DOI: https://doi.org/10.36094/sc.v91.2025.Revitalising_the_Ganges_Unlocking_Carbon.Das_Ghosh.444

ARTICLE

Sci. and Cult. 91 (7–8) : 444-449 (2025)

REVITALISING THE GANGES: UNLOCKING CARBON SEQUESTRATION POTENTIAL

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The present study was conducted in the middle and lower stretches of the river Ganga to monitor carbon accumulation in soil and water from 2023 to 2024. Besides the carbon content of soil and water, we have also examined some of the environmental variables that drives the carbon accumulation in rivers. In the present investigation, various water quality parameters, including dissolved oxygen, pH, free carbon dioxide, total alkalinity, total phosphate, and nitrate, were examined. The carbon accumulation in the different sites, which varied from 48.53 to 143.17 Mg C/ha in soil, were much higher than that in the corresponding upland sites. In water, total organic carbon (1.8-3.7mg/l) and total inorganic carbon (29.37-35.45mg/l) were varied. A positive correlation was also observed between silicate, water temperature, total phosphorus and the amount of C stored in the Ganga River.

Introduction

The global carbon cycle encompasses a complex network of reservoirs and fluxes that govern the distribution and exchange of carbon among the atmosphere, biosphere, hydrosphere, and lithosphere. In this context, the carbon sequestration process of capturing and long-term storing atmospheric carbon dioxide (CO_2) emerges as a vital climate regulation mechanism, especially amidst escalating anthropogenic emissions. While terrestrial forests and oceans are traditionally recognized as principal carbon sinks, freshwater systems, particularly riverine networks, have recently been acknowledged as significant yet under appreciated actors in the carbon cycle[1].

The river Ganga is one of the largest fluvial systems in the world, originating from the Gangotri Glacier in the Himalayas and traversing the northern Indian subcontinent before discharging into the Bay of Bengal[2]. It spans a basin area of over 1 million square kilometres, encompassing 11 Indian states and supporting the livelihoods of more than 500 million people. The basin is characterized by a wide range of geomorphological and climatic conditions, from glacial highlands and forested mid-hills to floodplains and deltaic wetlands. The major tributaries of Ganga contributed significantly to its hydrological and sediment regime, collectively influencing biogeochemical cycling of carbon within the system[3].

Carbon in river systems exists in various forms, including dissolved inorganic carbon (DIC), dissolved organic carbon (DOC), particulate organic carbon (POC), and gaseous CO_2[4]. These forms are subject to multiple physical, chemical, and biological processes, such as weathering, photosynthesis, microbial degradation, flocculation, sedimentation, and outgassing. The net balance between carbon inputs, transformation, and losses determines whether a river system acts as a net carbon sink or source. In the case of the Ganga River, the interplay of natural processes and intense anthropogenic pressures, including land use change, deforestation, agricultural intensification, dam construction, urbanization, and industrial discharge, creates a dynamic and spatially heterogeneous carbon landscape. The Ganga River system is a significant source of CO_2 emissions to the

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atmosphere, primarily due to the mineralization of organic carbon in the water column and sediments. However, total organic carbon content in the Ganges River System was reportedly found lower than Brahmaputra River System[5]. Numerous studies have reported supersaturation of CO_2 in tropical and subtropical rivers[6]. In urban stretches of the Ganga, untreated sewage and industrial waste introduce labile organic compounds, enhancing microbial degradation and promoting CO_2 evasion. From the literature survey, it was found that there are very few research conducted on the carbon storage or sequestration potential of the Ganga River. Hence, the present study aims to investigate the carbon accumulation in soil and water of the Ganga River to find their C sequestration potential, in comparison with the reference upland sites, and also to identify the strategies to enhance riverine carbon sequestration through ecosystem-based management.

Materials and Methods

To conduct the present study, eight sampling sites viz.,Farakka, Jangipur, Berhampore, Balagarh, Tribeni, Godakhali, Diamond Harbour, and Fraserganj (Fig.1) situated along the lower and estuarine stretches of the Ganga River covering a total of ~500 km length were selected and the sampling was carried out for a period of one year (2023-2024). Sample was collected in triplicate seasonally covering premonsoon (February–May), monsoon (June–September) and post-monsoon (October–January).

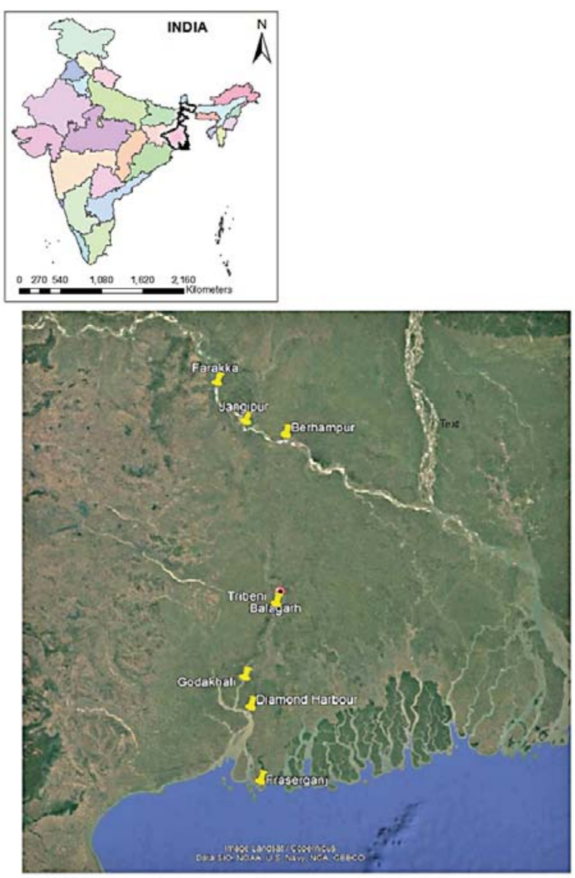

Fig.1 Study area map

Physico-chemical properties of water were analysed by employing standard procedures in Table 1.

Table 1. Physico-chemical properties of water by the standard procedure

Parameters	Methods (References)
Water temperature, pH, electrical conductivity (EC), and total dissolved solids (TDS)	Eutech Instruments, Multi-Parameter PCSTestrTM35
Dissolved oxygen (DO)	Winkler (1998)[7]
Water transparency	Secchi disc (Strickland and Parsons, 1972)[8]
Water depth	Depth sounder
Free CO_2, alkalinity, and hardness	(APHA, 2017)[9]
Gross Primary Production (GPP)	Light and dark bottle technique, Winkler method (Vollenweider, 1969)[10]
Total inorganic and Total organic carbon in water	M/s OI Analytical Instrument

Soil samples were taken from river sites as well as the corresponding reference upland sites. A stainless-steel ring core sampler was used to gather undisturbed soil samples. The samples were air-dried, crushed, and sieved through a 10-mesh sieve. The gravimetric approach measured moisture, and the core approach measured bulk density. Hydrometer-based particle size analysis was done. Soil pH and electrical conductivity (EC) were monitored using pH and conductivity meters. Nelson & Sommers[11] assessed soil carbon content using dry combustion at 900°C. Using an NDIR system in the TIC-TOC Analyser (Model Aurora 1030) CO_2 was measured during combustion in an oxygen stream with catalytic materials (Pt, Zr). Soil nitrogen was measured using the Kjeldahl technique[12], whereas phosphorus was analysed using $HClO_2$ digestion and molybdenum blue colorimetry[13].

Standard formulas for soil carbon estimation:

C (Mg/ha) = C content (%) * BD (g/cm^3) * depth (cm)

Where Mg = Megagram, ha = Hectare, BD = Bulk Density

The statistical analysis was computed by using MS Excel.

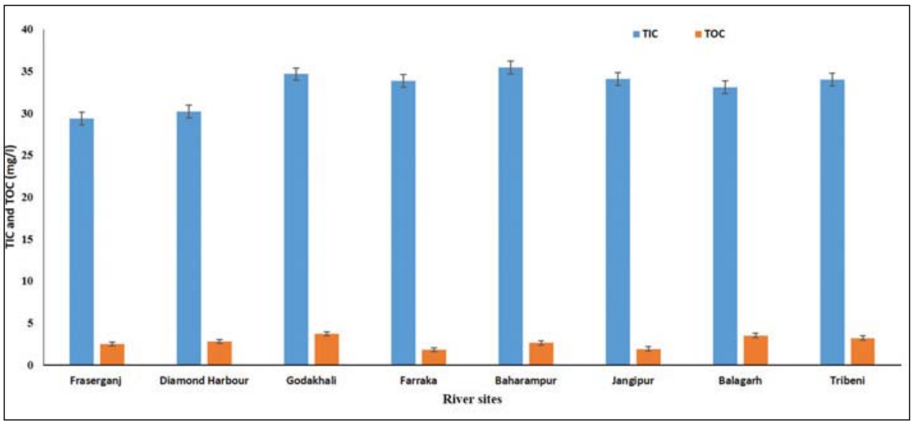

Fig.2 Variation in TIC and TOC in different sites of the River Ganga

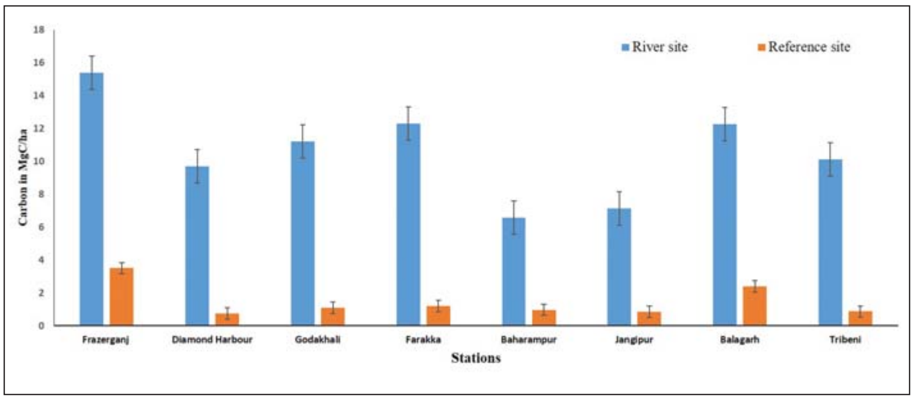

Fig.3 Accumulation of Carbon in the river and reference soil

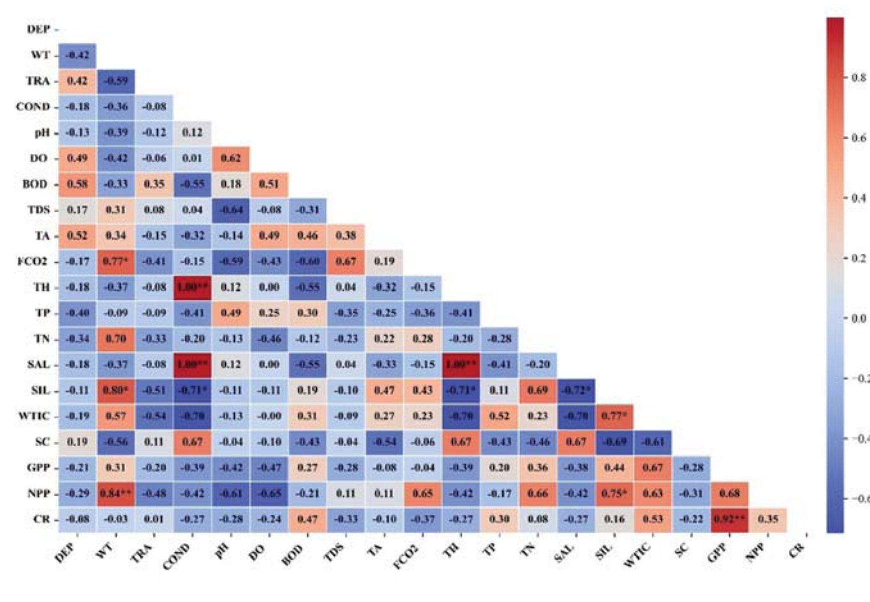

Fig.4 Relation between water physico-chemical parameters and Soil and water Carbon

Note: DEP: Depth; WT: Water temperature; TRA: Transparency; COND: Electical Conductivity; pH: pH; DO: Dissolved Oxygen: TDS: Total Dissolved Solids; TA: Total Alkalinity; FCO2: Free CO2; TH: Total Hardness; TP: Total Phosphorus; TN: Total Nitrogen; SAL: Salinity; SIL: Silicate; WTIC: Water Total Inorganic Carbon; SC: Soil Carbon; GPP: Gross Primary Production; NPP: Net Primary Production; CR: Community respiration

Result

Physico-chemical Parameter of Water: From the river Ganga, different sites of water quality parameters were measured, including pH, specific conductivity, dissolved oxygen, depth, transparency, total alkalinity, and total hardness. During the entire sampling period, the highest water temperature of 33.3±0.35°Cwas observed in Jangipur, and the lowest of 29.43±1.25°C was recorded in Diamond Harbour. The average depth of the studied stretch of the Ganga River system was 9.72±0.82 m. The highest and lowest average depths were observed at 18.36±2.66 m and 4.75±1.70 m, respectively, at Farakka and Balagarh. The transparency was in the range of 151.7- 2.86 cm. The pH of the water shows it to be alkaline in all the sites (7.34-8.73). Dissolved oxygen was highest in Farakka (7.33±2.10mg/l) and lowest in Jangipur (5.86±0.78mg/l). Total alkalinity was in the range of 93.33-117.66 mg/l, and total hardness was highest in Frazerganj, 4801.66±124.10 mg/l, and lowest in Balagarh, 89.33±47.25 mg/l (Table 2).

Sediment Quality Parameters

Soil pH was in the range of 7.93-8.98 is neutral to alkaline in nature, in all the 8 sites of the river Ganga. Electrical conductivity was much higher in Fraserganj (491.1±165.23µS/cm) and lowest in Godakhali (187±31.10 µS/cm). Total nitrogen content in soils was highest in Jangipur (0.22±0.05) and slightly lower in Diamond Harbour and Fraserganj (0.005±0.01). Total phosphorus and total nitrogen

Table 2. . Physico-chemical parameters of water recorded in selected sites of the river Ganga

Sites	Farakka	Jangipur	Berhampur	Balagarh	Tribeni	Godakhali	Diamond Harbour	Frazerganj
Water temp (°C)	30.4±0.29	33.3±0.82	31.23±0.62	31±0.74	32.87±0.45	30.07±0.62	29.3±0.16	29.67±0.47
Depth (m)	18.37±0.12	6.43±0.25	6.3±0.45	4.7±0.36	11±0.82	11±0.82	16.1±0.22	8.1±0.29
Transparency (cm)	9.52±0.12	7.03±0.31	2.87±0.21	41.66±0.21	30.67±0.12	73±0.21	151.7±2.31	34±0.8
Sp. Cond. (mS/cm)	0.27±0	0.24±0.02	0.27±0.01	0.21±0.03	0.23±0.03	0.17±0	0.21±0	24.4±0.45
pH	8.41±0.02	8.07±0.02	8.73±0.57	8.46±0.27	7.34±0.23	7.73±0.32	8.3±0.02	8.3±0.14
DO (mg/l)	7.33±0.25	4.33±0.24	7.3±0.74	4.4±0.12	4.7±0.16	4.57±0.29	6.27±0.17	5.57±0.29
TDS (g/l)	0.12±0.01	0.11±0.01	0.19±0.08	0.07±0.04	0.65±0.03	0.11±0.01	0.27±0.17	0.22±0.11
Total Alkalinity (mg/l)	117.67±1.25	115±1.7	114±0.47	93.33±0.82	115.67±1.41	103.33±0.94	113±2.94	102.33±2.62
Free CO_2 (mg/l)	4±0.56	6.1±0.21	2.1±0.5	5.6±0.51	12±0.11	1.03±0.33	1±0.05	3±0.05
Total Hardness (mg/l)	101±2.94	93±1.25	93.33±0.82	90±0.47	103.67±3.68	89.33±1.7	97.33±1.7	4801.67±3.86
Total Phosphorus (mg/l)	0.08±0.01	0.08±0.02	0.15±0.01	0.13±0.03	0.08±0.01	0.11±0.01	0.09±0.01	0.07±0.02
Total Nitrogen (mg/l)	0.03±0.001	0.23±0.01	0.02±0.001	0.04±0.002	0.03±0.001	0.02±0.004	0.02±0.001	0.02±0.0001
Salinity (ppm)	0.03±0.001	0.02±0.004	0.02±0.005	0.03±0.004	0.03±0.001	0.02±0.004	0.08±0.01	24.95±0.05

*Average±SD

were highest in Godakhali (390.88±91.22 mg/l), (0.18±0.05 mg/l) and lowest in Jangipur (96.42±25.31 mg/l), (4.03±0.78 mg/l). The bulk density (BD) in the river site was lower in Balagarh (0.12 g/cc) and higher in Baharampur (0.64 g/cc). About upland soil, the BD was lower in Baharampur (0.94 g/cc) and higher in Godakhali (1.65 g/cc).The BD of all the reference upland soils was higher than the BD of the river.

Carbon in Water

The Total Inorganic Carbon (TIC) levels across various sites along the River Ganga exhibit a noticeable range, reflecting the variability in water chemistry. Sites like Godakhali and Farakka have the highest TIC concentrations, with values of 34.64 mg/l and 33.87 mg/l, respectively, suggesting relatively higher inorganic carbon in these areas. On the other hand, Jangipur has the lowest TIC concentration at 34.06 mg/l, although still comparable to other sites (Fig.2). Total organic carbon (TOC) in the range of 1.8-3.7mg/l in the River Ganga.

Carbon in Soil

It was estimated that 15.4 MgC/ha in Frazerganj, 12.25 MgC/ha in Balagarh, 12.3 MgC/ha in Farraka, 11.2 MgC/ha in Godakhali, 10.11 MgC/ha in Tribeni, 9.7 MgC/ha in Diamond Harbour, 7.13 MgC/ha in Jangipur and 6.57 MgC/ha in Baharampur respectively. On the other hand, the reference sites of carbon are 3.5 MgC/ha in Fraseganj, 2.4 MgC/ha in Balagarh, 1.2 MgC/ha in Farakka, 1.1 MgC/ha in Godakhali, 0.97 MgC/ha in Baharampur, 0.84 MgC/ha in Jangipur, 0.87 mgC/ha in Tribeni, 0.75 mgC/ha in Diamond Harbour (Fig.3). The analysis of carbon accumulation in different sites of the reference sites shows that the upland site has lower carbon accumulation than the river site.

Statistical analysis: The Pearson correlation analysis revealed significant relationships between water quality parameters and key ecosystem productivity indicators. Water Total Inorganic Carbon (WTIC) showed strong positive correlations with silicate (SIL) ($r = 0.77$, $p < 0.05$), water temperature (WT) ($r = 0.57$), and total phosphorus (TP) ($r = 0.52$). In contrast, it exhibited negative correlations with Electrical conductivity (COND) ($r = -0.70$), total hardness (TH) ($r = -0.70$), salinity (SAL)($r = -0.70$), and transparency (TRA) ($r = -0.54$). Soil Carbon (SC) correlated positively with conductivity (COND)($r = 0.67$), total hardness (TH) ($r = 0.67$), and salinity (SAL) ($r = 0.67$), emphasizing the role of dissolved minerals in soil conductivity. However, SC was negatively correlated with silicate (SIL) ($r = -0.69$) and total alkalinity (TA) ($r = -0.54$), suggesting an inverse relationship between soil carbon accumulation and silicate deposition. Gross Primary Production (GPP) showed a strong positive correlation with WTIC (r = 0.67) and moderate correlations with silicate (SIL) (r = 0.44) and total nitrogen (TN) (r = 0.36), indicating that higher water temperature and carbon availability enhance productivity. Net Primary Production (NPP) had a significant positive correlation with water temperature (WT) (r = 0.84, $p < 0.05$) and silicate (SIL) (r = 0.75, $p < 0.05$), along with positive correlations with total nitrogen (TN) (r = 0.66) and free CO_2 (FCO) (r = 0.65), highlighting their influence on productivity. Recompression Coefficient (CR) exhibited a strong positive correlation with GPP (r = 0.92), reinforcing the link between carbon fixation and respiration rates (Fig.4). Additionally, CR correlated positively with WTIC (r = 0.53) and BOD (r = 0.47), suggesting that increased organic matter decomposition supports higher respiration.

Discussion

The Ganges River has been considered one of the world's holiest and most sacred rivers. An essential component of evaluating water resources is determining the quality of river water. Millions of people depend on the examined section of the Ganga for their livelihood, and it is widely acknowledged for its ecological diversity[14]. In the present study, found highest air temperature of 33.3±0.35°C was found in Jangipur, and the lowest of 29.43±1.25°C in Diamond Harbour. Total solids were observed maximum of 0.22 ± 0.11 mg/l and a minimum value was noticed as 0.07 ± 0.01 mg/l. A similar observation was found by Badola and Singh[15] in various rivers. pH was observed to be the highest, 8.73 ± 0.03, and the minimum value was noticed as 7.34 ± 0.05. Dissolved oxygen showed the value 7.33 ± 0.25 mg/l, while the lowest value was observed to be 4.33 ± 0.24 mg/l. Khaiwal[16] and Khanna[17] noted a similar thing in the river Yamuna and in the river Ganga, respectively. Some areas had higher levels of turbidity, COD, total alkalinity and total hardness, phosphate, and nitrate due to agricultural runoff, organic matter in the water, nutrient addition, and domestic sewage pollution[18,19]. In the riverbed, of sediment concentration of TOC and iron showed increasing trends on the spatio-temporal scales. The sediment TOC showed a positive correlation with Fe (R2 = 0.93, $p < .001$) whereas in the present study soil Carbon correlated positively with conductivity (r =0.67), total hardness (r = 0.67), and salinity (r = 0.67), emphasizing the role of dissolved minerals in soil conductivity. A portion of the DOC in the river settles as particulate organic carbon (POC) and builds up in the sediment, while another portion is transformed into dissolved inorganic carbon (DIC) and ultimately released into the atmosphere.

Carbon plays an important role in regulating the exchange of GHG to and from the atmosphere and thus influences the global carbon and nitrogen cycle. There are two important kinds of dissolved carbon found in river water- DOC and DIC. In the present study, the Ganga River total inorganic carbon is in the range of (29.37-35.45 mg/l). Khan and Tian[20] reported that in the Ramganga River, the concentration of DIC ranges between 9.6-36.6 and 4.6-42.36 mg/l). According to Sun[21] for most rivers, bicarbonate is the dominant form of DIC, primarily from chemical weathering of silicates and carbonates in the drainage basin. The DIC concentrations in the Hooghly River are higher than the DIC concentrations in other large rivers like the Amazon[22], the Mississippi[23], the Pearl[24]. In the present findings, soil carbon analysis shows a wide variation in-site-wise, from 6.57 to 15.4 Mg C/m^3, whereas various studies observed the carbon dioxide flux in the river. The current study reveals considerable spatial variability in soil carbon accumulation across different sites in the region, ranging from 6.57 MgC/ha in Baharampur to a maximum of 15.4 MgC/ha in Frazerganj. These differences likely reflect variations in land use, vegetation cover, hydrological connectivity, and sediment deposition patterns across the study sites. In comparison to reference sites, which exhibited significantly lower values (ranging from 0.75 to 3.5 MgC/ha), the measured sites demonstrated notably higher carbon accumulation. This contrast clearly suggests that riverine and associated floodplain ecosystems have a higher potential for soil organic carbon (SOC) sequestration than adjacent upland or reference sites. The site-specific results indicate that Frazerganj, Balagarh, and Farraka are hotspots for carbon accumulation. These areas, characterized by proximity to active fluvial systems and possibly greater allochthonous input, tend to accumulate more organic carbon[25]. Frazerganj, with the highest observed carbon accumulation (15.4 MgC/ha), also showed a high reference value (3.5 MgC/ha), suggesting persistent deposition and accumulation processes at work. For instance, Singh and Pandey[26] reported sediment organic carbon storage ranging from 0.61 to 0.68 tonnes OC ha^{-1} at the Chunar site and 1.67 to 1.82 tonnes OC ha^{-1} at the Rajghat site along the Ganga River. These values support the assertion that fluvial systems can serve as significant carbon sinks, particularly in sediment-rich zones. The total organic carbon (TOC) storage reported as 10.32 Gg, based on river length, further reinforces the river's role in carbon cycling at regional scales.

Conclusion

The River Ganga represents a critical frontier in the study of carbon sequestration in large river systems. Given their ecological complexity, socio-economic importance, and vulnerability to environmental change, a comprehensive understanding of carbon cycling in the Ganga basin is imperative. This variation in carbon suggests that factors such as location, soil composition, and local environmental conditions significantly influence the soil carbon content. The findings can inform future studies on soil health and carbon dynamics, especially about climate change mitigation efforts is necessary. The conservation of rivers, their sustainable use as natural habitats, the restoration of degraded, polluted rivers, the controlled harvesting of peat, and other scientifically based land and water management practices should thus be strongly supported by policy. These actions could help counteract the loss of carbon from the land surface caused by greenhouse gas emissions and global warming.

Acknowledgement

The authors express their sincere gratitude to the National Mission for Clean Ganga, Ministry of Jal Shakti, Government of India, for generously funding the experiments conducted in this study. They also extend their thanks to the ICAR-Central Inland Fisheries Research Institute for offering comprehensive research support and facilities. ❐

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