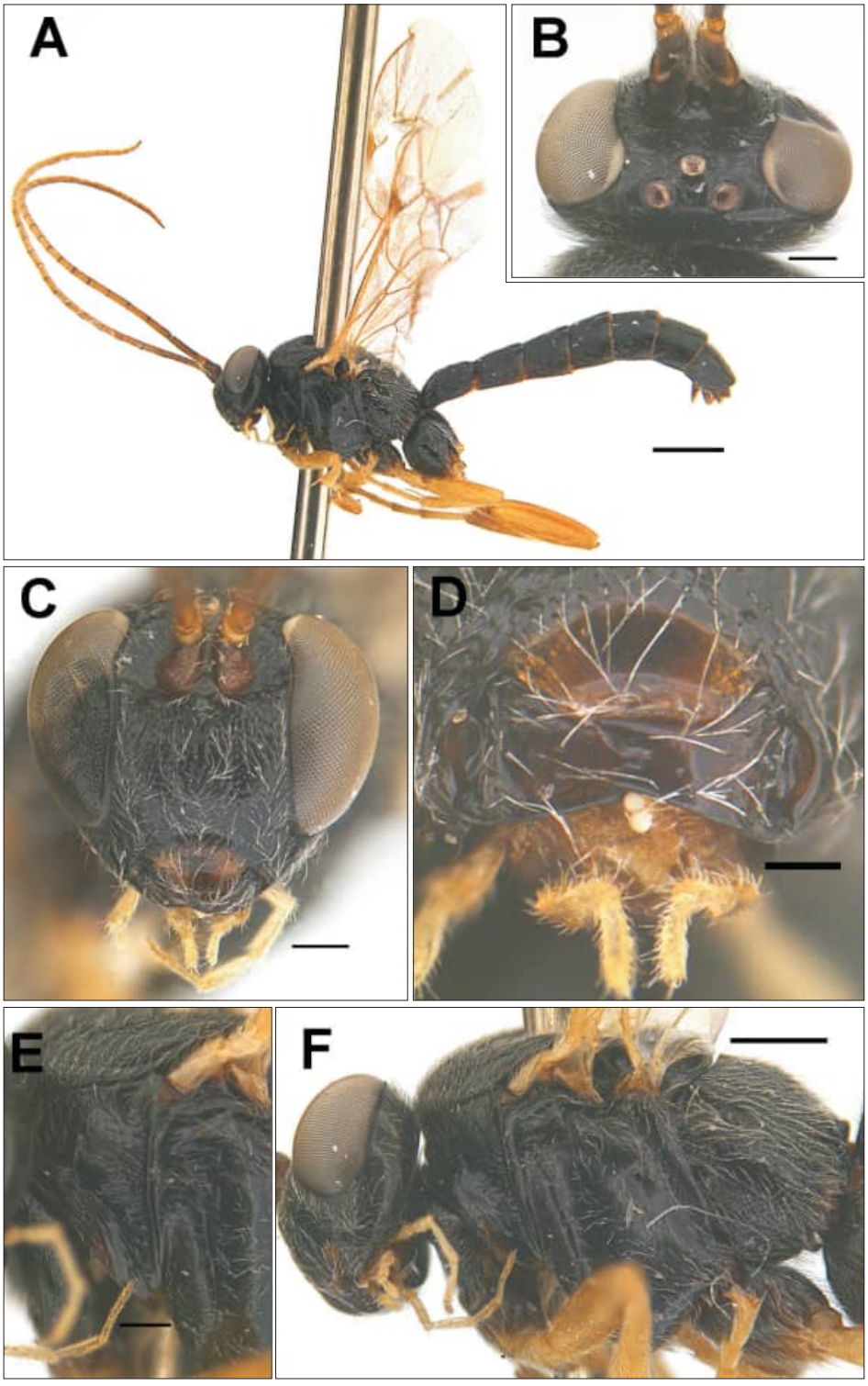

Fig. 1. *Pimpla spuria* Gravenhorst, 1829. (A) Habitus in lateral view. (B) Head in dorsal view. (C) Head in frontal view. (D) Mandible. (E) Pronotum. (F) Head and mesosoma in lateral view. Scale bars: (A) 1 mm; (B, C, E) 0.2 mm; (D) 0.1 mm; (F) 0.5 mm.

female; type depository: IZU (Instytut Zoologiczny Uniwersytetu, Sienkiewicza 21, Wroclaw, Poland. (Gravenhorst collection.)).

Pimpla bilineata Brullé, 1846: 56-521. Type: lost.

Pimpla strigipleuris Thomson, 1877: 732-777. Lectotype: female; type depository: ZI (Zoologiska Institutionen, Helgonavägen 3, S-223 62 Lund, Sweden).

Pimpla dubitata Pérez, 1895: 191-204. Type: female; type depository : unknown.

Pimpla nilotica Schmiedeknecht, 1914: 369-478. Lectotype: female; type depository: Gmn_rds_schmiedekne (Naturhistorisches Museum, Heidecksburg, Schlossbezirk 1, D-07407 Rudolstadt, Germany. O. Schmiedeknecht collection.)).

Pimpla turionelloides Aubert, 1959: 133-166. Type: unknown.

Specimens examined: South Korea: 1 ♂, Gyeongsangbuk-do Ulleung-gun Dokdo-ri Dongdo, 17.vi-30.x.2024, JC Jeong (DNUE-IIEI).

Diagnosis

Male: Body length 7.2 mm; fore wing length 5.5 mm. Generally black and yellowish brown (Fig. 1A).

Head: Head black with white hairs (Fig. 1C). Frons, temple and vertex polish; head Face convex in lateral view; clypeus dark brown and flat in lateral view, apical margin of clypeus cancave; upper tooth of mandible longer than lower tooth (Fig. 1D). Head 2.0 times as wide as height in frontal view, 1.86 times as wide as height in dorsal view (Fig. 1B); face as long as the distance between the clypeal margin and the margin of the antennal socket; malar space as long as the basal width of manbible; malar space with punctures, punctures less than those on the face. Antennae with 29 flagellomeres, ratio of flagellomeres I-V=2.3:1.6:1.5:1.4:1.2. Occipital carina distinct; ocellar diameter (OD) 0.76 times as long as postero-ocellar line (POL), 1.18 times as long as ocello-ocular line (OOL).

Mesosoma: Pronotum with distinct epomia (Fig. 1E). Mesopleuron with long epicnemial carina and polished (Fig. 1F). Mesoscutum polished and moderately punctate, without notauli (Fig. 2A). Scutellum and postscutellum black; propodeal carina incomplete, basal and petiolar area polished and glabrous (Fig. 2B). All coxae black; fore and mid legs yellowish brown; hind trochanters yellow, basal area of hind tibia white to pale yellow (Fig. 2E); tarsal claw simple and sharply curved (Fig. 2F), ratio of tarsomeres I-V=5.0:2.8:2.1:1.3:3.3.

Metasoma: Tergite black; sternite brownish. First metasomal tergite 1.14 times as long as the second metasomal tergite (Fig. 2C, D). First metasomal tergite finely punctulate-reticulate, spiracles situated at anterior 0.38.

Host

[Lepidoptera: Choreutidae] *Tebenna bjerkandrella*, [Lepidoptera: Crambidae] *Cynaeda dentalis*, *Loxostege sticticalis*, *Ostrinia nubilalis*, [Lepidoptera: Depressariidae] *Agonopterix heracliana*, *Agonopterix propinquella*, *Depressaria pastinacella*, [Lepidoptera: Erebidae] *Calliteara pudibunda*, *Hyphantria cunea*, *Lymantria dispar*, [Lepidoptera: Gelechiidae] *Psoricoptera gibbosella*, [Lepidoptera: Geometridae] *Eupithecia vulgata*, *Larentia clavaria*, [Lepidoptera: Noctuidae] *Sesamia nonagrioides*, [Lepidoptera: Psychidae] *Canephora hirsuta*, [Lepidoptera: Pyralidae] *Etiella zinckenella*, *Pempelia genistella*, [Lepidoptera: *Tortricidae*] *Archips rosana*, *Cydia pomonella*, *Enarmonia formosana*, *Eupoecilia ambiguella*, *Grapholita funebrana*, *Gypsonoma aceriana*, *Lobesia botrana*, [Lepidoptera: Yponomeutidae] *Yponomeuta malinella*, *Yponomeuta padella* (Yu *et al*., 2016).

Distribution

South Korea (new record), Afghanistan, Albania, Algeria, Armenia, Austria, Azerbaijan, Belarus, Belgium,

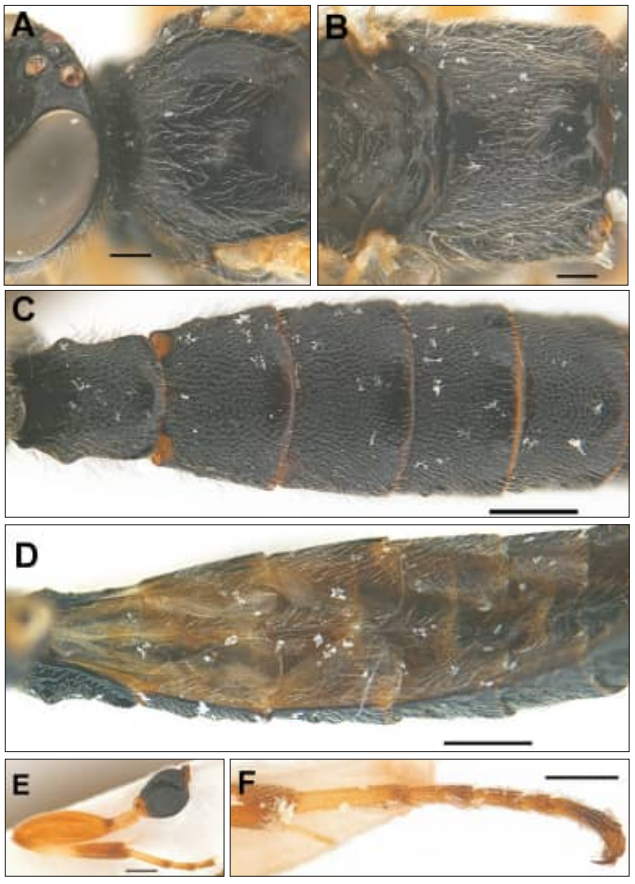

Fig. 2. *Pimpla spuria* Gravenhorst, 1829. (A) Mesoscutum in dorsal view. (B) Scutellum and propodeum in dorsal view. (C) Metasomal tergites in dorsal view. (D) Metasomal sternites in ventral view. (E) Hind leg. (F) Tarsomes. Scale bars: (A, B) 0.2 mm; (C-F) 0.5 mm.

Bulgaria, Canary Islands, China, Croatia, Czech Republic, Czechoslovakia, Denmark, Egypt, Finland, France, Georgia, Germany, Greece, Hungary, Iran, Ireland, Israel, Italy, Japan, Kazakhstan, Kyrgyzstan, Libya, Lithuania, Macedonia, Malta, Moldova, Mongolia, Morocco, Netherlands, Norway, Poland, Romania, Russia, Serbia & Montenegro, Spain, Sweden, Switzerland, Tajikistan, Turkey, Turkmenistan, Ukraine, United Kingdom, Uzbekistan, Yugoslavia.

Region

Eastern Palaearctic, Oriental and Western Palaearctic.

Conflict of Interest

The author declares that he has no competing interests.

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MANUSCRIPT SUBMISSION

1. Select Article Type

• Original (Research) Articles

Original (Research) Article is publishing research on basic ecological research on terrestrial and aquatic populations, communities, ecosystems, and landscapes, as well as ecological research in general. Manuscripts include a title page (with a running title), abstract and keywords, text (introduction, materials and methods, results, and discussion), author contributions, conflicts of interest, acknowledgments, funding, references, tables, figures, and figure legends.

• Review Articles

Review Article is expected to be focused discussion of defined topics relevant to the scope of PNIE. General remarks are same with original article. Manuscripts include a title page (with a running title), abstract and keywords, text, author contributions, conflicts of interest, acknowledgments, funding, references, tables, figures, and figure legends.

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Unique cases that make an important teaching point or scientific observation may be suitable for case report. This should consist of title page, abstract, text (including introduction, case report, and discussion), author contributions, conflicts of interest, acknowledgments, funding, references, tables, figures, and figure legends.

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Thank you for your interest in PNIE. Note that submission implies that the content has not been published or submitted for publication elsewhere except as a brief abstract in the proceedings of a scientific meeting or symposium.

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If tables or figures have been reproduced from another source, a letter from the copyright holder (usually the Publisher), stating authorization to reproduce the material, must be attached to the covering letter.

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MANUSCRIPT ORGANIZATION AND FORMAT

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The length of an article (including references, tables and appendices) should not exceed 20 printed pages for research papers and invited reviews.

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Manuscripts should be presented in the following order: (i) title page, (i) title page, (ii) abstract and keywords, (iii) text, (iv) author contributions, (v) conflicts of interest, (vi) acknowledgments, (vii) funding, (viii) supplementary information, (ix) references, (x) tables (each table complete with title and footnotes), (xi) figure legends and (xii) appendices. Figures and supporting information should be supplied in separate files, if relevant. Footnotes to the text are not allowed and any such material should be incorporated into the text as parenthetical matter.
Divide your article into clearly defined sections. Each subsection is given a brief heading. Each heading should appear on a separate line.

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All articles must have a brief abstract that states in 250 words or fewer the purpose, basic procedures, main findings and principal conclusions of the study. The abstract should not contain abbreviations or references.

Up to six key words (for the purposes of indexing) should be supplied below the abstract in alphabetical order. For the selection of keywords, refer Medical Subject Heading in Index

Medicus or in internet site, https://www.nlm.nih.gov/mesh/MBrowser.html.

3) Text

Authors should use the following subheadings to divide the sections of their manuscript: Introduction, Materials and Methods, Results, and Discussion.

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Study rationale and relevant background information should be described clearly and concisely.

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Study materials and methods should be described in the following order: study design, materials and methods.

Ensure correct use of the terms sex (when reporting biological factors) and gender (identity, psychosocial or cultural factors), and, unless inappropriate, report the sex and/or gender of study participants, the sex of animals or cells, and describe the methods used to determine sex and gender. If the study was done involving an exclusive population, for example in only one sex, authors should justify why, except in obvious cases (e.g., prostate cancer). Authors should define how they determined race or ethnicity and justify their relevance.

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Study results should be reported in a clear and logical manner.

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The results must be explained in relation to the hypotheses proposed in the Introduction. Keep in mind that the Discussion must not be a mere restatement of the results. Authors must emphasize new and important discoveries of the study and state the conclusions drawn from the results in relation to the purpose of the study. The shortcomings and limitations of the study must also be mentioned.

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• Example of author contributions:

Conceptualization: ***, ***. Data curation: ***, ***. Formal analysis: ***, ***. Funding acquisition: ***, ***. Investigation: ***, ***. Methodology: ***, ***. Project administration: ***, ***. Resources: ***, ***. Software: ***, ***. Supervision: ***, ***. Validation: ***, ***. Visualization: ***, ***. Writing – original draft: ***, ***. Writing – review & editing: ***, ***.

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The authors must disclose any potential conflicts of interest possibly influencing the research or interpretation of data at the time of submission. In particular, all sources of funding for a study should be explicitly stated. Statements on conflict of interest have no influence on the editorial decision to publish. If there are no competing interests, the statement should read, "The authors declare that they have no competing interests." Additionally, potential conflicts of interest of editorial board members should also be disclosed in the manuscript.

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Any persons that contributed to the study or the manuscript, but not meeting the requirements of an authorship could be placed here. For mentioning any persons or any organizations in this section, there should be a written permission from them.

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Sugumaran, M., Saul, S.J., and Ramesh, N. (1985). Endogenous protease inhibitors prevent undesired activation of prophenoloxidase in insect haemolymph. *Biochemical and Biophysical Research Communications*, 132, 1124–1129. https://doi.org/10.1016/0006-291x(85)91923-0

(2) Book
Chapman, R.F. (1971). *The Insects Structure and Function*, 3rd ed. Elsevier.

(3) Web Sites
Chapman, K., and Brown, M. (2010). The future of digital library in Asia. *Digital Libraries*, 7, 111-119. Retrieved May 5, 2010 from https://www.diglib.org/publist.htm.
GBIF. (2024). *Global biodiversity information facility*. Retrieved Dec 9, 2024 from www.gbif.org.

(4) Chapter in a Book
Driever, M. (1993). Maternal control of anterior development in the Drosphila embryo. In M. Bate, and A.M. Aris (Eds.), *The Development of Drosophila Melanogaster* (pp. 387–424). Cold Spring Harbor Laboratory Press.

(5) Conference Abstract
Hong, K.D., and Kim, L.P. (1997). *The sources and migratory pathway of locusts in Korea*. Paper presented at The 50th Annual Meeting of The Entomological Society of Korea, Seoul, Korea.

References in articles
We recommend the use of a tool such as EndNote or Reference Manager for reference management and formatting. EndNote reference styles can be searched for here: https://www.endnote.com/support/enstyles.asp. Reference Manager reference styles can be searched for here: https://www.refman.com/support/rmstyles.asp.

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Review Article is expected to be focused discussion of defined topics relevant to the scope of PNIE. General remarks are same with original article. Manuscripts include a title page (with a running title), abstract and keywords, text, author contributions, conflicts of interest, acknowledgments, funding, references, tables, and figures. Abstract should be written in English within 150 words in one paragraph. The text can be written in free style. The review articles should be submitted in the same way as regular papers and received the same review process.

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Research and Publication Ethics

PNIE PROCEEDINGS OF THE NATIONAL INSTITUTE OF ECOLOGY OF THE REPUBLIC OF KOREA

Enacted August 5, 2020
Revised July 26, 2022
Revised June 23, 2025

The *Proceedings of the National Institute of Ecology of the Republic of Korea* (PNIE) adheres to the ethical guidelines for research and publication described in Guidelines on Good Publication (http://publicationethics.org/resources/guidelines), the International Committee of Medical Journal Editors (ICMJE) Guidelines (http://www.icmje.org), and Principles of Transparency and Best Practice in Scholarly Publishing (http://doaj.org/bestpractice). PNIE follows the international standards for editors and authors press release, https://publicationethics.org/resources/international-standards-for-editors-and-authors and the Committee on Publication Ethics (COPE) flowcharts, https://publicationethics.org/resources/flowcharts.

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3. Ethical Aspects

The author should not use ideas, research or records of others without quoting them. The corresponding author is responsible for all the contents of the manuscript. Authors must deposit data, strains or other materials in scientific collections (e.g., culture collections, herbaria, GenBank, etc.) to make it possible to repeat the experiments and perform future research. Research published in the PNIE must have been conducted in accordance with institutional, national and international guidelines concerning the use of animals in research and/or the sampling of endangered species. For the policies on research and publication ethics that are not stated in these instructions, the Guidelines on Good Publication (https://publicationethics.org/resources/guidelines), Publication of Scholarly Work in Medical Journals (https://www.icmje.org/icmje-recommendations.pdf) and the Principles of Transparency and Best Practice in Scholarly Publishing (https://doaj.org/bestpractice).

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The corresponding author is responsible for disclosing any potential conflicts of interest that may influence the interpretation of the study's data or findings. Potential conflicts include, but are not limited to, financial support or affiliations with pharmaceutical companies, as well as academic or institutional relationships that could affect objectivity.

All sources of funding relevant to the research must be clearly stated. If no competing interests exist, the authors should include the following statement:
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Editor's & Reviewer's Guide

PNIE PROCEEDINGS OF THE NATIONAL INSTITUTE OF ECOLOGY OF THE REPUBLIC OF KOREA

Enacted August 5, 2020
Revised June 23, 2025

Editor's Guide

Editors have the following responsibilities:

- To acknowledge receipt of submitted manuscripts within a few days of receipt and to ensure the efficient, fair and timely review process of submitted manuscripts.
- To ensure that submitted manuscripts are handled in a confidential manner, with no details being disclosed to anyone, with the exception of the referees, without the permission of the author, until a decision has been taken as to whether the manuscript is to be published.
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Principles of Transparency and Best Practice in Scholarly Publishing

PNIE PROCEEDINGS OF THE NATIONAL INSTITUTE OF ECOLOGY OF THE REPUBLIC OF KOREA

Enacted October 26, 2022
Revised June 23, 2025

1. Name of Journal

The official journal title is *Proceedings of the National Institute of Ecology of the Republic of Korea*. Abbreviated title is PNIE.

2. Website

i. The URL address of official journal website is https://accesson.kr/pnie/.

ii. 'Aims and Scope' statement
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