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RESEARCH

# Different plant species and their traits on methane ($CH_4$) emission from wetlands of eastern Himalayan foothills

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**Background:** Plant species can alter the characteristics of wetlands soils and thereby influence methane ($CH_4$) flux and other greenhouse gas emissions. In addition, wetlands are important conduits of $CH_4$ without plants and may emit $CH_4$ at a higher rate when plants are present. In this study, we aimed to quantify the efficiency of *Mikania micrantha*, *Phragmites karka*, *Polygonum hydropiperoides*, *Enhydra fluctuans*, and *Ipomoea aquatica* plants, along with their respective traits, in mediating $CH_4$ emissions from wetlands.
**Results:** $CH_4$ emissions have significantly differed amongst different plant species studied. Further, $CH_4$ emission showed a strong and significant relationship with plant traits, soil physico-chemical, and biological properties. The average cumulative $CH_4$ emission from all the vegetation stands (10.30 mg $m^{-2}$ $h^{-1}$) was significantly higher (118.08%) than that of the $CH_4$ emission from unvegetated bare soil (4.70 mg $m^{-2}$ $h^{-1}$). Overall, the $CH_4$ emission increased by 15%, 44%, and 37% under *M. micrantha*, *P. karka,* and *P. hydropiperoides*, respectively, compared with *E. fluctuans* and *I. aquatica*.
**Conclusions:** Wetland plants could significantly alter the functions and services of wetlands and, cause $CH_4$ emissions. Hence, we suggest that restoration of these wetlands with periodical eradication and proper reuse/utilization of these wetland plants would be appropriate to mitigate the $CH_4$ emissions from the wetlands.

**Keywords:** methane emission, plant traits, soil respiration, wetland plants, wetland soil, wetlands

## Introduction

Increasing methane ($CH_4$) emissions is a huge threat any wetland ecosystem faces in a changing climatic scenario. According to the IPCC report (2023), $CH_4$ emissions from biogenic sources accounted for more than 70% of global production. The biogenic sources of $CH_4$ include wetlands, rice agriculture, livestock, landfills, oceans, and termites. The global warming potential of $CH_4$ is 27 times higher than that of $CO_2$ on a 100 years' time scale (IPCC 2023). Therefore, understanding the production and conduit mechanisms of $CH_4$ in the atmosphere is particularly important. Despite their numerous ecosystem services, wetlands are considered the single largest natural source of $CH_4$ with median emissions of 164 Tg $yr^{-1}$, which is about a third of total global emissions (Tian et al. 2016; Xiao et al. 2024). Chanton et al. (2002) reported that 80%–90% of the $CH_4$ was emitted from many wetlands through the plant aerenchymatous tissues. In contrast, Rusch and Rennenberg (1998) have shown that 'plant pathways' may or may not significantly contribute to the total gas emissions in wetland ecosystems. Hence, these uncertainties in the 'plant pathway' of $CH_4$ necessitate studies on the role of wetland plants and their functional traits in regulating $CH_4$ emission from wetlands (Bijak et al. 2024). Further, not considering the effect of vascular wetland plants on $CH_4$ emission and transport from wetlands into the atmosphere could lead to an underestimation of the $CH_4$ flux rate (Zhang et al. 2017).

Wetland vegetation is an important channel for $CH_4$ export from wetland soil into the atmosphere. Previous studies have also revealed that plants may significantly change the $CH_4$ emission rates from wetland soil/sediments to the atmosphere through vegetation (Kao-Kniffin et al. 2010; Mozdzer and Megonigal 2013; Tong et al. 2012). Kao-Kniffin et al. (2010) established that $CH_4$ transport through plants depends on movement through the root–shoot system, with several control points determining net $CH_4$ flux. Increases and decreases in $CH_4$ emissions could be regulated by several plant functional traits such as plant density, plant biomass, and productivity (Laanbroek 2010; Neubauer et al. 2005; Sutton-Grier and Megonigal 2011; Wang et al. 1996).

Wetland ecosystems continue to attract many plants due to their unique ecological settings, which favour the growth and reproduction. Particularly, wetlands in the eastern Himalayan region are characterized by several species of wetland dependent plant communities. Based on our periodical physical observation, we found that *Mikania micrantha*, *Phragmites karka*, *Polygonum hydropiperoides*, *Enhydra fluctuans*, *Ipomoea aquatica*, *Eupatorium* sp., *Alternanthera* sp., *Ludwigia* sp., and *Lantana camara* are the most abundant plant species in the flood plain wetlands of the eastern-Himalayan region.

Although the impacts of wetland plants on soil nutrient biogeochemistry are well documented, the effects on soil biochemicals, microbial activities, and greenhouse gas (GHG) emissions are poorly understood. While previous studies have examined $CH_4$ emissions from wetlands in temperate, tropical and constructed wetlands (Gauci et al. 2022; Johnson et al. 2022; Treat et al. 2021; Zhang et al. 2023), limited attention has been given to the eastern Himalayan foothills, which harbors unique wetland ecosystems and plant species with distinct traits that may influence $CH_4$ emissions. Our study seeks to address this gap by studying the seasonal pattern of plant mediated $CH_4$ emissions from the floodplain wetlands of the eastern-Himalayan foothills. Further, there have been few or no studies conducted on the effects of wetland plants on $CH_4$ emissions from wetlands in the eastern-Himalayan region so far. Our objectives are to analyze how specific plant traits, such as plant density, aboveground and belowground biomass influence $CH_4$ emissions from the soil, to understand how various plant and soil ecological conditions (e.g., soil moisture, temperature, soil nutrients, and microbial activity) regulate $CH_4$ flux in wetlands and to discuss the broader environmental implications of these findings, particularly in relation to $CH_4$ emissions and climate change mitigation. We hypothesize that (1) specific plant traits significantly influence $CH_4$ emissions from the soil and (2) the interaction between plant traits and soil ecological conditions (e.g., soil moisture, temperature, and nutrients) regulates $CH_4$ flux, with different plant species exerting varying degrees of influence on $CH_4$ emissions.

## Materials and Methods

### Study site

The present study was conducted in the floodplain wetlands of the Dikrong river basin at Doimukh village (27°09′21″N, 93°45′10″ E, and 233 m asl) in Papum Pare district of Arunachal Pradesh, India, during the growing seasons (July to December) of 2009, 2010, and 2011. The soil temperature reaches its peak in the summer months, ranging from 28.96°C in July 2009 to 30.48°C in June 2011 (Fig. S1). Water temperature, however, lags behind more significantly due to its higher heat capacity, typically being 1°C–2°C lower than the soil temperature. It remains more stable throughout the year, with a gradual increase during warmer months, reaching around 29.45°C in June 2011 (Fig. S1).

The plant species studied were: *M. micrantha* (50–55 cm height), *P. karka* (90–125 cm height), *P. hydropiperoides* (61–83 cm height), *E. fluctuans* (35–50 cm height), and *I. aquatica* (65–75 cm height). The selection of plant species was based on their ecological dominance and functional significance in the studied wetland ecosystem. *Mikania micrantha*, *P. karka*, *P. hydropiperoides*, *E. fluctuans*, and *I. aquatica* were chosen because: they are among the most widely distributed and naturally occurring wetland species in the Eastern Himalayan foothills, particularly in Arunachal Pradesh, these species exhibit distinct functional traits that influence $CH_4$ emissions, such as plant density and biomass allocation, they represent different plant growth forms (e.g., emergent, floating, and creeping), allowing a comparative assessment of plant-mediated $CH_4$ flux and these species as key contributors to wetland nutrient cycling, making them suitable candidate species for evaluating their role in $CH_4$ emissions. Thus, these species selection ensures that our findings reflect the dominant ecological processes regulating $CH_4$ flux in the region's wetlands.

All the vegetation stands have occurred in patches within the study sites. The growing season starts at the beginning of July and ends in December. Each patch occupied approximately 20 to 30 $m^2$ of area. The individual patches were at least 10 to 15 m distance apart from each other. There were intermittent gaps that were occupied with perennial grass and other forb species. The study site experiences a warm but pleasant climate throughout the year, with an average air temperature of 25°C (2009–2011) and an average annual total precipitation of 3,048.34 mm $yr^{-1}$ (2009–2011). The water level fluctuated within 40 to 45 cm of depth during different samplings at both vegetated and unvegetated sites. At the end of the growing season, there was a notable variance in the depth of litter accumulation among various plant species.

### $CH_4$ flux measurement

Conventionally, static chamber methods have been widely applied to directly measure $CH_4$ emissions from plants due to their low costs (Belger et al. 2011; Mosier 1990; Song et al. 2009). Five static chambers, made up of transparent poly-acrylic sheets (100 cm long × 50 cm wide × 90 cm height), were deployed in each vegetation stand (*M. mi-*

*crantha, P. karka, P. hydropiperoides, E. fluctuans* and *I. aquatica*) for the gas sampling. The chambers were supported by stainless steel anchors inserted at least 8 cm deep into the soil one month before starting the measurements. A rubber septum was fixed at the top of the chambers to sample the gas. Inside the chambers, a battery-operated fan (12 volts) was fitted to circulate air and homogenize the chamber gas ambiance before the sampling. To explain that plants are the conduit of $CH_4$ emission, we have set-up five replicates of the static chamber in bare (unvegetated) soil plots adjacent to each vegetation type for reference $CH_4$ emission measurements from bare soil devoid of vegetation.

$CH_4$ emissions were measured three times per month during the growing season (July to December). $CH_4$ flux was measured from July to December 2009, 2010, and 2011. Each month, $CH_4$ emission was measured on any three fine days at regular intervals, and mean values were worked out. All the samplings were done during rain-free days between 08.30 AM to 12:00 PM (IST) hours, and values were averaged. The study focused on the growing season (July–December), during which plant activity is at its peak, and $CH_4$ flux is likely to be influenced by plant-soil interactions. While this time frame provided valuable data relevant to the study's objectives, it is acknowledged that excluding the non-growing season limits our ability to capture the full annual variation in $CH_4$ emissions. Logistical constraints prevented the inclusion of data from the non-growing seasons, and future studies will aim to extend the temporal scope to provide a year-round perspective on $CH_4$ flux patterns.

Five samples (70 mL) from static chamber air were manually extracted into 100 mL polyethylene syringes at 0, 15, 30, and 45 minutes after closure and then injected into pre-evacuated vials for analysis. The gas samples were analyzed within 24 hours of sampling with a 3600-GC series gas chromatograph (Scientific Instruments, Kolkata, India) fitted with a flame ionization detector (FID) and stainless-steel column, Porapak® N (80/100 mesh). The temperature inside the chamber was recorded at each gas sampling. The carrier gas was $N_2$ with a 30 mL min-1 and column flow rate, injection, and FID temperatures were maintained at 90°C, 120°C, and 320°C, respectively. The difference in the rate of increase/decrease in $CH_4$ concentration over time was used to calculate the flux. As described by Morin et al. (2017) and Altor and Mitsch (2006), gas chromatography analyses of the static chamber samples were made. Concentrations of gas samples were corrected for field air density following Holland et al. (1999).

$$C_m = \frac{C_v \times M \times P_{atm}}{G \times T}$$

where $C_m$ is the mass/volume concentration of the gas (i.e., mg $CH_4$-C $m^{-3}$), $C_v$ is the volume (ppm) of gas, $M$ is the molecular weight of $CH_4$-C, $P_{atm}$ is atmospheric pressure, $G$ is the universal gas constant (0.0820575 L atm $K^{-1}$ $mol^{-1}$), and $T$ is the air temperature (K) of the static chamber. The accumulation rate of $CH_4$ was determined using the linear regression slope fitted to the time points collected for each static chamber (Morin et al. 2017). Flux was calculated using the equation from Holland et al. (1999).

$$F = \frac{v \times C_{rate}}{a}$$

where $F$ is the flux rate (mg $CH_4$-C $m^{-2}$ $h^{-1}$), $v$ is the volume of the static chamber ($m^3$), $C_{rate}$ is the accumulation rate in mg $CH_4$-C $m^{-3}$ $h^{-1}$, and $a$ is the area of soil surface ($m^2$).

## Plant traits

Five separate plots close to the $CH_4$ measurements were marked to measure plant density and biomass during each gas sampling time. The plant density and biomass of each plant species from each study site were estimated from randomly laid quadrates of 1 m × 1 m size. Plant density was calculated by counting individual plants in each quadrat and expressed as individual/$m^2$. Plant above ground biomass (AGB) and below-ground biomass (BGB) were estimated monthly (July to December) in five quadrates from 2009 to 2010. From each quadrat, the plants were uprooted, separated into above and belowground parts, washed, dried at 70°C until a constant weight, and weighed after oven drying to calculate plant biomass.

## Soil/sediment analysis

Rhizosphere soils/sediments (0–15 cm and 15–30 cm) in five replicates were also collected thrice monthly (July to December) during each gas sampling from the individual species stands and analyzed for soil physical, chemical, enzyme activities, and microbial biomass properties. Fresh field-moisture soil samples were divided into two parts. One part was dried and sieved for soil chemical analysis, while the other part was used for soil respiration, enzyme, and microbial properties. Before chemical analysis, the samples were ground using a mortar and pestle, sieved through a 2 mm mesh to remove coarse material, and then passed through another 0.5 mm mesh screen. A soil thermometer recorded the soil temperature (0–10 cm) in the field. Soil texture was determined, as suggested by Bouyoucos (1962). The soil core method determined bulk density (Blake and Hartge 1986). Keen's box method measured water holding capacity using copper cups of 5.6 cm inner diameter and 1.6 cm height. Soil moisture content (SMC) was determined gravimetrically by incubating 20 g of fresh soil in a hot air oven for 24 hours at 105°C. Soil pH was measured in a soil and water mixture of 1:2.5 w/v using an electrical pH meter (SYSTRONICS–335). Soil organic carbon (SOC) was determined by dichromate oxidation, followed by a rapid titration method (Walkley and Black 1934). Soil organic matter (SOM) content was obtained by multiplying the organic carbon content by 1.724, assuming that the SOM contains 58% carbon (Allen et al. 1974). Total nitrogen (TN) was determined following a semi-micro Kjeldahl procedure by tri–acid digestion (selenium as the catalyst), distillation, and titration (Anderson and Ingram 1993). Available phosphorus (P) was determined spectrophotometrically (SYSTRONICS–106) using the molybdenum blue method, as described by Anderson and Ingram (1993). The extractable sulfate ($SO_4^{-2}$) contents of soils were determined by the turbidimetric method (Verma et al. 1977).

Soil respiration was measured in fresh soil (after removing large litter particles) by the alkali absorption method (Anderson 1982). Dehydrogenase and $\beta$-glucosidase, and acid phosphatase activity were determined in fresh soil by following Tabatabai's (1994) and Tabatabai and Bremmer (1969) methods, respectively. Microbial biomass carbon (C), nitrogen (N), and phosphorous (P) were estimated in fresh field moist soil by the chloroform fumigation–incubation method (Brookes et al. 1985; Jenkinson and Powlson 1976; Vance et al. 1987). Only annual mean values (± SE) are presented for all soil properties.

## Statistical analysis

All the data were analyzed statistically using Microsoft Excel, STATISTICA 6.0, and ORIGIN 7.0. An analysis of variance (ANOVA) was used to compare the spatial and temporal variations in plant traits, soil properties, and $CH_4$ emission amongst plant species. A pair-wise comparison of means was carried out using Tukey's HSD test when the ANOVA showed significant differences ($p < 0.05$). Pearson's correlation matrix was performed to understand the relationship between plant species, plant traits, and soil properties. The significance level ($p$) in all the cases was held at 0.05.

# Results

## Plant traits

Plant density ranged from 49 ± 3 to 413 ± 16 individuals per $m^{-2}$ (ind. $m^{-2}$), 71 ± 7 to 401 ± 23 ind. $m^{-2}$, 55 ± 2 to 478 ± 15 ind. $m^{-2}$, 15 ± 2 to 254 ± 7 $m^{-2}$, and 11 ± 2 to 291 ± 10 in the *M. micrantha, P. karka, P. hydropiperoides, E. fluctuans* and *I. aquatica* vegetation stands, respectively, irrespective of month and year (Fig. 1). Plant density significantly ($F = 443.81$; $p < 0.05$) varied among different plant species (Table 1). In the present study, the plant density increased sharply (Fig. 1). Both AGB and BGB increased gradually from July to September and dropped markedly during November across different sampling years (Table 2).

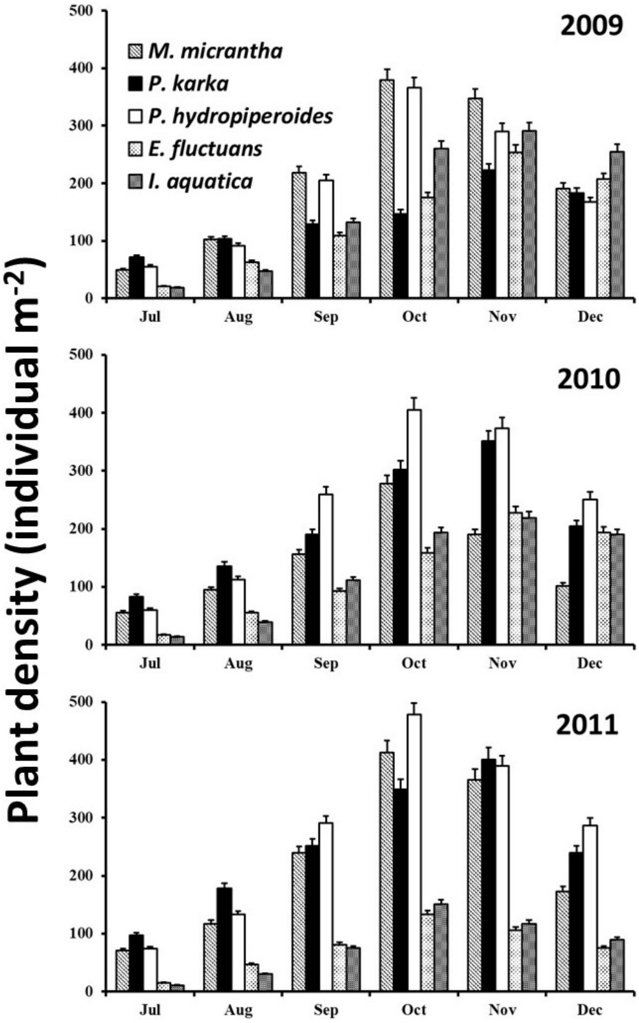

Fig. 1 Seasonal variations in density (individual $m^{-2}$) of different wetland plant communities.

The plant biomass (AGB and BGB) also significantly ($F = 3{,}671.02$; $p < 0.001$) varied between vegetation stands (Table 1). Among wetland plants, *P. karka* (AGB: 143.82 ± 20.14 to 1,193.87 ± 51.09 g $m^{-2}$ and BGB: 101.05 ± 11.04 to 1,007.65 ± 30.01 g $m^{-2}$) recorded higher above ground as well as belowground biomass, followed by *P. hydropiperoides* (AGB: 97.05 ± 6.28 to 1,023.94 ± 32.04 g $m^{-2}$ and BGB: 81.29 ± 9.54 to 959.33 ± 30.69 g $m^{-2}$) during the growing season (Table 2).

## Soil physical and chemical properties

SOC was highest in *P. karka* stands (5.85 ± 0.82%-topsoil and 2.02 ± 0.35%-subsoil layer). In addition, SOC showed a significant ($p < 0.05$) variation amongst different vegetation ($F = 18.90$) and soil depth ($F = 118.31$). Similarly, TN (3.46 ± 0.044%) and available P (7.78 ± 2.37 mg $g^{-1}$) were significantly ($p < 0.05$) greater in *P. karka* stands (Fig. 2). Three-way ANOVA showed that soil total N and available P significantly ($p < 0.05$) differed both spatially and temporally (Table 1). Further, soil properties were significantly different from the unvegetated bare soil sites (Table 3). Soil

**Table 1** Three-way factorial ANOVA of plant traits, soil properties, and $CH_4$ emission in shallow floodplain wetlands

| Factors | Source of variations/$F$-values | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Species (S) (df = 4) | Month (M) (df = 5) | Year (Y) (df = 2) | Depth (D) (df = 1) | S × M (df = 20) | S × Y (df = 8) | S × D (df = 4) | S × M × Y (df = 40) | S × D × Y (df = 8) |
| Plant traits | | | | | | | | | |
| Biomass | 3,671.02$^{***}$ | 976.24$^{**}$ | 1,940.32$^{**}$ | - | 2,033.19$^{***}$ | 1,509.83$^{**}$ | - | 745.96$^{**}$ | - |
| Density | 443.81$^{*}$ | 211.75$^{*}$ | 653.20$^{**}$ | - | 829.42$^{**}$ | 98.17$^{*}$ | - | 501.80$^{**}$ | - |
| Soil properties | | | | | | | | | |
| Bulk density | 0.26$^{ns}$ | 0.45$^{ns}$ | 0.11$^{ns}$ | 20.56$^{*}$ | 0.63$^{ns}$ | 0.30$^{ns}$ | 1.98$^{ns}$ | 0.51$^{ns}$ | 1.66$^{ns}$ |
| pH | 0.92$^{ns}$ | 1.01$^{ns}$ | 29.23$^{*}$ | 0.94$^{ns}$ | 0.09$^{ns}$ | 0.16$^{ns}$ | 0.17$^{ns}$ | 0.78$^{ns}$ | 0.90$^{ns}$ |
| Soil organic carbon | 18.90$^{*}$ | 219.07$^{*}$ | 1,067.98$^{**}$ | 118.31$^{*}$ | 59.94$^{*}$ | 38.55$^{*}$ | 47.19$^{*}$ | 84.26$^{*}$ | 72.01$^{*}$ |
| Total N | 399.51$^{*}$ | 1,285.93$^{**}$ | 924.04$^{**}$ | 505.66$^{**}$ | 85.29$^{*}$ | 40.01$^{*}$ | 156.40$^{*}$ | 18.70$^{*}$ | 91.03$^{*}$ |
| $NH_4^+$-N | 116.90$^{**}$ | 98.04$^{*}$ | 549.81$^{**}$ | 102.05$^{*}$ | 399.02$^{*}$ | 212.90$^{*}$ | 84.31$^{*}$ | 0.09$^{ns}$ | 55.94$^{*}$ |
| $NO_3^-$-N | 198.42$^{*}$ | 105.61$^{*}$ | 383.44$^{*}$ | 123.80$^{*}$ | 310.18$^{*}$ | 278.01$^{*}$ | 109.80$^{*}$ | 0.54$^{ns}$ | 151.11$^{*}$ |
| Available P | 10.87$^{*}$ | 46.59$^{*}$ | 91.04$^{*}$ | 28.17$^{*}$ | 59.11$^{*}$ | 17.07$^{*}$ | 0.21$^{ns}$ | 51.06$^{*}$ | 1.03$^{ns}$ |
| $SO_4^{2-}$ | 0.04$^{ns}$ | 1.11$^{ns}$ | 0.94$^{ns}$ | 0.87$^{ns}$ | 0.00$^{ns}$ | 0.18$^{ns}$ | 0.93$^{ns}$ | 0.00$^{ns}$ | 0.14$^{ns}$ |
| Soil respiration | 1,057.22$^{**}$ | 2,339.46$^{***}$ | 900.27$^{**}$ | 1,451.30$^{**}$ | 596.02$^{**}$ | 93.24$^{*}$ | 161.47$^{*}$ | 81.10$^{*}$ | 57.00$^{*}$ |
| Microbial biomass C | 3,968.35$^{***}$ | 1,691.83$^{**}$ | 2,499.04$^{***}$ | 940.19$^{**}$ | 334.50$^{*}$ | 265.96$^{*}$ | 147.15$^{*}$ | 175.04$^{*}$ | 138.91$^{*}$ |
| Microbial biomass N | 783.09$^{**}$ | 170.10$^{*}$ | 696.39$^{**}$ | 386.77$^{*}$ | 81.28$^{*}$ | 106.72$^{*}$ | 50.23$^{*}$ | 210.56$^{*}$ | 19.05$^{*}$ |
| Microbial biomass P | 412.56$^{*}$ | 287.15$^{*}$ | 149.81$^{*}$ | 301.04$^{*}$ | 199.51$^{*}$ | 53.10$^{*}$ | 76.98$^{*}$ | 40.08$^{*}$ | 27.11$^{*}$ |
| Dehydrogenase | 190.13$^{*}$ | 98.04$^{*}$ | 136.79$^{*}$ | 34.21$^{*}$ | 18.92$^{*}$ | 62.90$^{*}$ | 59.22$^{*}$ | 19.05$^{*}$ | 10.43$^{*}$ |
| Acid phosphatase | 78.00$^{*}$ | 11.01$^{*}$ | 56.91$^{*}$ | 119.39$^{*}$ | 40.02$^{*}$ | 21.17$^{*}$ | 90.79$^{*}$ | 12.56$^{*}$ | 25.07$^{*}$ |
| $\beta$-glucosidase | 978.09$^{**}$ | 467.20$^{*}$ | 2,905.44$^{***}$ | 590.05$^{**}$ | 192.51$^{*}$ | 430.86$^{*}$ | 82.01$^{*}$ | 263.03$^{*}$ | 91.44$^{*}$ |
| Methane emission | S | M | Y | S × M | S × Y | S × M × Y | | | |
| Vegetated vs. Un-vegetated | 118.01$^{*}$ | 81.62$^{**}$ | 44.21$^{*}$ | 98.56$^{*}$ | 120.94$^{*}$ | 30.97$^{*}$ | | | |

ANOVA: analysis of variance; $CH_4$: methane; C: carbon; N: nitrogen; P: phosphorous; ns: not significant.
$^{*}$, $^{**}$, $^{***}$Values are significant at $p < 0.05$, 0.01, 0.001 respectively.

extractable sulfate ($SO_4^{2-}$) content was relatively low ($p > 0.05$) in all vegetation stands (Table 1 and Fig. 2).

## Soil microbial and biochemical properties

In the present study, higher microbial biomass C, N, and P contents ($F = 3{,}968.35$, $p < 0.001$; $F = 783.09$, $p < 0.01$; $F = 412.56$, $p < 0.05$, respectively) were recorded for *E. fluctuans* and *I. aquatica* stands (Tables 1, 4). Soil respiration was highest ($p < 0.01$) in *P. karka* (276.78 ± 51.93 $\mu g\ g^{-1}\ day^{-1}$) followed by *M. micrantha* (220.11 ± 46.02 $\mu g\ g^{-1}\ day^{-1}$). Soil respiration rate (167.15 ± 24.90 $\mu g\ g^{-1}\ day^{-1}$) was highest ($p < 0.01$) in *I. aquatica* (Fig. 3).

## $CH_4$ flux

$CH_4$ emission increased gradually from July through October and decreased in November and December; this trend corresponded with the onset and offset of plant density and biomass development, respectively (Fig. 4A-E). In our study, the highest $CH_4$ emission was recorded from *P. Karka* (27.01 ± 6.02 $mg\ m^{-2}\ hr^{-1}$) during October 2011 and the lowest during July 2009 from *P. hydropiperoides* (1.73 ± 0.12 $mg\ m^{-2}\ hr^{-1}$) (Fig. 4A-C). $CH_4$ fluxes were significantly ($F = 44.21$; $p < 0.05$) increased from 2009 to 2011 (Table 1) by 30%, 27%, and 46% for *M. micrantha, P. karka,* and *P. hydropiperoides,* respectively (Fig. 4A-C). Overall, the average cumulative $CH_4$ emission from all the vegetation stands was 10.30 ± 1.95 $mg\ m^{-2}\ h^{-1}$ which was significantly ($F = 512.19$; $p < 0.05$) higher (118%) compared to $CH_4$ emission from bordering bare soil without any vegetation cover (4.70 ± 0.81 $mg\ m^{-2}\ h^{-1}$) (Fig. 4F). Overall, the $CH_4$ emission increased by 23% from 2009 to 2011 from vegetated wetlands (Fig. 4).

## The relationship between $CH_4$ emission, plant traits, and soil

The correlation coefficients ($r$) of $CH_4$ emission with plant traits such as plant density ($r = 0.848$) and plant biomass ($r = 0.923$) showed a stronger significant ($p < 0.001$) positive relationship (Fig. 5). In our study, $CH_4$ emission through plants was significantly affected by several physicochemical and biological properties of the soil (Table 5). Amongst soil properties, organic C ($r = 0.889$; $p < 0.001$), total N ($r = 0.673$; $p < 0.01$) and $\beta$-glucosidase activity ($r = 0.873$; $p < 0.001$) showed a significant positive ($p < 0.05$) correlation with $CH_4$ emission. SMC was also found to influence $CH_4$ emissions significantly ($r = 0.796$; $p < 0.001$). We did also find significant positive correlations of $CH_4$ with soil temperature ($r = 0.709$; $p < 0.001$) and a weak correlation with soil respiration ($r = 0.281$; $p < 0.001$) (Table 5).

# Discussion

## Effects of plant species and traits

Previous studies reported that wetland plants increased the $CH_4$ emission from wetland ecosystems (Cheng et al.

**Table 2** Above ground and below ground biomass (g $m^{-2}$) of different wetland plants

| Year/ Month | *Mikania micrantha* | | *Phragmites karka* | | *Polygonum hydropiperoides* | | *Enhydra fluctuans* | | *Ipomoea aquatica* | |
|---|---|---|---|---|---|---|---|---|---|---|
| | AGB | BGB | AGB | BGB | AGB | BGB | AGB | BGB | AGB | BGB |
| 2009 | | | | | | | | | | |
| July | 76.53 ± 12.31 | 31.87 ± 9.57 | 143.82 ± 20.14 | 101.05 ± 11.04 | 97.05 ± 6.28 | 81.29 ± 9.54 | 49.14 ± 5.32 | 27.56 ± 6.09 | 65.92 ± 7.44 | 41.77 ± 5.67 |
| Aug | 197.86 ± 24.90 | 85.61 ± 15.43 | 396.20 ± 17.66 | 273.58 ± 14.30 | 211.59 ± 19.02 | 180.04 ± 15.98 | 130.02 ± 9.47 | 78.17 ± 13.56 | 183.07 ± 10.06 | 130.82 ± 17.94 |
| Sep | 379.98 ± 30.05 | 254.04 ± 19.60 | 503.16 ± 25.09 | 467.33 ± 26.91 | 484.03 ± 23.85 | 400.56 ± 20.09 | 312.25 ± 18.60 | 235.80 ± 15.41 | 391.78 ± 15.30 | 264.09 ± 20.05 |
| Oct | 745.13 ± 30.98 | 590.26 ± 22.01 | 857.55 ± 36.13 | 755.17 ± 30.05 | 990.11 ± 36.73 | 872.15 ± 29.03 | 598.67 ± 26.98 | 451.19 ± 20.04 | 612.34 ± 21.17 | 516.41 ± 15.12 |
| Nov | 674.37 ± 28.03 | 382.09 ± 20.47 | 1,023.09 ± 70.98 | 910.63 ± 35.77 | 856.27 ± 14.64 | 785.92 ± 22.06 | 787.82 ± 31.03 | 691.94 ± 29.82 | 895.79 ± 36.03 | 720.17 ± 28.09 |
| Dec | 318.22 ± 17.22 | 201.56 ± 11.02 | 751.13 ± 29.61 | 427.81 ± 22.53 | 643.07 ± 24.90 | 498.37 ± 17.49 | 423.75 ± 13.68 | 321.02 ± 10.51 | 708.01 ± 24.19 | 596.91 ± 20.65 |
| 2010 | | | | | | | | | | |
| July | 90.26 ± 16.84 | 39.02 ± 6.40 | 156.87 ± 25.94 | 120.72 ± 10.46 | 114.07 ± 10.08 | 84.11 ± 9.32 | 45.92 ± 3.98 | 21.75 ± 5.14 | 58.02 ± 9.51 | 36.31 ± 8.75 |
| Aug | 183.51 ± 25.11 | 70.23 ± 10.36 | 364.03 ± 23.51 | 279.57 ± 18.25 | 226.51 ± 19.66 | 192.28 ± 14.20 | 117.90 ± 9.34 | 65.02 ± 7.23 | 164.75 ± 13.25 | 99.17 ± 11.09 |
| Sep | 390.11 ± 30.47 | 271.75 ± 16.90 | 515.20 ± 29.03 | 480.43 ± 25.88 | 500.61 ± 28.50 | 457.95 ± 19.55 | 294.17 ± 20.06 | 209.73 ± 15.09 | 337.41 ± 24.82 | 196.84 ± 18.33 |
| Oct | 781.09 ± 48.64 | 610.23 ± 19.03 | 911.09 ± 41.85 | 780.21 ± 29.02 | 1,023.94 ± 32.04 | 959.33 ± 30.69 | 566.81 ± 27.11 | 438.05 ± 23.82 | 640.32 ± 20.05 | 489.55 ± 20.01 |
| Nov | 657.25 ± 20.60 | 406.51 ± 24.09 | 1,111.46 ± 68.11 | 932.85 ± 37.05 | 871.65 ± 30.78 | 800.41 ± 23.56 | 725.11 ± 23.35 | 590.05 ± 25.41 | 828.31 ± 25.04 | 693.67 ± 27.78 |
| Dec | 299.34 ± 15.07 | 180.78 ± 10.25 | 740.22 ± 30.06 | 440.95 ± 13.19 | 690.40 ± 17.81 | 523.97 ± 28.04 | 388.61 ± 15.76 | 279.20 ± 20.03 | 589.37 ± 19.56 | 306.44 ± 14.91 |
| 2011 | | | | | | | | | | |
| July | 120.75 ± 10.87 | 63.19 ± 8.95 | 200.63 ± 9.54 | 154.01 ± 13.60 | 139.46 ± 12.15 | 102.19 ± 12.94 | 40.07 ± 5.03 | 17.84 ± 2.65 | 49.03 ± 5.25 | 27.54 ± 4.07 |
| Aug | 209.81 ± 19.03 | 137.95 ± 12.31 | 402.10 ± 23.02 | 328.97 ± 15.93 | 284.31 ± 20.07 | 215.06 ± 17.31 | 90.43 ± 14.69 | 39.91 ± 8.37 | 108.56 ± 10.59 | 58.81 ± 5.02 |
| Sep | 467.20 ± 31.56 | 315.78 ± 15.73 | 597.85 ± 17.37 | 511.42 ± 25.05 | 638.17 ± 29.34 | 580.59 ± 26.88 | 156.90 ± 20.70 | 84.03 ± 19.02 | 190.33 ± 18.21 | 113.01 ± 16.50 |
| Oct | 854.48 ± 27.19 | 729.15 ± 21.66 | 1,056.02 ± 44.91 | 937.88 ± 33.98 | 961.51 ± 30.49 | 894.25 ± 25.05 | 280.14 ± 25.54 | 195.76 ± 15.90 | 317.50 ± 26.04 | 169.09 ± 21.39 |
| Nov | 692.11 ± 30.82 | 513.86 ± 10.93 | 1,193.87 ± 51.09 | 1,007.65 ± 30.01 | 926.24 ± 31.02 | 873.07 ± 25.13 | 257.91 ± 16.06 | 164.39 ± 19.46 | 283.11 ± 15.62 | 120.95 ± 9.85 |
| Dec | 318.04 ± 24.90 | 205.37 ± 13.29 | 890.12 ± 27.01 | 783.09 ± 20.64 | 727.94 ± 23.37 | 689.59 ± 19.02 | 162.27 ± 19.44 | 77.56 ± 9.07 | 195.07 ± 20.75 | 86.32 ± 10.24 |

Values are presented as mean ± SE, *n* = 5.
AGB: above ground biomass; BGB: below ground biomass.

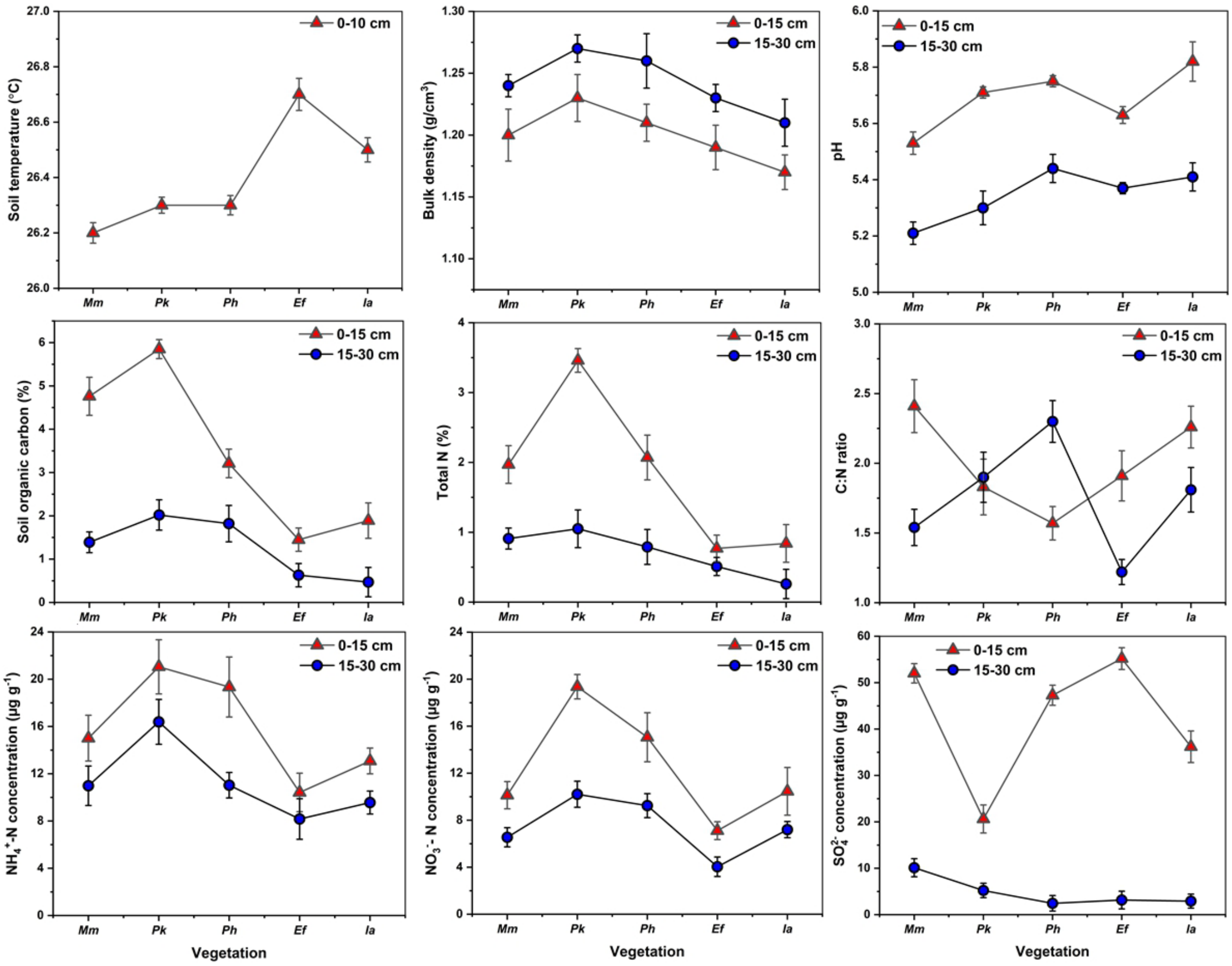

Fig. 2 Seasonal variations in soil physical and chemical properties under vegetated soil. C/N ratio: carbon/nitrogen ratio; $NH_4$-N: ammonical nitrogen; $NO_3$-N: nitrate nitrogen; $SO_4^+$: sulfate; *Mm*: *Mikania micrantha*; *Pk*: *Phragmites karka*; *Ph*: *Polygonum hydropiperoides*; *Ef*: *Enhydra fluctuans*; *Ia*: *Ipomoea aquatica*.

2007; Kao-Kniffin et al. 2010; Tong et al. 2012). In the wetland ecosystem, the transport of $CH_4$ through vascular plants is the critical transport system for $CH_4$ from soil to the atmosphere (Hendriks et al. 2010; Kao-Kniffin et al. 2010). In the present study, *M. micrantha*, *P. karka*, and *P. hydropiperoides* over the natural native wetland vegetation increased 15.81%, 44.20%, and 37.34% $CH_4$ emissions, respectively.

Among wetland plants, *M. micrantha*, *P. karka* and *P. hydropiperoides* had higher standing biomass than *E. fluctuans* and *I. aquatica* (Table 2), which could be attributed to the rapid colonization, higher plant density, and higher production rates (Table 2 and Fig. 1). Further, earlier studies have shown that enhanced $CH_4$ emissions from vegetated wetland are mainly attributed to plant-mediated transport (Belger et al. 2011; Hendriks et al. 2010; Rusch and Rennenberg 1998; Ström et al. 2005). In the present study, plant traits such as plant density and biomass (AGB and BGB) were found to have a strong significant ($p < 0.05$) influence on $CH_4$ emission. Cheng et al. (2007) observed similar relationships for *S. alterniflora* and *P. australis*. Further, higher $CH_4$ from vegetated wetlands could be attributed to variations amongst plant populations, overall productivity, and carbon allocation dynamics. Overall, $CH_4$ emissions were found to be well within the ranges of earlier reported values worldwide (Table S1). Further, Table S1 shows that earlier reported $CH_4$ emissions ranged from 0.21 to 21.82 mg $m^{-2}$ $h^{-1}$. In the present study, $CH_4$ emissions ranged from 1.19 to 27.01 mg $m^{-2}$ $h^{-1}$. For comparative purposes, we considered only the $CH_4$ emissions from natural wetlands colonized by plant species elsewhere.

## Effects of soil properties

$CH_4$ emissions from soils within a field may vary hugely with the spatial inconsistency in soil properties. In the present study, soil temperature was significantly correlated with $CH_4$ emission ($r = 0.709$; $p < 0.05$). Previous studies have also shown the significant effect of soil properties on $CH_4$ emissions (Itoh et al. 2009; Tamai et al. 2003). However, our study sites experience similar spatial settings, and

**Table 3** Soil physical and chemical properties of unvegetated bare soil

| Vegetation | Soil temperature (°C) | Soil depth (cm) | Soil physico-chemical properties | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | BD | pH | SOC (%) | Total N (%) | C/N | $NH_4^+$-N (μg $g^{-1}$) | $NO_3^-$-N (μg $g^{-1}$) | AP (mg $g^{-1}$) | $SO_4^{2-}$ (μg $g^{-1}$) |
| Unvegetated Bare Soil | 27.4 ± 0.15 | 0–15 | 1.16 ± 0.043 | 5.66 ± 0.03 | 2.02 ± 0.11 | 0.90 ± 0.003 | 2.24 ± 0.05 | 9.03 ± 0.85 | 6.13 ± 0.08 | 1.17 ± 0.05 | 21.36 ± 1.15 |
| | | 15–30 | 1.30 ± 0.041 | 5.72 ± 0.01 | 0.52 ± 0.09 | 0.21 ± 0.001 | 2.48 ± 0.01 | 5.31 ± 0.15 | 2.07 ± 0.03 | 0.29 ± 0.01 | 8.55 ± 1.02 |

Values are the average of all six measured months (July to December).
Values are presented as mean ± SE, *n* = 6.
BD: bulk density; SOC: soil organic carbon; Total N: total Kjeldahl nitrogen; C/N: carbon/nitrogen ratio; $NH_4$-N: ammonical nitrogen; $NO_3$-N: nitrate nitrogen; AP: available phosphorus; $SO_4^{2-}$: sulfate.

**Table 4** Soil/sediment microbial biomass and activities under different wetland plant communities

| Vegetation | Soil depth (cm) | Microbial biomass (C, N, P) | | | Soil microbial activities | | |
|---|---|---|---|---|---|---|---|
| | | MBC | MBN | MBP | Dehydrogenase (μg TPF $g^{-1}$ $h^{-1}$) | Acid phosphatase | β-glucosidase |
| | | ------------------- (μg $g^{-1}$) ----------------- | | | | ---------- (μg PNP $g^{-1}$ $h^{-1}$) --------- | |
| *Mikania micrantha* | 0–15 | 719.37 ± 109.47 | 53.09 ± 10.23 | 27.13 ± 7.68 | 21.85 ± 9.47 | 510.42 ± 167.88 | 264.08 ± 61.53 |
| | 15–30 | 435.81 ± 67.45 | 37.17 ± 6.90 | 15.48 ± 3.16 | 12.03 ± 5.06 | 394.75 ± 116.71 | 143.76 ± 35.27 |
| *Phragmites karka* | 0–15 | 905.16 ± 151.19 | 69.36 ± 7.02 | 33.02 ± 6.07 | 23.78 ± 9.82 | 562.13 ± 185.04 | 331.02 ± 129.11 |
| | 15–30 | 452.49 ± 113.04 | 40.72 ± 6.55 | 21.09 ± 2.91 | 15.12 ± 7.21 | 407.29 ± 144.38 | 167.51 ± 43.92 |
| *Polygonum hydropiperoides* | 0–15 | 780.71 ± 149.59 | 56.98 ± 7.43 | 30.71 ± 5.80 | 19.04 ± 6.91 | 489.58 ± 140.09 | 289.57 ± 73.14 |
| | 15–30 | 393.10 ± 98.04 | 31.04 ± 5.91 | 18.55 ± 4.82 | 7.81 ± 3.87 | 310.05 ± 107.24 | 149.05 ± 56.02 |
| *Enhydra fluctuans* | 0–15 | 953.85 ± 145.11 | 82.21 ± 9.29 | 37.06 ± 5.66 | 10.22 ± 3.53 | 203.97 ± 98.95 | 176.73 ± 61.34 |
| | 15–30 | 577.32 ± 80.92 | 45.13 ± 6.22 | 29.11 ± 7.81 | 4.09 ± 2.08 | 166.14 ± 39.28 | 89.22 ± 26.19 |
| *Ipomoea aquatica* | 0–15 | 1,076.51 ± 201.09 | 94.07 ± 15.02 | 45.19 ± 5.32 | 12.53 ± 5.02 | 368.01 ± 102.51 | 211.39 ± 75.27 |
| | 15–30 | 694.03 ± 120.44 | 50.81 ± 8.58 | 32.56 ± 4.90 | 4.76 ± 2.44 | 197.94 ± 60.05 | 105.17 ± 43.92 |
| Unvegetated bare soil | 0–15 | 251.22 ± 15.08 | 19.84 ± 1.25 | 25.11 ± 5.02 | 5.02 ± 1.01 | 166.18 ± 17.23 | 90.65 ± 9.02 |
| | 15–30 | 117.05 ± 5.19 | 6.42 ± 1.21 | 10.86 ± 5.31 | 1.17 ± 0.94 | 109.75 ± 11.82 | 28.09 ± 5.88 |

Values are the mean of all six measured months (July to December).
Values are presented as mean ± SE, *n* = 5.
C: carbon; N: nitrogen; P: phosphorous; MBC: microbial biomass carbon; MBN: microbial biomass nitrogen; MBP: microbial biomass phosphorus.

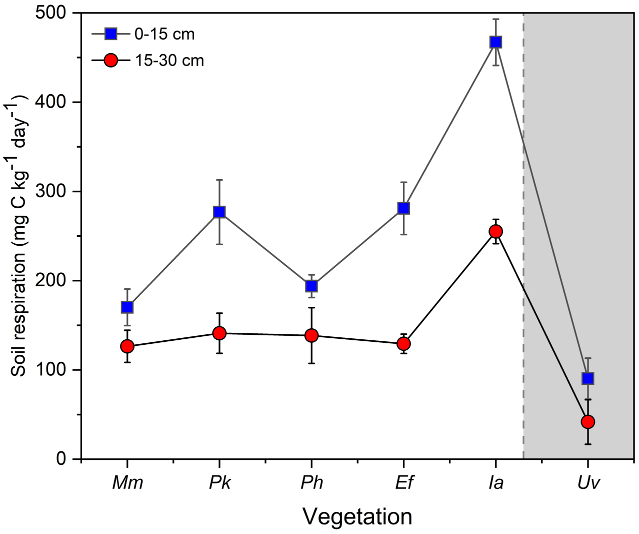

**Fig. 3** Variations in soil respiration (mg C kg$^{-1}$ day$^{-1}$) from vegetation stands and unvegetated (*Uv*) bare soil. *Mm*: *Mikania micrantha; Pk*: *Phragmites karka; Ph*: *Polygonum hydropiperoides; Ef*: *Enhydra fluctuans; Ia*: *Ipomoea aquatica.*

the results are inconsistent with those of the other authors (Altor and Mitsch 2008; Waletzko and Mitsch 2014), who suggested that soil temperature and moisture contents significantly affect $CH_4$ emissions. Czepiel et al. (1995) reported that moisture contents in soil have a significant role in influencing $CH_4$ emission and uptake in temperate soils. Correspondingly, in the present study, SMC showed a significant ($r = 0.796$; $p < 0.001$) positive correlation with $CH_4$ flux (Table 5). The present study shows that inconspicuous non-native species can influence community composition and trophic consequences on soil nutrient status and resource availability to soil biota. The increased $CH_4$ emission could be due to the higher organic C produced by the rhizodeposition of plant litters in the rhizosphere, which builds an oxidized anoxic zone by transporting oxygen to facilitate the activities of methanogenic bacteria. In our present study, *M. micrantha*, *P. karka* and *P. hydropiperoides* accumulated higher fresh litter biomass compared to *E. fluctuans* and *I. aquatica*, which may have led to anoxic soil conditions, which might have enthused $CH_4$ production and emission.

SOC showed a significant positive correlation with $CH_4$ emissions (Table 5). Chanton et al. (2008) reported that soil organic C serves as the electron donor to accelerate microbial metabolic activities such as respiration, methanogenesis, etc. $CH_4$ emission established a highly significant ($r = 0.889$; $p < 0.05$) positive correlation with the SOC (Table 5). The present study found that the soil sulfate content is relatively low in all wetland sites. Hence, there was no significant ($p > 0.05$) relationship between soil sulfate contents and $CH_4$ emissions. $CH_4$ cycling has a strong microbial component (Whalen 2005). The products of dehydrogenase and $\beta$-glucosidase activities represent an important substrate for microbial metabolism (Tabatabai 1982). Hence, higher rates of dehydrogenase and $\beta$-glucosidase activities may have led to accelerated degradation of the substrate products and thereby increase $CH_4$ emission rates. $CH_4$-dependent increase or decrease in dehydrogenase activity was earlier reported by Brzezińska et al. (2004). Evidently, in the present study, microbial nutrients C ($r = 0.775$; $p < 0.001$) and N ($r = 0.614$; $p < 0.01$), dehydrogenase ($r = -0.744$; $p < 0.001$) and $\beta$-glucosidase ($r = 0.873$; $p < 0.001$) activities were significantly correlated with $CH_4$ emission rates (Table 5).

## Plant mediated $CH_4$ emission

Plant removal may be linked to decreased $CH_4$ production and lower $CH_4$ emissions (Ge et al. 2023; Turner et al. 2020). We found that the $CH_4$ emission increased under vegetated wetlands (Fig. 4A-E) compared to unvegetated bare soil (Fig. 4F). Sheng et al. (2014) found that $CH_4$ emissions declined (~84.2%) significantly after removing *Spartina alterniflora* in a Yangtze River estuarine wetland. Previous studies, for example, Cronin et al. (2006) and Xu et al. (2019), revealed a 127 % increase in $CH_4$ emission from vegetated sites compared to the non-vegetated site in the littoral zone of a Colorado reservoir. Further, Zeleke et al. (2013) showed a 97% increase in $CH_4$ emission following the *S. alterniflora* invasion in the salt marsh of Dongtan, China. When plants were cut, there was a 97% reduction in $CH_4$ emission from *Scheuchzeria palustris* (Frenzel and Karofeld 2000), while *P. australis* gave a 62% reduction in emission (Grünfeld and Brix 1999). Duan et al. (2006) showed that $CH_4$ emissions declined by 14.43% to 17.65% when *P. australis* stems were clipped below the water surface.

Similarly, Mozdzer and Megonigal (2013) suggested that the growth of *P. australis* increased $CH_4$ emissions from North American wetlands. In the present study, the average $CH_4$ emission from unvegetated (Fig. 4F) bare soil was lower (118.08%) than the $CH_4$ emission from the vegetated wetlands (Fig. 4A-E). In unvegetated soil, the highest $CH_4$ emissions occurred in late summer, which coincides with the warmest temperatures and driest soil/sediments (Fig. 4F). Thus, wetland plant species may play significant roles in $CH_4$ production and transport and can be imperative suppliers of readily available substrates for the methanogenic archaea in wetland ecosystems (Bhullar et al. 2013; Joabsson et al. 1999; Ström et al. 2005).

Compared with the high-altitude temperate wetlands, $CH_4$ emissions from sub-tropical wetlands (present study) had higher $CH_4$ emissions (Table S1). Whiting and Chanton (1992) estimated that 90% of $CH_4$ emissions were plant-mediated in arctic fen wetlands. Similarly, Schimel (1995) measured $CH_4$ emission in wetlands of subarctic tundra and demonstrated that measured $CH_4$ flux rates from *Eriophorum* sp. and *Carex* sp. were 64% higher than

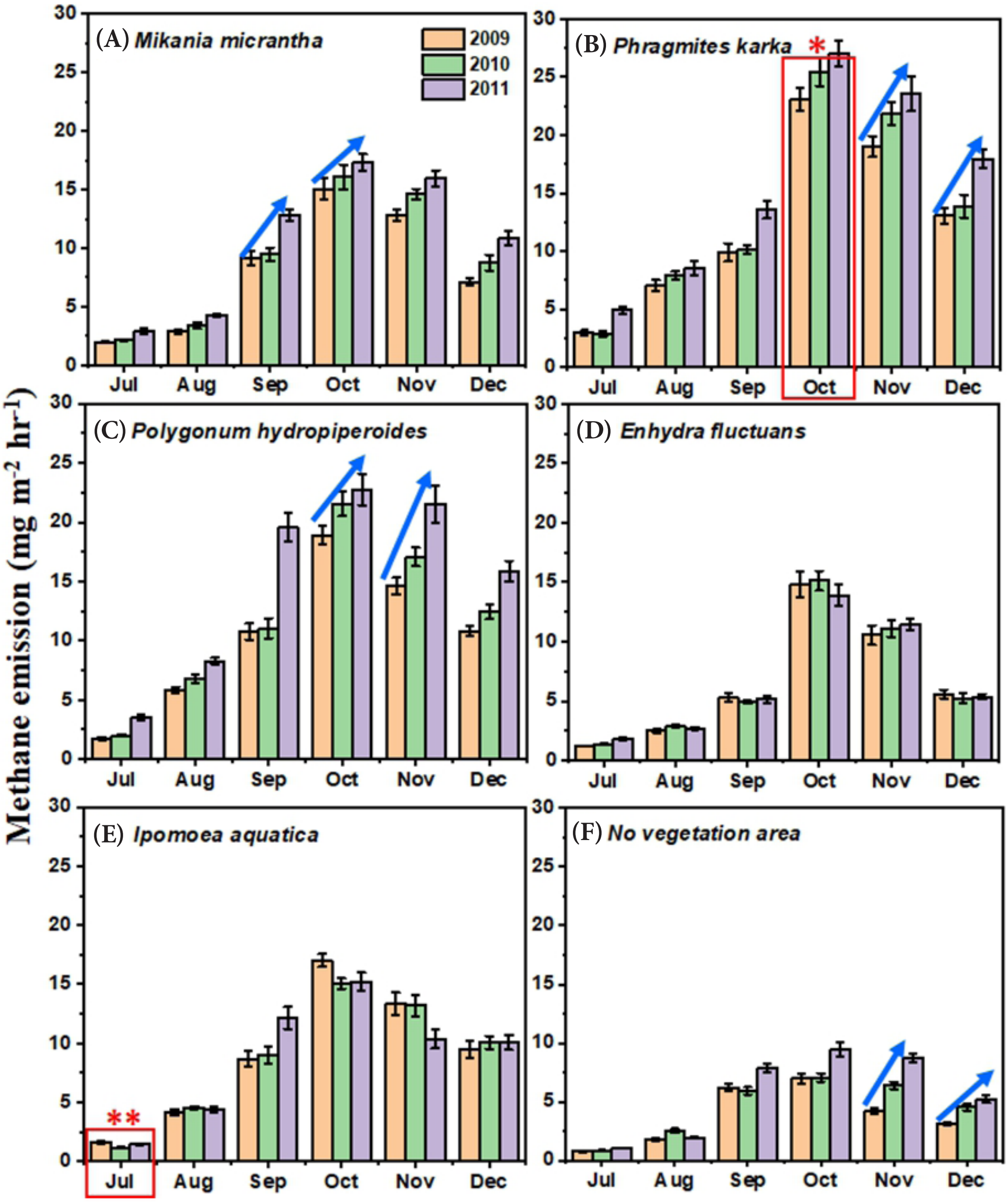

**Fig. 4** Seasonal variations in methane ($CH_4$) emission (mg $m^{-2}$ $hr^{-1}$) from vegetation stands (A-E) and without vegetation (F). *indicates the highest methene emission (*Phragmites karka*); **indicates the lowest methene emission (*Ipomoea aquatica*). The arrow (blue) symbols indicate the significant increase in the mean annual $CH_4$ emission.

the $CH_4$ emission estimated in bordering bare soils (unvegetated soils). In another study in subarctic tundra wetlands, Bartlett et al. (1992) showed that the average $CH_4$ flux from vegetated plots exceeded that without the plant cover. Removal of *Eriophorum* Sp. and *Carex* Sp. from a Swedish boreal peatland declined the annual cumulative $CH_4$ emission by 55 to 85% (Waddington et al. 1996).

Unlike prior research that primarily focuses on the bulk soil emissions and general plant contributions, the present study provides a trait-based analysis of $CH_4$ emissions across diverse plant species. Our results revealed that plant species with higher plant biomass and density contribute disproportionately to $CH_4$ emissions in this region. This suggests that plant trait diversity must be integrated into $CH_4$ emission models for tropical wetlands. Our findings confirm that plant species significantly influence $CH_4$ emissions in wetlands, consistent with global patterns observed in similar ecosystems (Xiao et al. 2024). The variation among *M. micrantha*, *P. karka*, *P. hydropiperoides*, *E. fluctuans*, and *I. aquatica* can be mechanistically linked to trait differences in biomass, aerenchyma development, and phenology.

Species possessing larger biomass and extensive root systems, such as *P. karka* and *M. micrantha*, exhibited higher $CH_4$ emissions. Larger biomass often correlates with increased root exudation and substrate availability, stimulat-

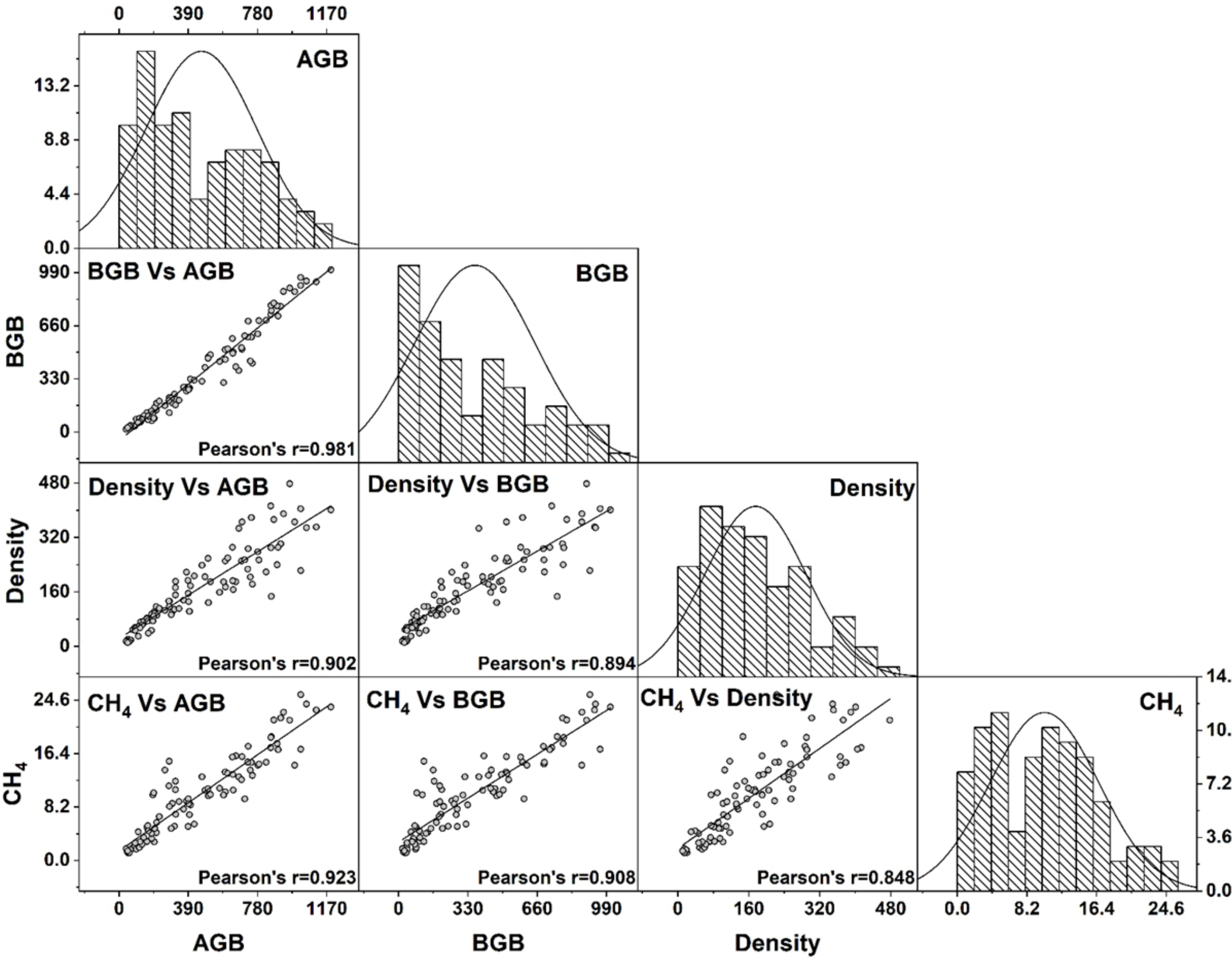

Fig. 5 Correlation between plant traits (density and biomass) and methane ($CH_4$) emission. AGB: above ground biomass; BGB: below ground biomass.

ing methanogenesis (Bijak et al. 2024). Similarly, studies in seagrass meadows showed that traits related to plant size (leaf/root area and volume) positively influence $CH_4$ fluxes (Bijak et al. 2024), and emergent wetlands demonstrated biomass-driven transport dynamics (Villa et al. 2020). Plant-mediated $CH_4$ transport efficiency was particularly high in species with welldeveloped aerenchyma, consistent with findings in boreal peatlands where species like *Carex rostrata* showcased phenology-linked fluxes (Ge et al. 2023). Zhao et al. (2023) found inundation depth amplified plant-mediated $CH_4$ emissions by enhancing aerenchyma pathways in reeds, reinforcing our observations.

As seen in boreal systems (Ge et al. 2023), the peak $CH_4$ flux aligns with active growth stages. This aligns with our seasonal emission patterns across July–December. Globally, wetlands contribute over 150 Tg $CH_4$ annually, with tropical and temperate regions dominating emissions (Xiao et al. 2024). Wetland restoration often alters these fluxes; meta-analysis indicates that restored wetlands with increased biomass and elevated water tables can enhance $CH_4$ output (Hu et al. 2023). Conversely, introducing species like *Cyperus alternifolius* has been shown to reduce emissions (Yu et al. 2023). Identifying species-specific trait effects offers targeted strategies for wetland management. Promoting species with lower transport efficiency or greater root oxidation potential could dampen emissions—parallel to findings that plants like *Cyperus papyrus* support oxygen-rich rhizospheres and suppress $CH_4$ (Yu et al. 2023). Additionally, planting strategies should consider phenological timing and biomass allocation to optimize outcomes.

A lower $CH_4$ emission rate from unvegetated sites implies the effectiveness of wetland plants as $CH_4$ conduits from soil to the atmosphere. Similarly, eradication of arctic sedge communities resulted in a 60% to 89% decrease in $CH_4$ flux (King et al. 1998). Overall, the quality and quantity of input substrates (soil nutrients), soil moisture, and temperature may be the natural driving forces behind the efficiency of plant-mediated $CH_4$ flux dynamics in the Himalayan wetland ecosystems.

The strong correlation between $CH_4$ emissions and specific plant traits (Fig. 5), as well as soil physico-chemical and biological properties (Table 5), underscores the importance of plant-soil-microbe interactions in regulating GHG fluxes. For instance, plant species with extensive root sys-

**Table 5** Pearson's correlation coefficients amongst soil physico-chemical, biological and methane emission

| Parameters | pH | ST | SMC | SOC | TKN | C/N | NH$_4$-N | NO$_3$-N | AP | SO$_4^+$ | SR | DHE | APE | $\beta$-GLUE | MBC | MBN | MBP |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ST | $0.284^{*}$ | 0 | | | | | | | | | | | | | | | |
| SMC | $0.327^{*}$ | $-0.863^{***}$ | 0 | | | | | | | | | | | | | | |
| SOC | $-0.493^{**}$ | $0.590^{**}$ | $0.337^{*}$ | 0 | | | | | | | | | | | | | |
| TKN | $0.745^{***}$ | $0.488^{**}$ | $0.709^{***}$ | $-0.456^{**}$ | 0 | | | | | | | | | | | | |
| C/N | $0.192^{ns}$ | $0.534^{**}$ | $0.866^{***}$ | $0.791^{***}$ | $0.575^{**}$ | 0 | | | | | | | | | | | |
| NH$_4$-N | $-0.234^{ns}$ | $0.781^{***}$ | $0.265^{ns}$ | $-0.599^{**}$ | $0.841^{***}$ | $0.156^{ns}$ | 0 | | | | | | | | | | |
| NO$_3$-N | $0.569^{**}$ | $-0.210^{ns}$ | $-0.381^{*}$ | $0.257^{ns}$ | $0.603^{***}$ | $0.801^{***}$ | $0.712^{***}$ | 0 | | | | | | | | | |
| AP | $-0.231^{ns}$ | $0.655^{**}$ | $0.732^{***}$ | $0.790^{***}$ | $0.679^{***}$ | $0.544^{**}$ | $0.296^{*}$ | $0.345^{*}$ | 0 | | | | | | | | |
| SO$_4^+$ | $-0.847^{***}$ | $0.703^{**}$ | $0.198^{ns}$ | $-0.167^{ns}$ | $0.272^{*}$ | $0.332^{*}$ | $-0.720^{***}$ | $-0.621^{**}$ | $-0.193^{ns}$ | 0 | | | | | | | |
| SR | $0.209^{ns}$ | $0.978^{***}$ | $0.831^{***}$ | $0.867^{***}$ | $0.303^{*}$ | $0.675^{**}$ | $0.784^{***}$ | $0.687^{**}$ | $0.572^{**}$ | $-0.844^{***}$ | 0 | | | | | | |
| DHE | $0.755^{***}$ | $0.432^{*}$ | $0.697^{**}$ | $0.744^{***}$ | $0.197^{ns}$ | $0.200^{ns}$ | $0.809^{***}$ | $0.640^{**}$ | $0.655^{**}$ | $0.401^{**}$ | $0.706^{***}$ | 0 | | | | | |
| APE | $-0.679^{**}$ | $0.512^{**}$ | $-0.689^{**}$ | $-0.701^{***}$ | $0.251^{ns}$ | $0.139^{ns}$ | $0.236^{ns}$ | $0.409^{**}$ | $0.893^{***}$ | $0.139^{ns}$ | $-0.751^{***}$ | $0.478^{*}$ | 0 | | | | |
| $\beta$-GLUE | $-0.801^{***}$ | $0.768^{***}$ | $0.711^{***}$ | $0.456^{**}$ | $0.523^{**}$ | $0.097^{ns}$ | $-0.150^{ns}$ | $-0.561^{**}$ | $-0.451^{*}$ | $0.353^{*}$ | $0.861^{***}$ | $0.632^{**}$ | $0.576^{**}$ | 0 | | | |
| MBC | $0.345^{*}$ | $0.593^{**}$ | $0.578^{**}$ | $0.905^{***}$ | $-0.206^{ns}$ | $0.627^{**}$ | $0.714^{***}$ | $0.236^{ns}$ | $0.194^{ns}$ | $0.478^{*}$ | $0.520^{**}$ | $-0.610^{**}$ | $0.290^{*}$ | $0.806^{***}$ | 0 | | |
| MBN | $-0.256^{ns}$ | $0.604^{**}$ | $0.304^{*}$ | $0.478^{**}$ | $0.591^{**}$ | $0.771^{***}$ | $0.647^{**}$ | $0.303^{*}$ | $0.263^{ns}$ | $0.654^{**}$ | $0.391^{*}$ | $0.565^{**}$ | $-0.368^{*}$ | $0.354^{*}$ | $-0.493^{*}$ | 0 | |
| MBP | $0.281^{*}$ | $0.722^{***}$ | $0.658^{**}$ | $0.532^{**}$ | $0.347^{*}$ | $0.278^{*}$ | $0.805^{***}$ | $0.297^{*}$ | $0.594^{**}$ | $0.621^{**}$ | $0.626^{**}$ | $0.296^{*}$ | $-0.165^{ns}$ | $0.711^{***}$ | $0.570^{**}$ | $0.773^{***}$ | 0 |
| CH$_4$ | $0.440^{**}$ | $0.709^{***}$ | $0.796^{***}$ | $0.889^{**}$ | $0.673^{**}$ | $0.756^{***}$ | $0.460^{**}$ | $0.515^{**}$ | $0.521^{**}$ | $-0.085^{ns}$ | $0.281^{*}$ | $-0.744^{***}$ | $0.340^{*}$ | $0.873^{***}$ | $0.775^{***}$ | $0.614^{**}$ | $0.432^{**}$ |

| Parameters | CH$_4$ | PB | PD |
|---|---|---|---|
| PB | $0.923^{***}$ | 0.00 | |
| PD | $0.848^{***}$ | $0.902^{***}$ | 0.00 |

| Power analysis | Lower 'r' | Total sample size | Actual power |
|---|---|---|---|
| | 0.270 | 150 | 0.9507317 |

$n = 150$.

ST: soil temperature; SMC: soil moisture content; SOC: soil organic carbon; TKN: total Kjeldahl nitrogen; C/N: carbon/nitrogen ratio; NH$_4$-N: ammonical nitrogen; NO$_3$-N: nitrate nitrogen; AP: available phosphorus; SO$_4^+$: sulfate; SR: soil respiration; DHE: dehydrogenase; APE: acid phosphatase; $\beta$-GLUE: $\beta$-glucosidase; MBC: microbial biomass carbon; MBN: microbial biomass nitrogen; MBP: microbial biomass phosphorus; CH$_4$: methane; PB: plant biomass; PD: plant density; ns: not significant.

$^{*}$, $^{**}$, $^{***}$Values are significant at $p < 0.05$, 0.01, 0.001 respectively.

tems and higher biomass may enhance $CH_4$ emissions by providing substrates for methanogenesis and facilitating gas transport through aerenchyma tissues (Ge et al. 2023; Korrensalo et al. 2022). Our study also found that vegetated areas had significantly higher cumulative $CH_4$ emissions compared to unvegetated bare soils (Fig. 4). This observation is consistent with global studies that highlight the role of vegetation in modulating $CH_4$ emissions from wetlands (Ge et al. 2023; Yang et al. 2022). The IPCC (2023) emphasizes the critical role of wetlands in the global $CH_4$ budget and the need to understand the factors influencing these emissions to develop effective mitigation strategies. Our findings contribute to this understanding by elucidating how specific plant species and their traits can modulate $CH_4$ emissions in wetland ecosystems. Thus, our research highlights the significant impact of plant species on $CH_4$ emissions in wetlands. These insights are vital for informing conservation and management practices aimed at mitigating GHG emissions from wetland ecosystems.

Few limitations of this study are its focus solely on the growing season (July–December), which does not capture $CH_4$ emissions during the non-growing season. Although the growing season is typically when plant and soil activity have the greatest influence on $CH_4$ flux, the exclusion of the non-growing season means that the full annual variation in $CH_4$ emissions was not assessed. However, we acknowledge that excluding the non-growing season limits our ability to capture annual $CH_4$ flux variability. In future research, we aim to conduct year-round measurements to assess seasonal dynamics more comprehensively, particularly during the dormant periods when abiotic factors may dominate $CH_4$ regulation. This will help build a more complete understanding of wetland $CH_4$ budgets in the eastern Himalayan region. In addition, direct measurements of $CH_4$ partitioning across soil, water, and plant tissues were not conducted. Hence, the future research will seek to address this limitation by incorporating data from the non-growing seasons and quantifying $CH_4$ fluxes within plant compartments, thereby providing a more comprehensive understanding of annual $CH_4$ flux patterns and species-specific contributions to $CH_4$ emissions.

While wetland plant removal strategy is an effective in reducing $CH_4$ emissions by eliminating $CH_4$-transporting pathways, large-scale removal may disrupt wetland ecosystems and require continuous labor-intensive efforts. Costs include manpower, disposal, and potential ecological restoration. Periodic harvesting can reduce $CH_4$ emissions while providing economic benefits through bioenergy production, fodder use or biofertilizers (Balasubramanian et al. 2013; Dhadse et al. 2021; Kiehbadroudinezhad et al. 2023). Although initial investments in harvesting equipment and processing infrastructure are required, long-term sustainability and carbon offset potential improve cost-effectiveness. Promoting low-emission plant species in constructed wetlands can provide a sustainable alternative with minimal maintenance costs. However, further research on plant traits and site-specific management is necessary for practical implementation.

## Conclusions

To our knowledge, this is the first study directly comparing the $CH_4$ emissions from different wetland plant species in wetlands in the eastern Himalaya. In the present study, *M. micrantha*, *P. karka* and *P. hydropiperoides* increased $CH_4$ emission rates compared to *I. aquatica* and *E. fluctuans* stands due to their higher plant density and more abundant biomass, which may enhance available nutrients in the soil and have the potential to produce and transport more $CH_4$. Further, the present study revealed that changes in plant community composition could firmly control the $CH_4$ emission from the vegetation into the atmosphere. Overall, from the present study, it is evident that the rapid colonization of wetland plant species may significantly influence $CH_4$ emissions and other GHG in the atmosphere in the eastern Himalayan region. Further, it could be said that plant traits and soil ecological conditions are major driving forces for the $CH_4$ efflux from seasonally flooded wetlands in the foothills of the Eastern Himalaya. The results from the present study may have significant environmental repercussions due to the high global warming potential of $CH_4$ in the atmosphere. Periodical removing/harvesting and their utilization as green mulch in soil nutrient management could be an option to minimize $CH_4$ emissions from wetlands. However, that may further lead to a feedback/feedforward action to fuel the $CH_4$ uptake/emission upon storage by rapid nutrient recycling with enhanced decomposition rate, albeit further studies are needed. The present study contributes to a deeper understanding of $CH_4$ dynamics in the eastern Himalayan wetlands by linking plant functional traits to $CH_4$ emissions. The findings highlight the importance of regional studies to refine global $CH_4$ emission estimates, particularly for biodiversity-rich and less-explored ecosystems.

## Supplementary Information

Supplementary Information accompanies this paper at https://doi.org/10.5141/jee.24.091.

**Fig. S1.** Monthly changes in soil (0–10 m) and water temperature from 2009–2011. **Table S1.** Comparative analysis of $CH_4$ emission studied in various wetland plant species.

**Abbreviations**

$CH_4$: Methane

GHG: Greenhouse gas
FID: Flame ionization detector
AGB: Above ground biomass
BGB: Below ground biomass
SMC: Soil moisture content
SOC: Soil organic carbon
SOM: Soil organic matter
TN: Total nitrogen
ANOVA: Analysis of variance

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## Authors' contributions

DB conceived the ideas, designed the experiment, conducted the field work, collected data, conducted statistical analysis, and wrote the initial draft of the manuscript. JD helped in field data collection and literature review, checked the published database, and co-written the initial draft of the manuscript. KA and AA acquired the research funding for the present study and supervised progress and reviewed the manuscript. AKD reviewed the manuscript and provided constructive comments to improve the manuscript. All authors read and approved the final manuscript.

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None.

## Availability of data and materials

Data and supplementary materials will be available on reasonable request to corresponding author.

## Ethics approval and consent to participate

Not applicable.

## Consent for publication

Not applicable.

## Competing interests

The authors declare that they have no competing interests.

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