International Journal of Advanced Biochemistry Research

**ISSN Print:** 2617-4693
**ISSN Online:** 2617-4707
IJABR 2025; 9(3): 192-204
www.biochemjournal.com
Received: 04-01-2025
Accepted: 05-02-2025

**Rohit Kishor**
M.Sc. Agriculture, Department of Soil Science and Agricultural Chemistry, Indira Gandhi Krishi Vishwavidyalaya Raipur, Chhattisgarh, India

**Corresponding Author:**
**Rohit Kishor**
M.Sc. Agriculture, Department of Soil Science and Agricultural Chemistry, Indira Gandhi Krishi Vishwavidyalaya Raipur, Chhattisgarh, India

# Microbial activity and soil carbon sequestration potential in mangrove and rice ecosystems of the Sundarbans delta

**Rohit Kishor**

**DOI:** https://www.doi.org/10.33545/26174693.2025.v9.i3c.3914

**Abstract**
Mangroves ecosystems are one of the most productive systems in coastal wetlands. They are adapted to harsh climatic conditions and various abiotic and biotic stresses like high salinity, high temperature, high tides, strong winds, etc. The present paper depicts the comparative analysis of microbial activity and soil carbon sequestration potential in mangrove and rice ecosystem of the Sundarban delta. In our study seven different sites were selected based on the degradation status of mangroves from 1930 to 2013 by National Remote Sensing Agency (NRSA), Hyderabad in Sagar Island, Sundarban, India. In order to calibrate the carbon sequestration potential and microbial activity, soil physico-chemical properties (pH, EC, salinity, soil organic carbon (SOC), soil labile carbon (C) pools [readily mineralizable C (RMC), microbial biomass C (MBC), potassium permanganate oxidizable C ($KMnO_4$-C), and dissolved organic carbon (DOC)] and soil enzymatic activities [Dehydrogenase activity (DHA), fluorescein Di-acetate activity (FDA) and β-glucosidase activity (β-GLU)] were estimated in both mangrove and rice ecologies. Samples were collected from all the three depths (0-15 cm, 15-30 cm & 30-45 cm) of all sites. The soil labile C pools were significantly higher in mangrove ecosystem then the rice ecosystem. In contrast, the enzymatic activities were significantly higher in rice ecosystem. This paper investigates the significant impact of all three factors (i.e. ecology, site and depth) on the C-sequestration. In order to know the carbon sequestration potential, the interrelationship of microbial activity with SOM decomposition in the ecosystem need to understand.

**Keywords:** Mangroves, soil labile carbon pools, carbon sequestration, microbial activity

## Introduction

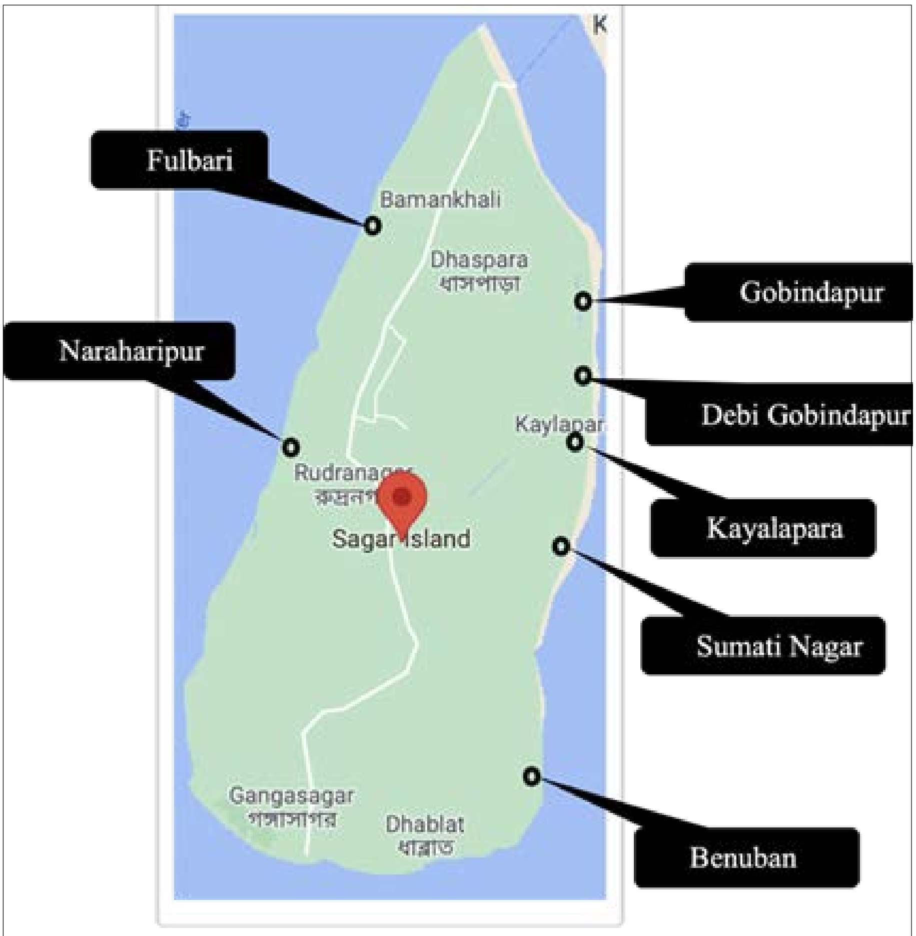
The Sundarbans, situated between 21°32' to 22°40' N and 88°05' to 89°51' E, span an area of 10,000 square kilometres in Southeast Asia, with 62% of it located in Bangladesh and the remaining 38% in India. This unique mangrove ecosystem, the largest in the world, is located at the confluence of salty seawater and freshwater, providing crucial ecosystem services and supporting a rich biodiversity. The Sundarbans' mangrove forests are especially vital due to their role in carbon sequestration, with Asia holding 42% of the global mangrove area (Kathiresan, 2021) [10]. Soil carbon (C) sequestration, the process of storing atmospheric CO2 in soil, is influenced by soil microbial biomass (SMB), which plays a critical role in soil organic carbon (SOC) turnover and stabilization (Khatoon *et al.*, 2017) [23].

Soil microbial activity and labile carbon pools are key indicators of the soil's carbon sequestration potential. These pools, which include water-soluble organic carbon, potassium permanganate oxidizable organic carbon, and microbial biomass carbon, are easily degradable and subject to rapid decomposition by soil microbes (Padhy *et al.*, 2021) [16]. In the Sundarbans, parts of the mangrove forest have been converted to rice fields, creating a unique interphase between the two ecosystems. This conversion has led to specific changes in soil physicochemical properties, microbial activity, and carbon sequestration potential. The degradation of mangrove ecosystems and their transformation into rice fields has significant implications for carbon storage and microbial dynamics, necessitating a detailed comparative study. This research aims to evaluate the microbial activity and soil carbon pools in both degraded mangrove and adjacent rice ecosystems within the Sundarbans delta. By analysing the differences between these two land-use systems, the study seeks to provide insights into their respective contributions to carbon sequestration and the overall ecological balance of the region.

## Material and methods

### Site Description and sample collection

The location of this study was the Sundarbans is situated at the delta of the Meghna, Padma, and Brahmaputra rivers in India. The location of seven different sites was as follows, Sumatinagar (21°43′26.59″N, 88°09′48.33″E), Kayalapara (21°45′23.02″N, 88°10′12.21″E), Debigobindapur (21°46′16.40″N, 88°10′13.96″E), Gobindapur (21°47′15.06″N, 88°09′56.42″E), Fulbari (21°51′57.73″N, 88°07′21.24″E), Naraharipur (21°45′49.81″N, 88°04′25.17″E) and Benuban (21°40′43.46″N, 88°08′50.27″E). The soil samples were collected from seven different sites in winter season (Dec 2021). Samples were collected from the mangrove and rice system with five replications. In each site, samples were collected from two locations at three depths (0-15; 15-30; 30-45cm) in mangroves and rice system. After the collection of samples, one part of those were kept in the refrigerator at 4℃ for the analysis of microbial and enzymatic activity assay. The left portion of soil samples was air-dried, processed and allowed to pass through the 2.0 mm sieve. The processed soil samples were kept in a sealed plastic bag for further physical, chemical and physicochemical analysis.




**Sagar Island**

### Soil Physicochemical and chemical Properties

**Soil pH:** The soil pH was estimated by a potable Multi-Parameter Tester (Eutech, PCSTEST35-01X441506/Oakton 35425-10). The electrical conductivity (EC) and salinity were measured by using Eutech, ECCONWP15003K conductivity/salinity meter. Organic carbon present in the soil sample was estimated by Walkley and Black, 1934 method [19].

### Readily mineralizable carbon (RMC)

Readily mineralizable carbons present in the wet soil sample were estimated by extraction with 0.5M $K_2SO_4$ (Inubushi *et al.*, 1991) [9] followed by analysis with the wet digestion method with $K_2Cr_2O_7$ (Vance *et al.*, 1987) [18]. 0.5M $K_2SO_4$ were added in wet soil samples in 4:1 ratio for the extraction of carbon. 0.035N $K_2Cr_2O_7$ were used to oxidize the extracted carbon and the left $K_2Cr_2O_7$ were estimated by the titration with 0.04N FAS. At the end of the titration, the colour of the content changed from dark blue to green.

### Microbial biomass carbon (MBC)

Microbial biomass carbons present in the wet soil sample were estimated by the chloroform fumigation-extraction method. 20 g of wet soil samples were fumigated with ethanol-free chloroform in dark conditions for 24 hrs in the desiccator. The MBC was estimated from the fumigated soil samples by the same wet digestion method which we used in the RMC estimation.

**Potassium permanganate ($KMnO_4$)-extractable carbon (C):** $KMnO_4$-extractable carbon is estimated by oxidizing the carbon present in the soil sample by $KMnO_4$ (Blair *et al.*,

1995) [3]. 20mM $KMnO_4$ were added to the air-dried soil sample to oxidize the C present in the sample. The left $KMnO_4$ were estimated by taking the absorbance of the content at 565 nm in the spectrophotometer (Model name: Thermo scientific evolution 350 UV-VIS) and the concentration of the left $KMnO_4$ after oxidation of C was estimated from the standard calibration curve.

**Water soluble carbon (WSC)**

The water-soluble carbon (WSC) represents the portion of organic C which are naturally dissolved in water. The WSC present in the soil was determined by the method given by Haynes and Swift, (1990) [7]. WSC were extracted from dry soil sample having a particle size less than 2 mm by using hot distilled water having a temperature of 80℃ and estimated by adding freshly prepared anthrone reagent (dissolving 200 mg anthrone in the 100 ml of ice-cold conc. $H_2SO_4$). The absorbance of the solution colour was taken at 630 nm in the spectrophotometer (Model name: Thermo scientific evolution 350 UV-VIS). The concentration of sugar in the soil sample extract was calculated from the D-glucose-anthrone standard calibration curve.

**Soil Enzymatic Activities**

**Fluorescein-diacetate (FDA) activity**

The fluorescein diacetate (FDA) assay measured the total hydrolytic enzymatic activities in the soil. FDA hydrolysis activity was measured by the procedure given by Adam and Duncan, (2001) [1]. The FDA acted as a substrate for the hydrolytic micro-organisms. In the presence of hydrolytic enzyme FDA produce fluorescein which gave yellow-green colour. The intensity of the yellow-green colour was measured at 490 nm wavelength in the spectrophotometer (Model name: Thermo scientific evolution 350 UV-VIS).

**Dehydrogenase activity (DHA)**

Dehydrogenase activities (DHA) were estimated by the method given by Casida *et al.*, (1964) [4]. In this method, 2,3,5-triphenyl-tetrazolium chloride (TTC) acted as a substrate. The TTC acted as an electron acceptor during microbial respiration and got reduced to triphenyl formazan (TPF) which in the presence of methanol gave red colour. Volume of TPF was made up to 100 ml by adding methanol and the intensity of the red colour was then measured at 485 nm wavelength in the spectrophotometer (Model name: Thermo scientific evolution 350 UV-VIS).

**β-glucosidase activity (β-GLU)**

The β-glucosidase activity (β-GLU) was estimated by the method given by Eivazi and Tabatabai, (1988) [6] which was based on the colorimetric method. In this method, p-nitrophenyl-β-D-glucoside (pNG) used as substrate which got converted into p-nitrophenol (pNP) that gave yellow colour. The intensity of the yellow colour was measured at 420 nm wavelength in the spectrophotometer (Model name: Thermo scientific evolution 350 UV-VIS).

**Statistical Analysis**

The OPSTAT was used for the analysis of variance (ANOVA) and the least significant difference at $p \leq 0.05$ levels and the interaction effect of three factors i.e., (i) site (S) (Sumatinagar, Kayalapara, Debigobindapur, Gobindapur, Fulbari, Naraharipur and Benuban), (ii) ecology (E) (mangrove and rice) and (iii) soil depth (D) (0-15, 15-30, 30-45 cm) was estimated for each parameter. The Pearson correlation matrix among the soil labile carbon pools, soil physico-chemical properties and soil enzymatic activities of both mangrove and rice ecologies in Sagar Island, Sundarban, India were estimated by using the R software (version 4.0.3).

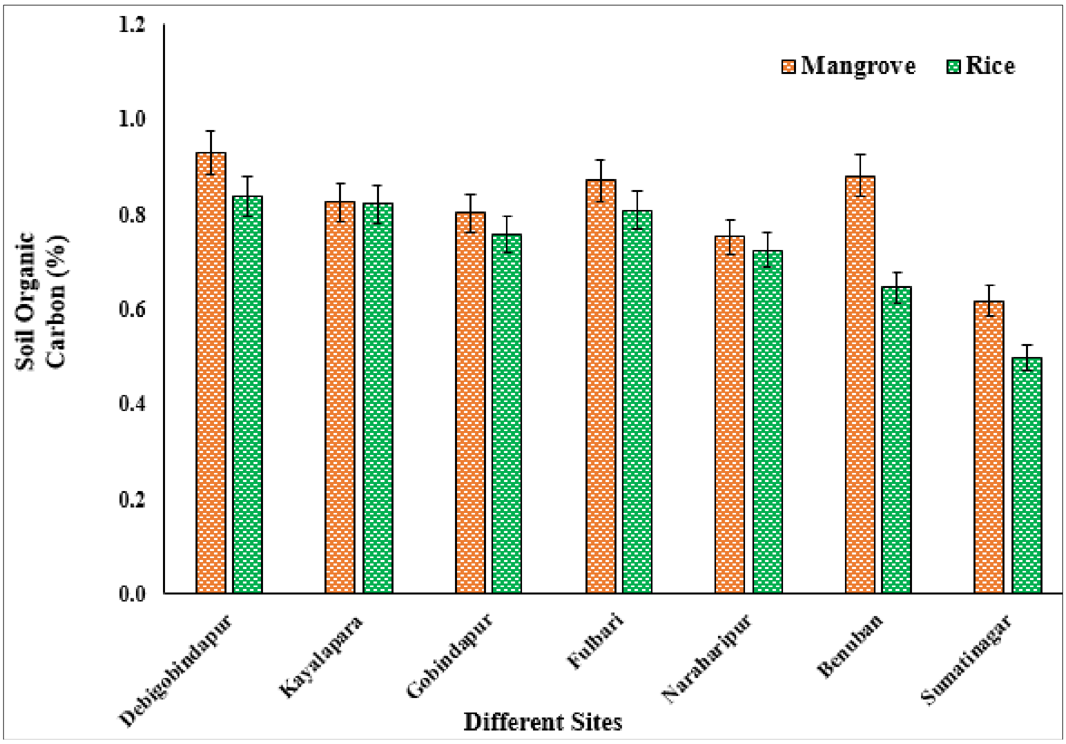
## Results

**Soil physico-chemical properties**

The pH of the soils were ranged from 8.03±0.04 to 8.18±0.06 and 6.95±0.05 to 7.74±0.13 among the seven different sites of mangrove and rice system respectively. pH in mangrove ecologies were significantly higher (alkaline range) than the rice ecologies (neutral range) in all sites. Ecologies (E) had a significant effect on pH (Table 1). In mangroves, the electrical conductivity (EC) of the soils were ranged from 13.95±0.75 to 19.65±1.33 mS $cm^{-1}$ whereas salinity was ranged from 7.43±0.21 to 10.58±0.73 ppt and in rice system the EC of the soils were ranged from 1.46±0.03 to 3.42±0.36 $mScm^{-1}$ whereas salinity was ranged from 0.77±0.04 to 1.87±0.68 ppt. Both EC and salinity were significantly higher in mangrove ecologies than that of rice ecologies in all sites. Both site (S), ecologies (E) and their interaction (S×E) had a significant effect on EC and salinity (Table 1).

**Soil organic carbon**

The average soil organic carbon (SOC) contents varied between 0.62 to 0.93% and 0.50 to 0.84% among the sites in mangroves and rice system respectively (Figure 1). In both system it was significantly higher in the top soil layer (0-15 cm) and the lower in the sub-soil layer (30-45 cm). In mangrove, SOC contents were observed higher at the lower soil layer (30-45 cm) in some site i.e. Kayalapara (0.86%) whereas in rice, the SOC contents were significantly higher in the top soil layer (0-15 cm) and the lower in the sub-soil layer (30-45 cm) irrespective of the sites (Table 2). The average SOC contents were significantly higher in the mangrove systems (0.81%) as compared to rice system (0.73%) (Figure 1). It was also found that among the sites the effect of depths on the SOC were at par (Table 2).




**[Note:** C.D. value: S= 0.044; E= 0.023; S×E= 0.062]

**Fig 1:** Average soil organic carbon content in mangrove and rice ecology at seven different sites of Sagar Island, Sundarban, India.

**Table 1:** Various physico-chemical properties under mangrove and adjacent rice systems in Sundarban, India.

| Site | | Latitude | Longitude | Ecology | pH | EC ($mScm^{-1}$) | Salinity (ppt) |
|---|---|---|---|---|---|---|---|
| Sumatinagar | | 21°43′26.59″N | 88°09′48.33″E | Mangrove | 8.08±0.06 | 14.99±0.37 | 10.58±0.73 |
| | | | | Rice | 6.95±0.05 | 3.14±0.20 | 1.71±0.03 |
| Kayalapara | | 21°45′23.02″N | 88°10′12.21″E | Mangrove | 8.03±0.04 | 14.18±0.87 | 7.43±0.21 |
| | | | | Rice | 7.74±0.13 | 3.42±0.36 | 1.82±0.19 |
| Debigobindapur | | 21°46′16.40″N | 88°10′13.96″E | Mangrove | 8.17±0.03 | 16.35±0.13 | 8.70±0.48 |
| | | | | Rice | 7.13±0.59 | 2.82±0.08 | 1.87±0.68 |
| Gobindapur | | 21°47′15.06″N | 88°09′56.42″E | Mangrove | 8.08±0.06 | 13.95±0.75 | 8.00±0.37 |
| | | | | Rice | 6.97±0.20 | 3.02±0.17 | 1.36±0.06 |
| Fulbari | | 21°51′57.73″N | 88°07′21.24″E | Mangrove | 8.17±0.08 | 17.10±0.82 | 7.86±0.53 |
| | | | | Rice | 7.09±0.08 | 3.27±0.15 | 1.74±0.07 |
| Naraharipur | | 21°45′49.81″N | 88°04′25.17″E | Mangrove | 8.18±0.06 | 19.65±1.33 | 9.85±0.46 |
| | | | | Rice | 7.21±0.06 | 2.43±0.06 | 1.57±0.06 |
| Benuban | | 21°40′43.46″N | 88°08′50.27″E | Mangrove | 8.07±0.05 | 18.02±0.10 | 9.29±0.16 |
| | | | | Rice | 7.45±0.18 | 1.46±0.03 | 0.77±0.04 |
| **ANOVA Statistics ($p \leq 0.05$)** | | | | | | | |
| | **Factors** | **S** | | **E** | | **S×E** | |
| **CD Value** | pH | 0.216 | | 0.115 | | 0.305 | |
| | EC | 0.672 | | 0.359 | | 0.951 | |
| | Salinity | 0.441 | | 0.236 | | 0.624 | |

**Note:** Values are presented as mean±standard deviation (SD) [$mScm^{-1}$ = milliSimen per centimeter, ppt = parts per thousand, S= Sites, E= Ecology]

**Table 2:** Soil organic carbon (%) content in mangrove and rice ecology at seven different sites of Sagar Island, Sundarban, India.

| Ecology | Depth (cm) | Debigobindapur | Kayalapara | Gobindapur | Fulbari | Naraharipur | Benuban | Sumatinagar | Mean of sites |
|---|---|---|---|---|---|---|---|---|---|
| Mangrove | 0-15 | 1.00 | 0.84 | 0.82 | 0.92 | 0.83 | 0.90 | 0.54 | 0.83 |
| | 15-30 | 0.86 | 0.78 | 0.79 | 0.86 | 0.77 | 0.97 | 0.75 | 0.82 |
| | 30-45 | 0.94 | 0.86 | 0.80 | 0.83 | 0.66 | 0.78 | 0.58 | 0.78 |
| | Mean | 0.93 | 0.83 | 0.80 | 0.87 | 0.75 | 0.88 | 0.62 | 0.81 |
| Rice | 0-15 | 0.94 | 0.93 | 0.87 | 0.89 | 0.80 | 0.73 | 0.65 | 0.83 |
| | 15-30 | 0.84 | 0.78 | 0.75 | 0.83 | 0.78 | 0.65 | 0.47 | 0.73 |
| | 30-45 | 0.74 | 0.76 | 0.66 | 0.71 | 0.60 | 0.57 | 0.38 | 0.63 |
| | Mean | 0.84 | 0.82 | 0.76 | 0.81 | 0.73 | 0.65 | 0.50 | 0.73 |
| | Mean of depth (0-15) | 0.97 | 0.88 | 0.84 | 0.90 | 0.81 | 0.81 | 0.59 | 0.83 |
| | Mean of depth (15-30) | 0.85 | 0.78 | 0.77 | 0.85 | 0.77 | 0.81 | 0.61 | 0.78 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Mean of depth (30-45) | 0.84 | 0.81 | 0.73 | 0.77 | 0.63 | 0.67 | 0.48 | 0.70 |
| | Grand mean | 0.88 | 0.82 | 0.78 | 0.84 | 0.74 | 0.76 | 0.56 | |
| ANOVA Statistics ($p \leq 0.05$) | | | | | | | | | |
| Factors | | S | E | S×E | D | S×D | E×D | S×E×D | |
| C.D. | | 0.044 | 0.023 | 0.062 | 0.028 | NS | 0.04 | 0.107 | |
| SE (m) | | 0.015 | 0.008 | 0.022 | 0.01 | 0.026 | 0.014 | 0.037 | |

[S= Sites (Debigobindapur, Kayalapara, Gobindapur, Fulbari, Naraharipur, Benuban and Sumatinagar); E= Ecology (Mangrove and rice); D= Soil depth (0-15, 15-30, 30-45cm)].

## Labile carbon pools

### Readily mineralizable carbon

In mangroves the average readily mineralizable carbon (RMC) contents ranged from 317.29 to 367.69 µg C $g^{-1}$ soil however in rice it varied between 287.36 to 343.97 µg C $g^{-1}$ soil among the sites. The average RMC contents were significantly higher in Fulbari (367.69 µg C $g^{-1}$ soil) and Kayalapara (343.97 µg C $g^{-1}$ soil) in mangrove and rice system respectively (Figure 2). In both systems, the RMC contents were significantly higher at the top soil layer (0-15 cm) and the lower at the sub-soil layer (30-45 cm) (Table 3). The average RMC contents were significantly higher in the mangroves (354.27 µg C $g^{-1}$ soil) as compared to rice system (324.54 µg C $g^{-1}$ soil). The effect of interaction of sites and depths on RMC were at par (Table 3).

### Microbial biomass carbon

In both mangrove and rice system, significantly higher microbial biomass carbon (MBC) contents were observed at the top soil layer (0-15 cm) and the lower at the sub-soil layer (30-45 cm) (Table 4). In mangroves, average MBC contents varied between 716.18 to 868.01 µg C $g^{-1}$ soil whereas in rice it varied between 611.16 to 817.25 µg C $g^{-1}$ soil (Figure 3). The average MBC contents were significantly higher in the mangrove systems (784.21 µg C $g^{-1}$ soil) as compared to rice system (695.57 µg C $g^{-1}$ soil). The factors S, E, D and their interaction S×D, S×E, E×D and S×E×D had a significant effect on MBC (Table 4).

### Potassium permanganate oxidizable carbon

The average $KMnO_4$ oxidizable carbon ($KMnO_4$-C) contents were significantly higher in the mangrove systems (547.27 µg C $g^{-1}$ soil) as compared to rice system (514.94 µg C $g^{-1}$ soil) (Table 5).Among the sites, in mangrove it varied between 332.19 to 688.24 µg C $g^{-1}$ soil whereas in rice varied from 308.02 to 660.61 µg C $g^{-1}$ soil (Figure 4). In both systems, average $KMnO_4$-C were significantly higher at the top soil layer (0-15 cm) (611.38 and 605.88 µg C $g^{-1}$ soil in mangrove and rice respectively). The factors S, E, D and their interaction S×D, S×E, E×D and S×E×D had a significant effect on $KMnO_4$-C (Table 5).

### Water soluble carbon

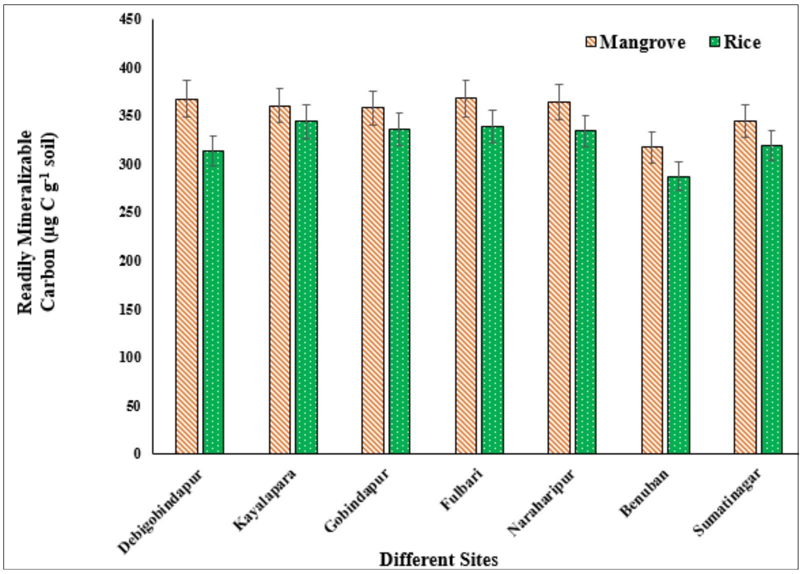
In mangroves, the average water-soluble carbon (WSC) contents varied between 32.19 to 44.87 µg C $g^{-1}$ soil whereas in rice it was ranged from 24.95 to 39.19 µg C $g^{-1}$ soil among the sites (Figure 5). It was significantly higher in the mangrove systems (39.39 µg C $g^{-1}$ soil) as compared to rice system (33.39 µg C $g^{-1}$ soil). The factors S, E, D and their interaction S×D, S×E, E×D and S×E×D had a significant effect on WSC (Table 6).

**Table 3:** Readily mineralizable carbon (µg C $g^{-1}$ soil) content in mangrove and rice ecology at seven different sites of Sagar Island, Sundarban, India.

| Ecology | Depth (cm) | Debigobindapur | Kayalapara | Gobindapur | Fulbari | Naraharipur | Benuban | Sumatinagar | Mean of sites |
|---|---|---|---|---|---|---|---|---|---|
| Mangrove | 0-15 | 421.94 | 441.94 | 407.48 | 428.25 | 425.09 | 383.30 | 419.64 | 418.23 |
| | 15-30 | 362.38 | 374.55 | 377.65 | 373.45 | 387.95 | 332.37 | 353.54 | 365.98 |
| | 30-45 | 318.61 | 265.30 | 288.53 | 301.39 | 280.95 | 236.21 | 259.21 | 278.60 |
| | Mean | 367.64 | 360.60 | 357.89 | 367.69 | 364.66 | 317.29 | 344.13 | 354.27 |
| Rice | 0-15 | 361.76 | 418.17 | 379.55 | 376.09 | 380.85 | 314.22 | 374.18 | 372.12 |
| | 15-30 | 304.20 | 340.58 | 327.98 | 339.74 | 314.64 | 301.70 | 322.02 | 321.55 |
| | 30-45 | 273.28 | 273.16 | 299.07 | 300.34 | 306.73 | 246.15 | 260.97 | 279.96 |
| | Mean | 313.08 | 343.97 | 335.53 | 338.72 | 334.08 | 287.36 | 319.06 | 324.54 |
| | Mean of depth (0-15) | 391.85 | 430.05 | 393.51 | 402.17 | 402.97 | 348.76 | 396.91 | 395.18 |
| | Mean of depth (15-30) | 333.29 | 357.56 | 352.82 | 356.59 | 351.30 | 317.04 | 337.78 | 343.77 |
| | Mean of depth (30-45) | 295.94 | 269.23 | 293.80 | 300.87 | 293.84 | 241.18 | 260.09 | 279.28 |
| | Grand mean | 340.36 | 352.28 | 346.71 | 353.21 | 349.37 | 302.32 | 331.60 | |
| **ANOVA Statistics ($p \leq 0.05$)** | | | | | | | | | |
| Factors | | S | E | S×E | D | S×D | E×D | S×E×D | |
| C.D. | | 11.539 | 6.168 | NS | 7.554 | 19.985 | 10.683 | NS | |
| SE (m) | | 4.039 | 2.159 | 5.712 | 2.644 | 6.996 | 3.739 | 9.893 | |

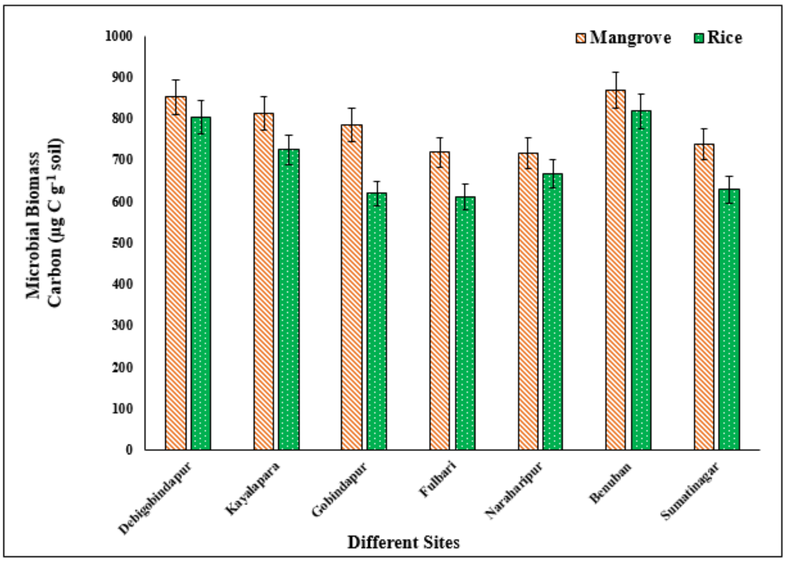
**Table 4:** Microbial biomass carbon (µg C $g^{-1}$ soil) content in mangrove and rice ecology at seven different sites of Sagar Island, Sundarban, India.

| Ecology | Depth (cm) | Debigobindapur | Kayalapara | Gobindapur | Fulbari | Naraharipur | Benuban | Sumatinagar | Mean of sites |
|---|---|---|---|---|---|---|---|---|---|
| Mangrove | 0-15 | 1096.52 | 1017.68 | 956.76 | 926.32 | 949.35 | 1146.50 | 1018.95 | 1016.01 |
| | 15-30 | 873.25 | 821.39 | 860.80 | 679.19 | 703.23 | 853.70 | 724.33 | 787.99 |
| | 30-45 | 585.65 | 594.95 | 535.21 | 550.61 | 495.94 | 603.83 | 474.31 | 548.64 |
| | Mean | 851.81 | 811.34 | 784.26 | 718.71 | 716.18 | 868.01 | 739.20 | 784.21 |
| Rice | 0-15 | 901.60 | 797.67 | 734.07 | 688.87 | 767.23 | 947.36 | 691.93 | 789.82 |
| | 15-30 | 788.36 | 730.59 | 616.63 | 607.60 | 655.15 | 784.98 | 639.91 | 689.03 |
| | 30-45 | 718.34 | 644.89 | 504.73 | 537.03 | 579.05 | 719.41 | 551.58 | 607.86 |
| | Mean | 802.77 | 724.38 | 618.48 | 611.16 | 667.14 | 817.25 | 627.81 | 695.57 |
| | Mean of depth (0-15) | 999.06 | 907.68 | 845.42 | 807.60 | 858.29 | 1046.93 | 855.44 | 902.92 |
| | Mean of depth (15-30) | 830.81 | 775.99 | 738.72 | 643.40 | 679.19 | 819.34 | 682.12 | 738.51 |
| | Mean of depth (30-45) | 652.00 | 619.92 | 519.97 | 543.82 | 537.50 | 661.62 | 512.95 | 578.25 |
| | Grand mean | 827.29 | 767.86 | 701.37 | 664.94 | 691.66 | 842.63 | 683.50 | |
| ANOVA Statistics ($p \leq 0.05$) | | | | | | | | | |
| Factors | | | S | E | S×E | D | S×D | E×D | S×E×D |
| C.D. | | | 21.622 | 11.558 | 30.579 | 14.155 | 37.451 | 20.018 | 52.964 |
| SE (m) | | | 7.569 | 4.046 | 10.704 | 4.955 | 13.109 | 7.007 | 18.54 |




**[Note:** C.D. value: S= 11.539; E= 6.168; S×E= NS]

**Fig 2:** Average readily mineralizable carbon content in mangrove and rice ecology at seven different sites of Sagar Island, Sundarban, India.




**[Note:** C.D. value: S= 21.622; E= 11.558; S×E= 30.579]

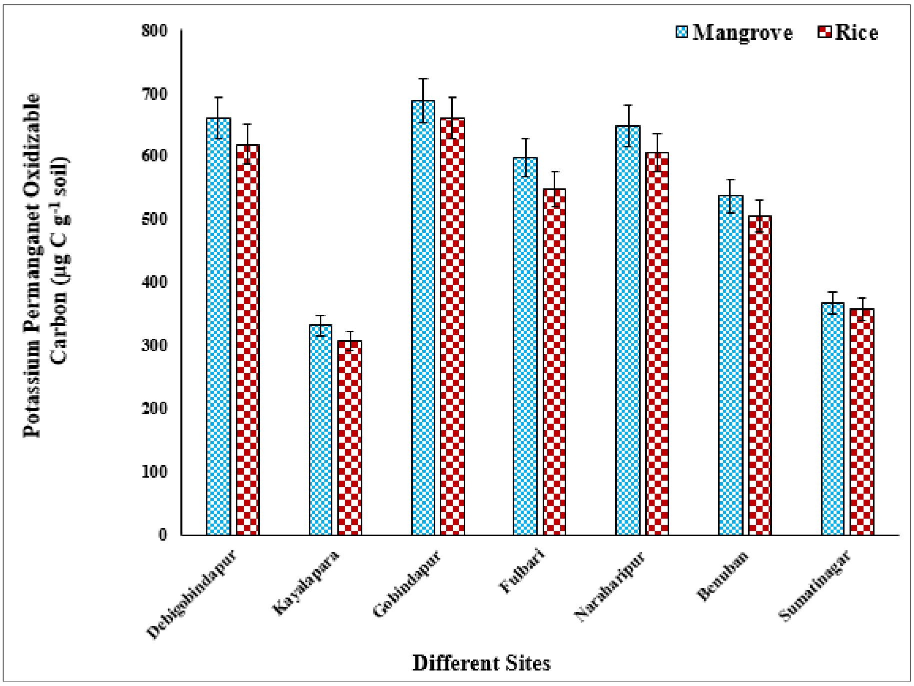
**Fig 3:** Average microbial biomass carbon content in mangrove and rice ecology at seven different sites of Sagar Island, Sundarban, India.

**Table 5:** Potassium permanganate oxidizable carbon (μg C $g^{-1}$ soil) content in mangrove and rice ecology at seven different sites of Sagar Island, Sundarban, India.

| Ecology | Depth (cm) | Debigobindapur | Kayalapara | Gobindapur | Fulbari | Naraharipur | Benuban | Sumatinagar | Mean of sites |
|---|---|---|---|---|---|---|---|---|---|
| Mangrove | 0-15 | 706.02 | 387.39 | 787.53 | 682.35 | 703.97 | 655.45 | 356.93 | 611.38 |
| | 15-30 | 686.45 | 295.15 | 640.40 | 594.44 | 657.11 | 518.24 | 412.86 | 543.52 |
| | 30-45 | 587.59 | 314.03 | 636.80 | 516.29 | 583.73 | 436.97 | 332.91 | 486.90 |
| | Mean | 660.02 | 332.19 | 688.24 | 597.69 | 648.27 | 536.89 | 367.57 | 547.27 |
| Rice | 0-15 | 645.24 | 332.91 | 797.15 | 667.72 | 777.42 | 634.97 | 385.75 | 605.88 |
| | 15-30 | 626.14 | 296.01 | 703.62 | 620.38 | 538.86 | 479.57 | 373.02 | 519.66 |
| | 30-45 | 585.89 | 295.15 | 481.07 | 356.93 | 497.67 | 403.27 | 314.89 | 419.27 |
| | Mean | 619.09 | 308.02 | 660.61 | 548.35 | 604.65 | 505.94 | 357.89 | 514.94 |
| | Mean of depth (0-15) | 675.63 | 360.15 | 792.34 | 675.04 | 740.70 | 645.21 | 371.34 | 608.63 |
| | Mean of depth (15-30) | 656.29 | 295.58 | 672.01 | 607.41 | 597.98 | 498.91 | 392.94 | 531.59 |
| | Mean of depth (30-45) | 586.74 | 304.59 | 558.93 | 436.61 | 540.70 | 420.12 | 323.90 | 453.09 |
| | Grand mean | 639.56 | 320.11 | 674.43 | 573.02 | 626.46 | 521.41 | 362.73 | |
| **ANOVA Statistics ($p \leq 0.05$)** | | | | | | | | | |
| Factors | | | S | E | S×E | D | S×D | E×D | S×E×D |
| C.D. | | | 10.709 | 5.724 | 15.145 | 7.001 | 18.549 | 9.915 | 26.232 |
| SE (m) | | | 3.749 | 2.004 | 5.301 | 2.454 | 6.493 | 3.471 | 9.182 |

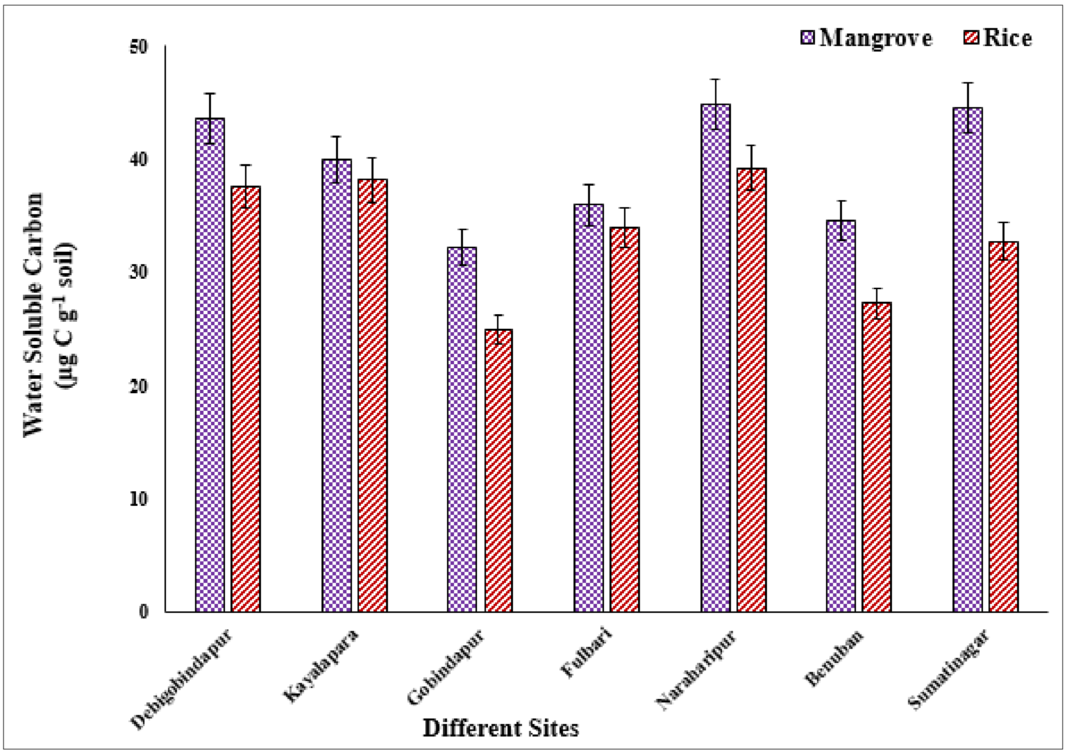
**Table 6:** Water-soluble carbon (μg C $g^{-1}$ soil) content in mangrove and rice ecology at seven different sites of Sagar Island, Sundarban, India.

| Ecology | Depth (cm) | Debigobindapur | Kayalapara | Gobindapur | Fulbari | Naraharipur | Benuban | Sumatinagar | Mean of sites |
|---|---|---|---|---|---|---|---|---|---|
| Mangrove | 0-15 | 47.06 | 41.68 | 33.53 | 42.38 | 46.18 | 62.26 | 66.32 | 48.49 |
| | 15-30 | 35.12 | 37.24 | 32.74 | 38.26 | 41.62 | 24.03 | 29.24 | 34.03 |
| | 30-45 | 48.53 | 40.88 | 30.29 | 27.29 | 46.82 | 17.65 | 38.03 | 35.64 |
| | Mean | 43.57 | 39.93 | 32.19 | 35.98 | 44.87 | 34.65 | 44.53 | 39.39 |
| Rice | 0-15 | 56.76 | 50.88 | 34.71 | 48.53 | 53.82 | 35.88 | 49.41 | 47.14 |
| | 15-30 | 32.95 | 33.82 | 21.76 | 34.71 | 33.74 | 24.41 | 32.94 | 30.62 |
| | 30-45 | 22.94 | 29.71 | 18.38 | 18.53 | 30.00 | 21.47 | 15.80 | 22.40 |
| | Mean | 37.55 | 38.14 | 24.95 | 33.92 | 39.19 | 27.25 | 32.72 | 33.39 |
| | Mean of depth (0-15) | 51.91 | 46.28 | 34.12 | 45.46 | 50.00 | 49.07 | 57.87 | 47.82 |
| | Mean of depth (15-30) | 34.03 | 35.53 | 27.25 | 36.49 | 37.68 | 24.22 | 31.09 | 32.33 |
| | Mean of depth (30-45) | 35.73 | 35.29 | 24.34 | 22.91 | 38.41 | 19.56 | 26.91 | 29.02 |
| | Grand mean | 40.56 | 39.03 | 28.57 | 34.95 | 42.03 | 30.95 | 38.62 | |
| **ANOVA Statistics ($p \leq 0.05$)** | | | | | | | | | |
| Factors | | | S | E | S×E | D | S×D | E×D | S×E×D |
| C.D. | | | 2.091 | 1.118 | 2.957 | 1.369 | 3.622 | 1.936 | 5.122 |
| SE (m) | | | 0.732 | 0.391 | 1.035 | 0.479 | 1.268 | 0.678 | 1.793 |




**[Note:** C.D. value: S= 10.709; E= 5.724; S×E= 15.145]

**Fig 4:** Average Potassium permanganate oxidizable carbon content in mangrove and rice ecology at seven different sites of Sagar Island, Sundarban, India.




**[Note:** C.D. value: S= 2.091; E= 1.118; S×E= 2.957]

**Fig 5:** Average water-soluble carbon content in mangrove and rice ecology at seven different sites of Sagar Island, Sundarban, India.

**Soil enzymatic activities**

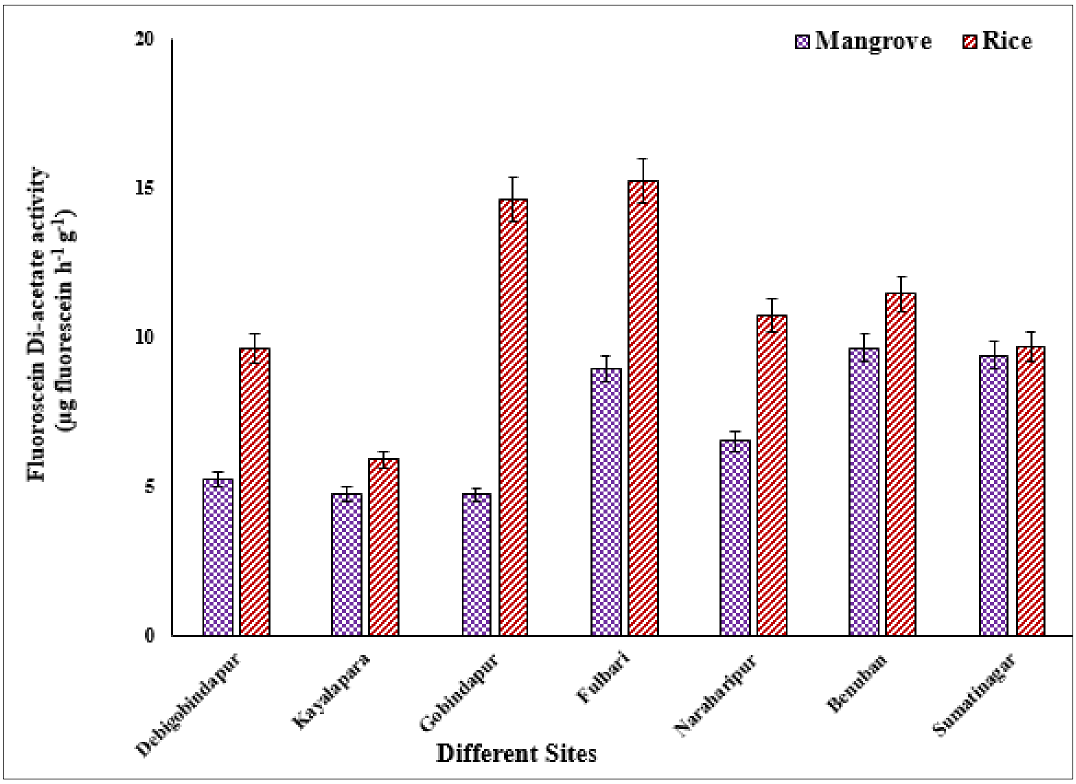
**Fluorescein di-acetate assay**

The average fluorescein di-acetate assays (FDA) ranged from 4.72 to 9.64 µg fluorescein $h^{-1}$ $g^{-1}$ soil and 5.89 to 15.23 µg fluorescein $h^{-1}$ $g^{-1}$ soil among the different sites in mangrove and rice respectively. In mangrove, it was significantly higher in Benuban (9.64 µg fluorescein $h^{-1}$ $g^{-1}$ soil) whereas in rice, it was significantly higher in Fulbari (15.23 µg fluorescein $h^{-1}$ $g^{-1}$ soil) (Figure 6). In both system, higher FDA contents were observed at the top soil layers (0-15 cm) and lower at the sub-soil layer (30-45 cm). The average FDA were significantly higher in the rice systems (11.03 µg fluorescein $h^{-1}$ $g^{-1}$ soil) as compared to mangrove systems (7.03 µg fluorescein $h^{-1}$ $g^{-1}$ soil). The factors S, E, D and their interaction S×D, S×E, E×D and S×E×D had a significant effect on FDA (Table 7).

**Dehydrogenase Activity:** The average DHA contents were significantly higher in Kayalapara (167.82 µg TPF $d^{-1}g^{-1}$ soil) and in Naraharipur (251.46 µg TPF $d^{-1}$ $g^{-1}$ soil) in mangroves and rice system respectively. In mangrove, it ranged from 115.58 to 167.82 µg TPF $d^{-1}$ $g^{-1}$ soil whereas in rice it varied between 214.61 to 251.46 µg TPF $d^{-1}g^{-1}$ soil among the sites (Figure 7). The significantly higher DHA content was observed at the top soil layers (0-15 cm) and the lower at the sub-soil layers (30-45 cm) in both the system. The average DHA were significantly higher in the rice systems (232.00 µg TPF $d^{-1}$ $g^{-1}$ soil) as compared to mangrove systems (133.45µg TPF $d^{-1}$ $g^{-1}$ soil). The factors S, E, D and their interaction S×E and E×D had a significant effect on DHA except S×D and S×E×D (Table 8).

**β-glucosidase Activity**

Among the sites, in mangroves the average β-glucosidase activities (β-GLU) contents were varied between 7.96 to 17.01 µg pNP $h^{-1}$ $g^{-1}$ soil whereas in rice it varied between 15.40 to 42.53 µg pNP $h^{-1}$ $g^{-1}$ soil. The average β-GLU activities were significantly higher in Fulbari (17.01 µg pNP $h^{-1}$ $g^{-1}$ soil) and in Gobindapur (42.53 µg pNP $h^{-1}$ $g^{-1}$ soil) in mangrove and rice system respectively (Figure 8). In both systems the significantly higher β-GLU contents were observed at the top soil layer (0-15 cm) than the sub-soil layers (30-45 cm). The average β-GLU activities were significantly higher in the rice systems (21.89 µg pNP $h^{-1}$ $g^{-1}$ soil) as compared to mangrove systems (11.12 µg pNP $h^{-1}$ $g^{-1}$ soil). The factors S, E, D and their interaction S×D, S×E, E×D and S×E×D had a significant effect on β-GLU (Table 9).




**[Note:** C.D. value: S= 0.530; E= 0.283; S×E= 0.750]

**Fig 6:** Average fluorescein Di-acetate activity in mangrove and rice ecology at seven different sites of Sagar Island, Sundarban, India.

**Table 7:** Fluorescein Di-acetate (µg fluorescein $h^{-1}$ $g^{-1}$ soil) activity in mangrove and rice ecology at seven different sites of Sagar Island, Sundarban India.

| Ecology | Depth (cm) | Debigobindapur | Kayalapara | Gobindapur | Fulbari | Naraharipur | Benuban | Sumatinagar | Mean of sites |
|---|---|---|---|---|---|---|---|---|---|
| Mangrove | 0-15 | 7.74 | 5.81 | 5.50 | 11.57 | 6.98 | 10.81 | 9.85 | 8.32 |
| | 15-30 | 5.00 | 4.84 | 5.43 | 9.38 | 6.30 | 10.52 | 9.64 | 7.30 |
| | 30-45 | 2.99 | 3.62 | 3.24 | 5.88 | 6.23 | 7.59 | 8.67 | 5.46 |
| | Mean | 5.24 | 4.76 | 4.72 | 8.94 | 6.50 | 9.64 | 9.39 | 7.03 |
| Rice | 0-15 | 12.23 | 8.73 | 19.07 | 22.07 | 11.67 | 12.82 | 10.33 | 13.84 |
| | 15-30 | 8.73 | 4.70 | 14.55 | 19.01 | 11.63 | 11.92 | 9.85 | 11.48 |
| | 30-45 | 7.93 | 4.23 | 10.28 | 4.62 | 8.90 | 9.56 | 8.89 | 7.77 |
| | Mean | 9.63 | 5.89 | 14.63 | 15.23 | 10.73 | 11.44 | 9.69 | 11.03 |
| | Mean of depth (0-15) | 9.99 | 7.27 | 12.28 | 16.82 | 9.33 | 11.82 | 10.09 | 11.08 |
| | Mean of depth (15-30) | 6.86 | 4.77 | 9.99 | 14.19 | 8.96 | 11.22 | 9.75 | 9.39 |
| | Mean of depth (30-45) | 5.46 | 3.93 | 6.76 | 5.25 | 7.57 | 8.58 | 8.78 | 6.62 |
| | Grand mean | 7.44 | 5.32 | 9.68 | 12.08 | 8.62 | 10.54 | 9.54 | |
| **ANOVA Statistics ($p \leq 0.05$)** | | | | | | | | | |
| Factors | | | S | E | S×E | D | S×D | E×D | S×E×D |
| C.D. | | | 0.53 | 0.283 | 0.75 | 0.347 | 0.918 | 0.491 | 1.299 |
| SE (m) | | | 0.186 | 0.099 | 0.262 | 0.122 | 0.321 | 0.172 | 0.455 |

[h= hour, g= gram]

**Table 8:** Dehydrogenase (µg TPF $d^{-1}$ $g^{-1}$ soil) activity in mangrove and rice ecology at seven different sites of Sagar Island, Sundarban, India.

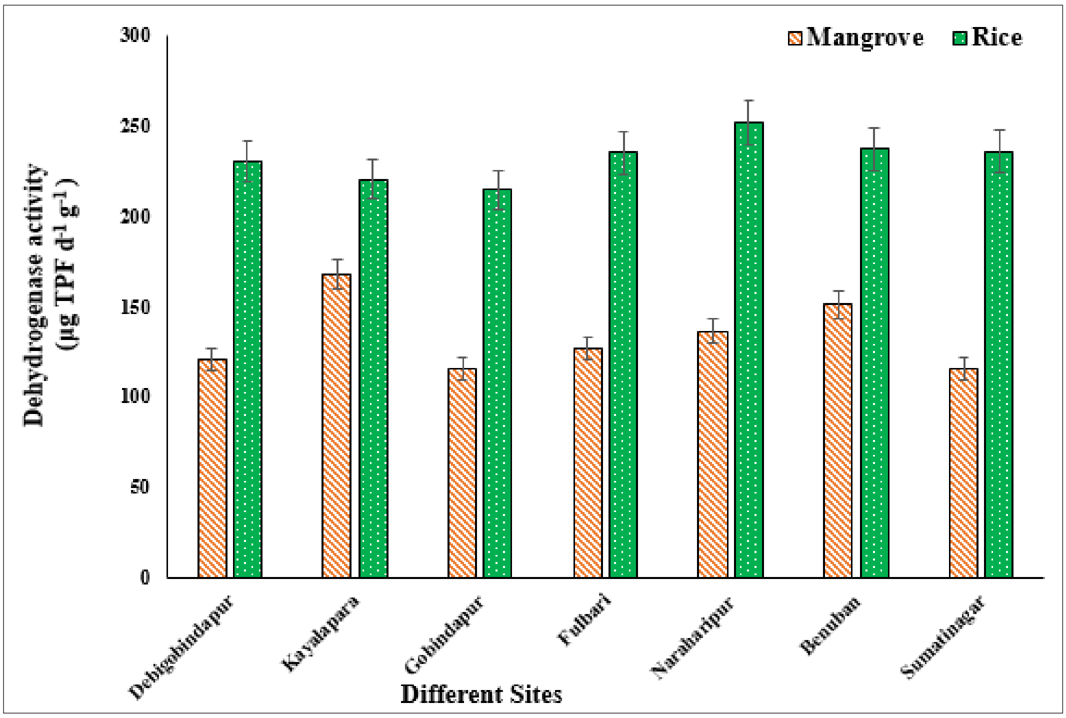
| Ecology | Depth (cm) | Debigobindapur | Kayalapara | Gobindapur | Fulbari | Naraharipur | Benuban | Sumatinagar | Mean of sites |
|---|---|---|---|---|---|---|---|---|---|
| Mangrove | 0-15 | 150.84 | 191.92 | 154.25 | 156.19 | 178.16 | 184.64 | 146.57 | 166.08 |
| | 15-30 | 107.69 | 166.13 | 103.39 | 123.27 | 137.87 | 152.41 | 114.08 | 129.26 |
| | 30-45 | 104.51 | 145.42 | 89.11 | 101.13 | 92.89 | 115.62 | 86.43 | 105.01 |
| | Mean | 121.01 | 167.82 | 115.58 | 126.86 | 136.31 | 150.89 | 115.69 | 133.45 |
| Rice | 0-15 | 261.46 | 279.60 | 255.06 | 279.04 | 299.17 | 281.57 | 270.62 | 275.22 |
| | 15-30 | 239.25 | 206.50 | 209.38 | 241.85 | 249.95 | 227.67 | 244.02 | 231.23 |
| | 30-45 | 190.36 | 174.60 | 179.38 | 184.38 | 205.25 | 201.34 | 191.46 | 189.54 |
| | Mean | 230.36 | 220.23 | 214.61 | 235.09 | 251.46 | 236.86 | 235.37 | 232.00 |
| | Mean of depth (0-15) | 206.15 | 235.76 | 204.65 | 217.62 | 238.67 | 233.10 | 208.60 | 220.65 |
| | Mean of depth (15-30) | 173.47 | 186.32 | 156.39 | 182.56 | 193.91 | 190.04 | 179.05 | 180.25 |
| | Mean of depth (30-45) | 147.44 | 160.01 | 134.24 | 142.76 | 149.07 | 158.48 | 138.95 | 147.28 |
| | Grand mean | 175.69 | 194.03 | 165.09 | 180.98 | 193.88 | 193.88 | 175.53 | |
| **ANOVA Statistics ($p \leq 0.05$)** | | | | | | | | | |
| Factors | | S | E | S×E | D | S×D | E×D | S×E×D | |
| C.D. | | 9.537 | 5.098 | 13.488 | 6.244 | NS | 8.83 | NS | |
| SE (m) | | 3.338 | 1.784 | 4.721 | 2.186 | 5.782 | 3.091 | 8.178 | |

[TPF= Triphenyl formazan, d= day]

**Table 9:** β-glucosidase (µg pNP $h^{-1}$ $g^{-1}$ soil) activity in mangrove and rice ecology at seven different sites of Sagar Island, Sundarban, India.

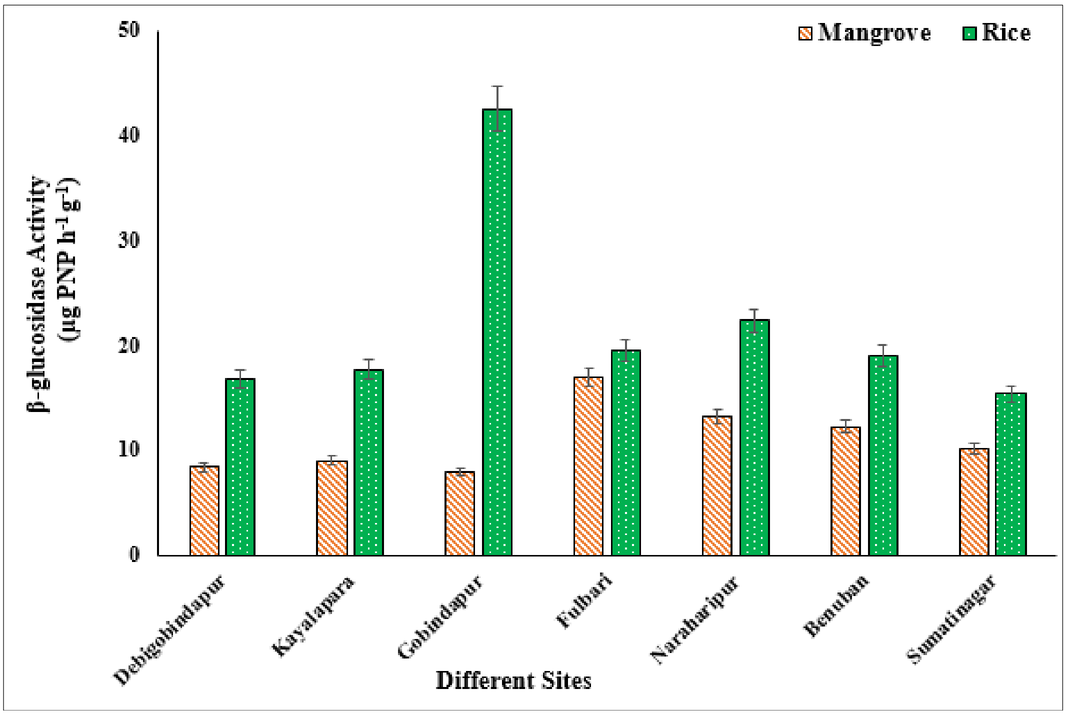
| Ecology | Depth (cm) | Debigobindapur | Kayalapara | Gobindapur | Fulbari | Naraharipur | Benuban | Sumatinagar | Mean of sites |
|---|---|---|---|---|---|---|---|---|---|
| Mangrove | 0-15 | 12.98 | 11.20 | 10.72 | 19.85 | 19.36 | 15.94 | 12.46 | 14.64 |
| | 15-30 | 8.44 | 8.36 | 9.28 | 19.53 | 11.22 | 12.93 | 10.53 | 11.47 |
| | 30-45 | 3.72 | 7.42 | 3.88 | 11.67 | 8.97 | 7.86 | 7.34 | 7.26 |
| | Mean | 8.38 | 8.99 | 7.96 | 17.01 | 13.18 | 12.24 | 10.11 | 11.12 |
| Rice | 0-15 | 22.80 | 20.68 | 61.05 | 29.35 | 31.98 | 35.62 | 24.50 | 32.28 |
| | 15-30 | 14.83 | 18.16 | 39.26 | 21.59 | 19.06 | 14.28 | 11.28 | 19.78 |
| | 30-45 | 12.79 | 14.22 | 27.29 | 7.50 | 15.92 | 7.12 | 10.41 | 13.61 |
| | Mean | 16.80 | 17.69 | 42.53 | 19.48 | 22.32 | 19.00 | 15.40 | 21.89 |
| | Mean of depth (0-15) | 17.89 | 15.94 | 35.89 | 24.60 | 25.67 | 25.78 | 18.48 | 23.46 |
| | Mean of depth (15-30) | 11.63 | 13.26 | 24.27 | 20.56 | 15.14 | 13.60 | 10.91 | 15.62 |
| | Mean of depth (30-45) | 8.25 | 10.82 | 15.58 | 9.58 | 12.44 | 7.49 | 8.87 | 10.43 |
| | Grand mean | 12.59 | 13.34 | 25.25 | 18.25 | 17.75 | 15.62 | 12.75 | |
| **ANOVA Statistics ($p \leq 0.05$)** | | | | | | | | | |
| Factors | | S | E | S×E | D | S×D | E×D | S×E×D | |
| C.D. | | 0.951 | 0.508 | 1.345 | 0.623 | 1.647 | 0.881 | 2.33 | |
| SE (m) | | 0.333 | 0.178 | 0.471 | 0.218 | 0.577 | 0.308 | 0.816 | |

[pNP= p-nitrophenol]




**[Note:** C.D. value: S= 9.537; E= 5.098; S×E= 13.488]

**Fig 7:** Average dehydrogenase activity in mangrove and rice ecology at seven different sites of Sagar Island, Sundarban, India.




**[Note:** C.D. value: S= 0.951; E= 0.508; S×E= 1.345]

**Fig 8:** Average β-glucosidase activity in mangrove and rice ecology at seven different sites of Sagar Island, Sundarban, India.

**Discussion**

Soil microbial population and their activities are primarily regulated by salinity, pH, temperature and dissolved oxygen concentration in both mangroves and rice system (Lv *et al.*, 2016; Padhy *et al.*, 2020) [11, 14]. In study, both system (degraded mangrove and rice) had incomparable soil physico-chemical properties (pH, electrical conductivity (EC) and salinity). pH, EC and salinity were higher in the mangroves systems than that of rice systems. Factors which affect the pH, EC and salinity are a tidal disturbance, anthropogenic activity, sea-level rise, seasonal rainfall, etc. (Chowdhury *et al.*, 2019) [5]. Mangroves system is situated near the estuaries which carries saline water due to influence of sea. During high tide saline water intrudes to the mangrove systems resulting increase in pH, EC and salinity (Padhy *et al.*, 2022) [15]. SOC and the labile soil carbon pools act as a good indicator to analyze the C dynamics in the mangrove ecosystem (Tian *et al.*, 2013) [17]. The labile C pools also provide information related to the rate of GHGs emission and nutrient transformation in mangrove soils (Wohlfart *et al.*, 2012) [20]. It was found that SOC and labile carbon pools were more in the mangroves than adjacent rice ecologies. We found the labile carbon pools in mangrove systems were more than rice systems. Further, in the rice systems, SOC and labile C pools were more in the top soil layer than the sub-soils. However, in the mangroves, in some sites we found more SOC and labile C pools in sub-soil than of the top soil layers. In the mangroves, several factors like sea-level rise, tidal disturbance and seasonal precipitation create anaerobic conditions in the soil. Due to anaerobic conditions, the decomposition rate of organic matter by microbes decreases. Hence, the carbon sequestration potential of the soil increases (Padhy *et al.*, 2022) [15]. In our study, SOC was positively correlated with labile carbon pools and soil physico-chemical properties but negatively correlated with soil enzymatic activities. Labile carbon pools were negatively correlated with soil enzymatic activities but positively correlated with soil physico-chemical properties (Fig 9). Soil of mangroves have the higher retention capacity. Due to higher retention capacity, soil is rich with nutrients content. Enrichment of soil nutrients promote the mangrove trees and plants to grow roots and shoots (Manoj *et al*,. 2024) [13]. It has been found that C- sequestration potential of mangrove is 50 times higher than tropical terrestrial forest. This is because of higher under- ground biomass production and storage of considerable amount of organic carbon in mangrove sediments. Data states that mangroves store higher amount of OC in the soil whereas tropical forests accumulate maximum part of OC in the trunks and branches (Macintosh *et al.*, 2012) [12]. Soil enzyme activities provide information about the functions of microbes and their activities in the soil (Bhattacharyya *et al.*, 2013) [2]. Enzymatic activities were found higher in the rice system than mangroves system in our study. The soil samples were collected at the panicle initiation (most phonological active stage of rice) stage of rice. Hence, the enzymatic activities in the rice system were relatively higher. The soil enzymatic activities were negatively correlated with soil physico-chemical properties (Fig 9). The soil of the mangroves system had a less microbial population in comparison to the soil of the rice system due to more environmental stresses i.e., high salinity, pH, EC, tidal disturbance, etc. (Padhy *et al.*, 2021) [16]. Higher salinity inhibits the growth and development of microbes (Yoshie *et al.*, 2004; Seo *et al.*, 2008) [21, 22]. Soil microbial diversity and their activities are primarily regulated by salinity, pH, temperature and dissolved oxygen concentration, nutrient status, soil type and plant community associations (Ikenaga *et al.*, 2010; Padhy *et al.*, 2021) [8, 16].

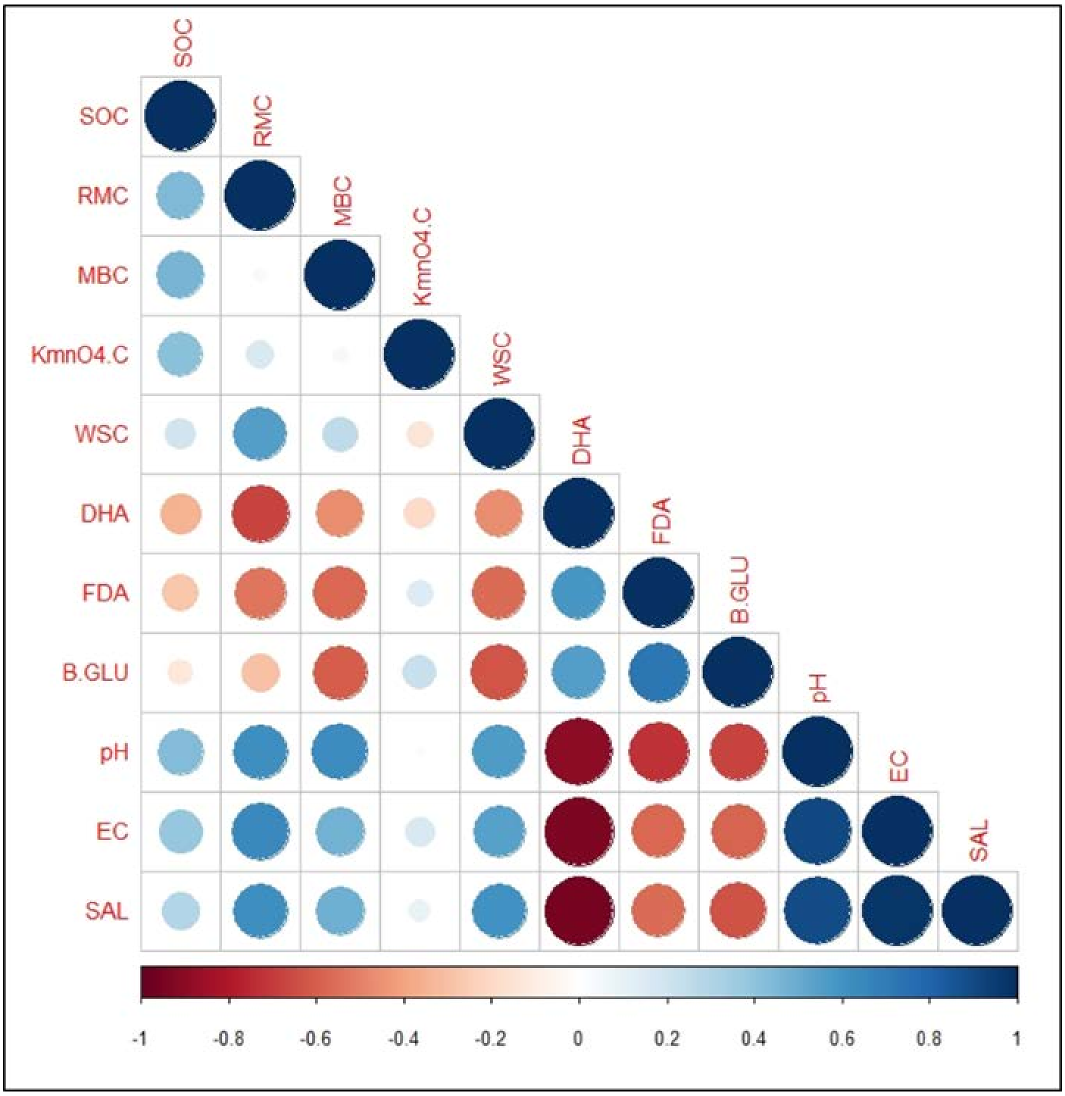



**Fig 9:** The Pearson correlation matrix among the labile carbon pools with soil physico-chemical properties and soil enzymatic activities.

## Conclusion

In the executed experiment we estimated the Soil physico-chemical properties, labile C pools (RMC, MBC, WSC and $KMnO_4$- C) along with soil enzymatic activities (FDA, DHA and β- GLU) in Sagar Island, Sundarban of India in mangrove and rice ecosystem. It was observed that labile C-pools were significantly higher in mangrove than rice ecosystem. Soil organic matters consist of two parts, the living part (consists of bacteria, fungi and insects) and non-living part (include dead plants and animals' additives). During decomposition, the living part attack on the non-living part of the soil organic matter (SOM) and transformed them (non-living part of SOM) into Carbon dioxide ($CO_2$), energy, water, plant nutrients and reunification of highly stable and complex organic matter (humus). In addition, soil enzymatic activity was significantly higher in rice than mangrove ecosystem. Negative correlation of soil enzymatic activity with soil labile- C pools and soil physico- chemical properties indicates that microbial activity influences the carbon sequestration. Soil physico- chemical properties, temperature and dissolved oxygen concentration regulate the growth and activities of microbes. It was observed that in the mangrove ecosystem- sea- level rise, tidal disturbance and seasonal precipitation create anaerobic condition in the soil which decreases the decomposition activity of the microbes. Due to decrement in decomposition rate of SOM in mangrove ecosystem, it has higher carbon sequestration potential. All three factors (ecology, site and depth) had the significant impact on the C- sequestration. The interrelationship of microbial activity with SOM decomposition in the ecosystem need to be understand in order to know the carbon sequestration potential.

## References

1. Adam G, Duncan H. Development of a sensitive and rapid method for the measurement of total microbial activity using fluorescein diacetate (FDA) in a range of soils. Soil Biol Biochem. 2001;33(7-8):943-951.
2. Bhattacharyya P, Roy KS, Neogi S, Dash PK, Nayak AK, Mohanty S, *et al.* Impact of elevated CO2 and temperature on soil C and N dynamics in relation to CH4 and N2O emissions from tropical flooded rice (*Oryza sativa* L.). *Sci Total Environ*. 2013;461:601-611.
3. Blair GJ, Lefroy RD, Lisle L. Soil carbon fractions based on their degree of oxidation, and the development of a carbon management index for agricultural systems. Aust J Agric Res. 1995;46(7):1459-1466.
4. Casida Jr LE, Klein DA, Santoro T. Soil dehydrogenase activity. Soil Sci. 1964;98(6):371-376.
5. Chowdhury R, Sutradhar T, Begam MM, Mukherjee C, Chatterjee K, Basak SK, *et al.* Effects of nutrient limitation, salinity increase, and associated stressors on mangrove forest cover, structure, and zonation across Indian Sundarbans. Hydrobiologia. 2019;842(1):191-217.
6. Eivazi F, Tabatabai MA. Glucosidases and galactosidases in soils. Soil Biol Biochem. 1988;20(5):601-606.
7. Haynes RJ, Swift RS. Stability of soil aggregates in relation to organic constituents and soil water content. J Soil Sci. 1990;41(1):73-83.
8. Ikenaga M, Guevara R, Dean AL, Pisani C, Boyer JN. Changes in community structure of sediment bacteria along the Florida coastal Everglades marsh-mangrove-seagrass salinity gradient. Microb Ecol. 2010;59(2):284-295.
9. Inubushi K, Brookes PC, Jenkinson DS. Soil microbial biomass C, N and ninhydrin-N in aerobic and anaerobic soils measured by the fumigation-extraction method. Soil Biol Biochem. 1991;23(8):737-741.
10. Kathiresan K. Mangroves: types and importance. Mangroves: Ecol Biodivers Manage. 2021;1-31.
11. Lv X, Ma B, Yu J, Chang SX, Xu J, Li Y, *et al.* Bacterial community structure and function shift along a successional series of tidal flats in the Yellow River Delta. Sci Rep. 2016;6(1):1-10.
12. Macintosh DJ, Mahindapala R, Markopoulos M, editors. Sharing lessons on mangrove restoration. Mangroves for the Future; Bangkok, Thailand: IUCN; 2012.
13. Manoj K, Arumugam T, Prakash A. A comparative study on carbon sequestration potential of disturbed and undisturbed mangrove ecosystems in Kannur district, Kerala, South India. Results Eng. 2024;21:101716.
14. Padhy SR, Bhattacharyya P, Nayak AK, Dash PK, Roy KS, Baig MJ, *et al.* Key metabolic pathways of sulfur metabolism and bacterial diversity under elevated CO2 and temperature in lowland rice: a metagenomic approach. Geomicrobiol J. 2020;37(1):13-21.
15. Padhy SR, Bhattacharyya P, Dash PK, Nayak SK, Parida SP, Baig MJ, *et al.* Elucidation of dominant energy metabolic pathways of methane, sulphur and nitrogen in respect to mangrove-degradation for climate change mitigation. J Environ Manage. 2022;303:114151.
16. Padhy SR, Bhattacharyya P, Nayak SK, Dash PK, Mohapatra T. A unique bacterial and archaeal diversity make mangrove a green production system compared to rice in wetland ecology: a metagenomic approach. *Sci Total Environ*. 2021;146713.
17. Tian J, Pausch J, Fan M, Li X, Tang Q, Kuzyakov Y. Allocation and dynamics of assimilated carbon in rice-soil system depending on water management. Plant Soil. 2013;363:273-85.
18. Vance ED, Brookes PC, Jenkinson DS. An extraction method for measuring soil microbial biomass C. Soil Biol Biochem. 1987;19(6):703-707.
19. Walkley A, Black IA. An examination of the Degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. Soil Sci. 1934;37(1):29-38.
20. Wohlfart T, Exbrayat JF, Schelde K, Christen B, Dalgaard T, Frede HG, *et al.* Spatial distribution of soils determines export of nitrogen and dissolved organic carbon from an intensively managed agricultural landscape. Biogeosciences. 2012;9(11):4513-4525.
21. Yoshie S, Noda N, Tsuneda S, Hirata A, Inamori Y. Salinity decreases nitrite reductase gene diversity in denitrifying bacteria of wastewater treatment systems. Appl Environ Microbiol. 2004;70(5):3152-3157.
22. Seo DC, Yu K, Delaune RD. Influence of salinity level on sediment denitrification in a Louisiana estuary receiving diverted Mississippi River water. Arch Agron Soil Sci. 2008;54(3):249-257.
23. Khatoon M, Shah KU, Din FU, Shah SU, Rehman AU, Dilawar N, *et al*. Proniosomes derived niosomes: recent advancements in drug delivery and targeting. Drug delivery. 2017 Nov 1;24(2):56-69.