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Carbon Sequestration in Low Land Paddy Soils: Effect of Certain Cultural and Nutrient Management Practices: A Review

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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Review Article

ABSTRACT

Carbon(C) is the only key to running in this worldly life and without carbon, nothing can be ensured, but the amount and form of C in different spheres of the earth make numerous changes. Changes in the carbon levels cause the lives of all living things. Soil carbon flux directly or indirectly affects the global climate and thus agriculture productivity. To ensuring the human rations, protection is

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intended for the rising populace worldwide, where the critical challenges in the agriculture sector are inevitable. Improved soil and nutrient supervisions and cultural practices are very imperative to tackling these troubles. Augmenting the productivity of various agro-ecosystems, soil productiveness, and carbon accretion via certain approaches become a must concern towards sustainable food production. “Paddy soils form the huge area of artificial swamplands on the earth, and serves as food basket for the world population also responsible for sequestering soil organic carbon potentially”. Rice accounts for around 9-10 % of the total cropland area globally, and their environmental conditions are responsible for storing organic carbon in soil, methane (CH_4) production, and emit nitrous oxide (N_2O) in meager amount. The present review signifies the present and future potential agricultural management practices, particularly soil and plant nutrition and their effects on soil organic carbon storage (SOCS) and carbon sequestration (CS) by paddies grown under submerged conditions compared to other crops. Increasing carbon inputs and reducing SOC losses in low land paddy soils need attention as its concern with GHGs that implies direct causes of global climate. As future direction, life-cycle assessments of certain practices in low land paddy soils helps in assessing the carbon footprints and sustaining the crop productivity consequently mitigating climate change. With this view, this review study was taken to the life of carbon in the terrestrial ecosystem and its accumulation in low land paddy soils moderated by cultural and nutrient management practices adapted for rice production in low lands.

Keywords: Carbon sequestration; greenhouse gases; life cycle assessment; low land paddy soils; nutrient management; soil carbon pools.

1. INTRODUCTION

The agricultural network supplies food and also remarkably carries carbon (C) in all nutrient element cycles naturally especially carbon and nitrogen. The agricultural production system (APS) produce greenhouse gases (GHGs) i.e. gases containing no $CO_{2,}$ and APS alone accounts roughly 50 % of manmade emissions of GHGs [1]. Global agricultural ecosystems (GAES) alone emits methane around 3.22×10^6 Gg CO_2-eq yr^{-1} [2]. In an agricultural ecosystem(AES), paddy fields are being vital parts and their potential harvest area accounts for more than 20 % of the entire area of cereal crop farming all-inclusive of global total (FAO, 2020). Since, long-drawn-out floodwater supervision, the soil has been kept in reduced condition (anaerobic) in rice growing periods that affords approving circumstances for methanogenesis. Rice paddies alone have the credit of 16 -18 % methane when accounting emissions from agricultural sources (FAO, 2020). Further, the inevitable challenge for the food producers in the future will be to convene the demand of increasing the global population's basic livelihoods (food, water fuel, energy, etc.). As soils are the heart of regulating the global carbon, water, and nutrient cycles also act as a sink for all these three keys of the natural ecosystem [3] (Global Carbon Project, 2018). Among these three cycles, carbon plays a major role in deciding the other two via climatic disturbances (CDs). CDs directly or indirectly affect terrestrial carbon accumulation (TCA).TCA is decided by natural (soil and climatic) and artificial (manmade) circumstances. But, the world's soils are tired of producing more and more with green revolutionary fertilizer strategies and degraded the soils to very poor soil health status. Organic matter is the vital factor that upholds the soil health sustainably. Currently, employing more fertilizers and inadequate application of manures in agricultural crop production systems brought the soils with low organic carbon content thus soil health index is drastically reduced. Implementation of diverse farming systems might have either positive or negative effects on addition of carbon by influencing the amount as well as nature of crude or processed organic materials added to soil and pace of decomposition. Although using high nutrient responsive crop varieties and increased use of chemicals fertilizers tied with better irrigation amenities, the production and productivity of crops increased significantly.

On the other hand, yield of crop may either idle or rundown due to the destitute use efficiency of sources, nutrient removal, and soil deprivation. Stumpy soil organic carbon content of cultivated / cropped soils (0.1 to 0.5%) and quality of carbon is the prime cause of turn downing the soil quality and crop productivity. Though, the labile carbon pool entails straight brunt on nutrient supply as well as crop yields. A highly intractable or inert carbon pool contributes to the overall carbon stock, also productivity and quality of soil moderated by microbial actions [4];[5].Thus, nutrient management practices have to be premeditated in such a way as to transfer a considerable quantity of carbon pools from active to stable pools to augment the organic carbon content in the soil i.e. as per the soil continuum model (SCM) given by [6] Lehmann and Kleber (2015); progressive decomposition of organic matter by biotic resources playing a vital role C accumulation in soil via humic substances addition in different soil layers. There are several pieces of evidence indicated that various fractions of SOC play a key role in upholding the quality soil environment and crop yield [7]; agronomic practices are probably to contour carbon retention in soil by disrupting soil aggregates which provide an enhanced entree for the decomposers thus gradual reduction in soil organic carbon content [8,9]. Numerous lessons from research reports have indicated that “a strong positive relationship between the amount of carbon incorporated annually into the soil and soil organic carbon content” [10];[11];[12]. Hence, carbon management of a given crop production system provides information to indicate whether such a production system is a carbon restorative one or not; whether it is responsible for climate change and global warming via emitting CO_2 in the atmosphere.

In consequence, the perceptive of the soil organic carbon dynamics (SOCDys) and their fractions in various soil types needs to be understood to make them healthy and sustainable. Adoption of management practices like organic farming with the addition of natural green and brown sources, and other sources of nutrients returns a good amount of carbon to the soil that enhances carbon input in soils [13]. When organic amendments are added to the soil, a very small portion of them are stabilized against microbial attacks as soil organic carbon and then distributed into different carbon fractions. The real picture of overall sustainability in nutrient management practices (NMPs), however, continues to face many challenges. Globally, agricultural activities release approximately 78 Gt (78 $x10^{15}$g) C $year^{-1}$ by mineralizing soil organic matter [14]. For illustration, agricultural practices usually increases crop yields up to the harvest index remains steady and the system should balance the carbon inputs. But, agricultural practices (cultural and nutrient management) leading to the increased decomposition rate of soil organic carbon [15]; there by depleting the soil organic carbon drastically. Hence, amalgamating inorganic and organic nutrient sources for crop production might be a viable option for meeting both soil and crop productivity as well as to sustaining the soil health along with a shift in cultivation practices especially in paddy soils. Amongst cereals, rice is one of the most important crop grown globally and hence improving carbon storeroom in paddy fields is crucial under extenuating global warming situations [16]. The carbon storage and C sequestration potential of paddy soils is to be studied critically to get the exact carbon footprint. Consequently, while appeasing rice production, adoption of cultivation practices must increase the carbon pool quantum and reduce non-CO_2 gases emission will be a crucial measure to ensure and coping with global climate change. Previous research reports emphasized the impact of NMPs on carbon management in different cropping systems, but only scarce information on low land paddy soils (LLPS). In this article, we review literature on C depletion, C sequestration in terrestrial ecosystem and the effect of various cultural and nutrient management practices on carbon sequestration in low land paddy soils by detailing and discussing the aspects of cultural and NMPs to sequester carbon in the soil, CO_2 evolution, CH_4 evolution, and carbon dynamics in low land paddy soils (CarDy-LLPS) to enlightening the future nutrition management studies in rice crop both in low land and upland conditions to pave a new direction of carbon management through life cycle thinking (LCT) of resources to be used to mitigate climate change and global warming.

2. CARBON DEPLETION (CarDn) IN SOILS

Naturally soils have a sizeable mass of soil organic carbon i.e. global terrestrial organic C pool accounts for 2.27- 2.77 x 10^{15} kg of C in the top 3 m soil [17]. The extent and properties of organic carbon pool depend on the properties of soil, soil development processes, relief / topography, and other characteristics including climatic factors. Range of SOC pool in virgin soils or natural vegetation between 40 - 400 Mg C/ ha was reported by Post et al.,[18]; [19] USGCRP 2018 reported that a change SOC pools from -72 to 253 Pg. Shifting from natural ecosystem to agricultural system can quickly worn-out the soil organic carbon. The degree of depletion ranges from 50 – 75 % next 5 to 20 years after deforestation in tropical soils then temperate soil which take 25 - 50% over 20 - 50 years was reported by Lal, (2004a)[20].Perhaps global decrease in SOC of 5% in the upper 3 m would result in 117 Pg of C released into the atmosphere, causing an increase in the atmospheric C pool (829 pg in 2013) reported by Nave et al.(2018)[21]. Depletion rate may get elevated as inputs of carbon as well in certain administered ecosystems i.e. addition of organic materials may be lower than the outputs like mineralization, accelerated erosion, and leaching losses in sub soil too [22];[23]. Further, carbon depletion occurs in a higher level in structure-less soils certain areas (tropic and sup-tropics) of the world due to their unfair properties coupled with lesser biomass production. Rainfall and runoff erosivity get intensified with relief and topographic characteristics thus leading to depletion of soil organic carbon at a higher rate.

Whereas in agricultural systems, inputs and outputs are maintained in a balanced way results lower SOC depletion than practices where this balance is ignored. Organic carbon depletion in soils commonly higher under plow-based system of soil preparation than no-till system. As well as higher in systems where crop residues not returned to soil, and other bio-sources than mulching based system, and imbalanced casual use of organic amendments. The exhaustion of the soil organic carbon pool adversely influences the atmospheric CO_2 concentration [24];[25]. A relentless exhaustion of the SOC pool causes soil quality; unconstructive nutrient and water balance deteriorate further higher fatalities to soil by rigorous runoff, elevated soil evaporation, and decline soil biodiversity particularly earthworms. Deprived soil quality condenses the net prime output as a result the amount and quality of biomass returned to the soil get reduced and heighten the reduction of soil organic carbon pool. Soil organic matter (SOM) turnover and carbon depletion (CD) directed by CO_2 equivalent emission [26] and apposite management practices be able to improves the SOC [27];[28]. Thus, attention needs to curtail the carbon depletion to revive the different soil ecosystems of the global agro-climatic regions, especially in low land cropping systems by conserving more carbon in soil than atmosphere. Here, studying energetic of crop production systems helps to curtail soil carbon depletion and helps to increase accretion carbon in soil. This can be achieved through life cycle analysis of products that we wanted and it helps to identifying the best possible ways reducing carbon depletion in soils using climo-sequential and or chromo-sequential approaches in paddy soils of the world. Yet there are several limitations to assessments in broader scale such national and global assessment of C depletion in terrestrial ecosystems.

3. CARBON SEQUESTRATION (CS)

3.1 Terrestrial Carbon Capture (TCC)

Relocating CO_2 from atmosphere to terrestrial pool (carbon capture) in order to that CO_2 impounded is not instantly released atmospheric air. “Three predominant components of terrestrial C sequestration/capture include soil, biota, and biofuel” (Fig. 1). Soil organic carbon pool increment may be calculated to a depth of 2 meter owing to determine the changes in SOC pool induced by management practices [29]. Further increase in SOC pool can be identified either by fixed depth or equal soil mass basis in main land utilization and soil management systems. Changes brought by management practices may occur in labile, intermediate, or passive carbon fractions of the SOC pool. Variation in the labile fraction can occur in short phase; whereas in the intermediate and passive fractions may be take time with certain known soil carbon capture processes. Perfection in soil structure and stable micro-aggregates formation are the first-rate processes in terrestrial carbon capture (TCC)[30];[31];[32]. Micro-aggregate dynamics and stabilization of macro-aggregates received enduring effects from humic substances and other importunate composites [33] in that way encapsulating and protecting organic matter against microbial activity, clay content, and mineral compositions all have a strong contact on formation of soil aggregates [8];[9]. Additionally, the total soil organic carbon (TSOC) content increases by aggregate size growth [34;35] (Beare et al., 1994 a,b). Humification efficiency of biomass carbon (HuEBC) depends on certain factors like climatic conditions, properties of soil, tillage type, and available soil nutrients. HuEBC is always higher under cool and humid climates than warm and dry. In addition, humification efficiency(HuE) of clay soils higher than that of coarse textured soils and HuE strongly inclined by available nutrients since C is only one that build humus, the others elements being nitrogen(N), phosphorus(P), sulphur(S),zinc (Zn),copper(Cu) etc. Himes (1998) [36] reported that sequestration of 10 Mg of C in crop residue into 17.241 Mg of humus would require 28 Mg of C in 62 Mg of oven-dry residue and it would require 833 Kg N, 200 Kg P, and 143 Kg S. *Thus, humification of residue* *carbon cannot occur if essential nutrients such as N, P, & S become unavailable in soil*. The residual carbon conversion into soil organic carbon expected to be 14 – 16 % and 30-32 % without and with the application of fertilizer, respectively. SOC stocks through low residue applications similar to with and without fertilizer applications. Conversely, when the organic addition rate is high, additional SOC accumulation can be occurred only if additional fertilizer is applied to the soil. The rate fertilizer N application and placement have a significant impact on SOC sequestration rate (SOCSeqR) [37][38]. Illuviation and translocation of C into subsoil horizons is another important mechanism in SOC sequestration. Deep translocation, away from the zone of anthropogenic and climatic disturbances, it can occur as a result of bio-pedoturbation by earthworms [39], and termites, and profound development in root system [29]. Several factors augment SOC pool upon conversion to a restorative crop and land use and adoption of recommended management practices (RMPs).

In general, structurally-active or expansive soils have a higher SOCSeq capacity than structurally inert soils such as Kaolinitic clay, low surface area, low aggregation, etc. Soils formed on low slope or terrains that are less or not prone to erosion and make positive soil moisture and temperature regimes which sequester more SOC than soils of highly vulnerable to erosion. Land use is an important factor and on the whole, perennial land use practices causes less soil disturbance and adds higher biomass that enhances SOC pool more than seasonal crops, significantly. Ecosystems with high productivity, continuous ground cover and fewer disturbances have a high SOC pool and vice versa. Whereas, the low land paddy production system differs in sequestering carbon under anoxic and oxic conditions. Soil types also inclined the carbon accumulation in paddy fields unlike other crops or crop ecosystems. For instance low land paddies are able to convert approximately 30 -35 % atmospheric carbons and hydrogen as carbohydrates by photosynthesis which is more effective practice of carbon dioxide removal (CDR) than growing trees of equivalent area considered. Further, anoxic and or hypoxic conditions in LLPS altered through addition of nutrient elements through organic or inorganic fertilizers, regenerates the various biogeochemical cycles. Which in turn, enhances capture the above ground carbon more significantly by means of higher biomass productivity while comparing the unfertilized paddies. Hence, rice productivity flux assessment is required for each agro climatic zones according to blanket recommendation of fertilizers and sources used with respect to crop duration. Further, the biomass produced (carbon captured) and carbon evolved (methane) has to be calculated as carbon credit/foot print for assessing the effectiveness management practices on carbon flux in LLPS.

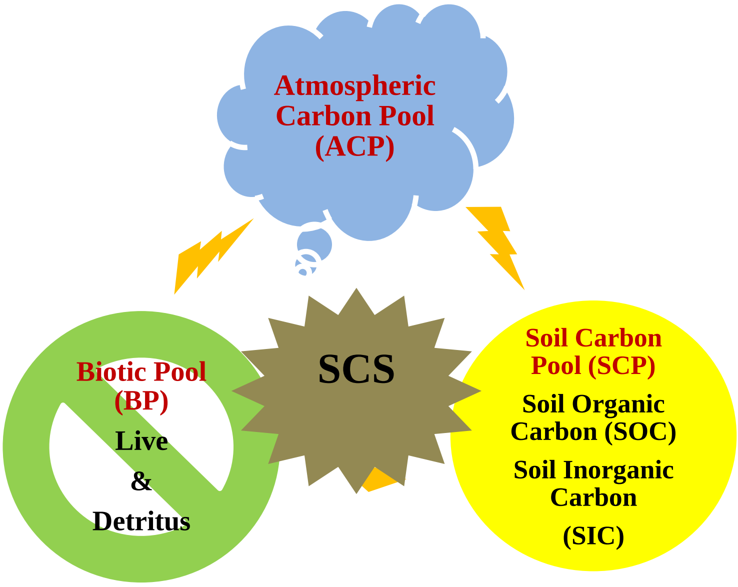

Fig. 1. A critical balance between atmospheric, soil, and biotic carbon pools [Soil Carbon Sequestration (SCS)]

3.2 Soil Inorganic Carbon Sequestration (SICS)

Soil inorganic carbon (SIC) pool is considered to be an inevitable part of carbon farming [40,41] (Schlesinger 1982, 1997), and the SIC pool typically encompasses carbonates. Pedogenic or derived carbonates development is an input mechanism of soil carbon sequestration. Monger (2002) [42] illustrated four mechanisms that forms derived or secondary carbonates: "(a) dissolution of existing carbonates in the upper layers, translocation onto the sub-soil, and re-precipitation with cations added from outside the ecosystem [43], (b) rise of Ca^{++} from shallow water table by capillarity and subsequent precipitation in the surface layer through reaction with carbonic acid formed through dissolution of CO_2 in soil air [44], (c) carbonate dissolution and re-precipitation in situ with the addition of cations from elsewhere [45], and (d) carbonate formation through the activity of soil organisms (e.g., termites and micro-organisms)" [46]; [47];[48]. In some soils, secondary carbonates forms at the depth of one meter or even deeper, particularly if dynamic organic matter deposit in the subsoil layers by plants with profound root system. The suspension of carbon-dioxide into carbonic acid amplifies by raise in easily decomposable biomass in the sub-soil either added from decaying roots or crop residues, compost, etc. In all the four processes stated previously, the cations (Ca^{+2}, Mg^{+2}) enter from outside the system through weathering of bedrock, fertilizer applications, irrigation, run-on water, dust deposition, and applications of organics. An enhanced microbial action is also vital to underpin these processes. Leaching of carbonates (CO_3) into the groundwater is a supplementary mechanism in SIC sequestration and it is very crucial when waters unsaturated with Ca $(HCO_3)_2$ are used for irrigation. This mechanism is extremely relevant to 275 M ha of irrigated cropland in arid and semi-arid regions of the world and 50 % of this area includes paddy lands. Adoption of certain management practices to enhance crop yields and reclaim salinized soils (e.g., use of gypsum, application of compost, biochar, and other wastes) accentuate the leaching of bio-carbonates, particularly if no carbonates are found in irrigation water. The use of lime to acidic soils is another important factor that needs to be addressed on SIC dynamics in agricultural soils. However, a sizeable fraction of dissolved lime on agricultural soils may be leached and re-sequestered by natural carbon cycle. West and McBride (2005)[49] used IPCC (2000) [50] data and reported that a net emission from the application of lime on agricultural soils is 0.12 and 0.13 Mg C per Mg of limestone and dolomite, respectively. The function of SIC sequestration on soil C dynamics with climate change is less understood than that of SOC sequestration, especially under low land paddy production systems. There is a strong need to assess the development of secondary carbonates, the leaching scale, and the impact of land use and management on overall SIC dynamics because the paddy soils of the world cannot be omitted when thinking of carbon both above and below ground.

4. CARBON SEQUESTRATION IN LOW LAND PADDY SOILS (CS-LLPS)

Carbon sequestration is a vital phenomenon of the present obscure world of climate change where it helps in carbon trading and mitigating greenhouse gases (CO_2), to improve soil quality for profitable crop production and arrest the degree of land degradation. Farming soils, being depleted of huge quantity of organic carbon as a result of cultivation, have significant potential to sequester atmospheric CO_2. Carbon sequestration is highly related to the soil management system which contributes a lot to improving soil carbon status. Sequestering carbon in agricultural soil or plants to reduce the impact of CO_2 emission can be accomplished by producing more biomass within a given period, tillage reduction to maintain the soil organic matter, and adding up an external carbon source to the soil.

Methane (CH_4) and carbon dioxide (CO_2) are the two most radioactively imperative greenhouse gases attributable to human activity. Collectively they account for approximately 80% of the total 2.5 W m^{-2} increase in radioactive forcing caused by the anthropogenic release of greenhouse gases in the industrial age according to IPCC (2001)[51] . Six *et al*. (2006)[52] reported that some cultivation regimes results in larger SOC levels compared to the native state and reported that the potential of carbon sequestration in agricultural soils (54 Pg carbon) that act as a major sink for the ever-rising atmospheric CO_2 levels seems rather slight, but really need a fresh approach to curtail. Dlugokencky *et al*. [53] and Cunnold *et al*. [54] reported that the dominant increases are from wetlands (22-23 Tg yr-^{1} total) and rice (6-11 Tg yr^{-1}). Monika *et al*. (2002)[55] exposed that carbon dioxide is the key greenhouse gas and account for 60% of the total greenhouse effect globally. The SOC sequestration potential of rice accounted as 401 kg C ha^{-1} y^{-1} with 3.96 t ha^{-1} rice yield, and C input by means of crop residues around 2.67 t ha^{-1} year $^{-1}$ [56]. Paddy soils in China have reported a greater potential of C sequestration than upland cultivated soils and a notable trend of C enrichments recorded in paddy soils [57]. Lal (2006) [24] reported that by using the Recommended Management Practices (RMPs) it is possible to increase the SOC content and boost the yield of 15-25 kg ha^{-1} year $^{-1}$ at least with 0.5 Mg C ha $^{-1}$ $year^{-1}$ SOC pool in soil. Verge *et al*. [58] reported that methane emissions of rice paddies were 705 Tg CO_2 equivalent and 732 Tg CO_2 equivalent, compared to global emissions of 845 and 898 Tg CO_2 equivalent, respectively during 1990 to 2000 in Asia. Franzluebbers (2010)[59] observed that soil organic carbon (SOC) sequestration was 0.45 ± 0.04 Mg C ha^{-1} yr^{-1} with conservation tillage compared with conventional tillage cropland. Stratification of SOC with depth notified in conservative agricultural practices and appears to be connected with controlling of soil erosion, improving water quality, and appropriation of soil organic carbon.

Soil carbon sequestration was higher under the combined treatments with higher carbon input [60]. For instance, the NPKS treatments plus incorporating low quantity of rice straw accumulated carbon rates of 0.20 to 0.23 t ha^{-1} year-^{1}, whereas the combined treatments of pig manure and green manure input obtained 0.22 - 0.88 t ha^{-1} $year^{-1}$. Therefore, adapting to restorative land use patterns (LUP) and recommended management practices (RMPs) can significantly improve the SOC pool, soil quality, and agronomic productivity. Further, sequestering carbon in soils through various agro-ecosystems helps to ensure global food security, enhance soil resilience to adapt to extreme climatic events and mitigate climate change by offsetting fossil fuel emissions [25]. Soil organic carbon stock (SOCS) and sequestration rates were positively correlated with cumulative C input, and with sustainable yield index (SYI) of rice and lentil [61]. Applying NPK + FYM, and NPK + PS sequestered higher carbon in the Kharif season compared to control [62]. Application of NPK either as inorganic form or combining inorganic fertilizer and organics significantly improved the SOC, particulate organic carbon (POC), microbial biomass carbon (MBC) concentration and their sequestration rate [63]. Shanthi *et al*. [64] reported that soil organic carbon (SOC), particulate organic carbon (POC), and microbial biomass carbon (MBC) were found to be greater with biochar when compared to other organic manure application. The application of biochar considerably influenced the growth profile and grain yield of the rice plants. Apart from the addition of organic materials plus inorganic fertilizers, paddies grown in lowland and upland areas have significant differences in the pathways of C dynamics. (Fig. 2.). The pathways of C additions in paddy lands fluctuate with temperature and microbial activities. From the report of Chen et al. (2021)[65], it was evident that low land paddy fields under anoxic conditions have lower microbial-derived SOC but more CH_4 than upland crop vice versa.

Carbon (C) gains in fertilized soils due to nitrogen and other nutrients stimulating plant growth and rhizo-depositions thus mounting soil C input rates (Liu et al., 2019)[65a]. Addition of fertilizer nitrogen can also encourage soil C storage via slow decay of plant debris and soil organic matter [66];[67]. In particular, “N additions might reduce the microbial N mining, whereby nutrient-poor conditions stimulate recalcitrant SOC decomposition by N-acquiring microbes” [68];[69]. Moreover, organic fertilizers are extra C input into the soil and kindle the series of microbial communities favorable to SOC accumulation [70]. Conversely, in addition to previous findings, considerable differences in SOC stocks were recorded between organic sources and integrated application of organic and inorganic fertilizers [71]. Higher nitrogen and other nutrient levels increases the microbial growth on the available C pools, thus more microbial necromass can be produced, as it is the main component of soil organic matter(SOM) and augments the C pool in soils.

[Diagram illustrating the formation of SOC in waterlogged paddy and well-drained upland. Black and red arrows represent the pathways of plant- and microbial-derived C, respectively. The size of the arrows reflects the intensity of the pathways. The weaker microbial respiration (CO_2 release) in O_2-limited paddy than in O_2-sufficient upland was previously reported by Deng et al. (2021) [72]. The pool size of SOC in paddy is larger than that in upland. Paddy soil is enriched with a greater proportion of plant-derived C, whereas upland soil is more replenished by microbial-derived C. Complementary patterns between plant- and microbial-derived C in response to MAT occur in upland but not in paddy soil [65].

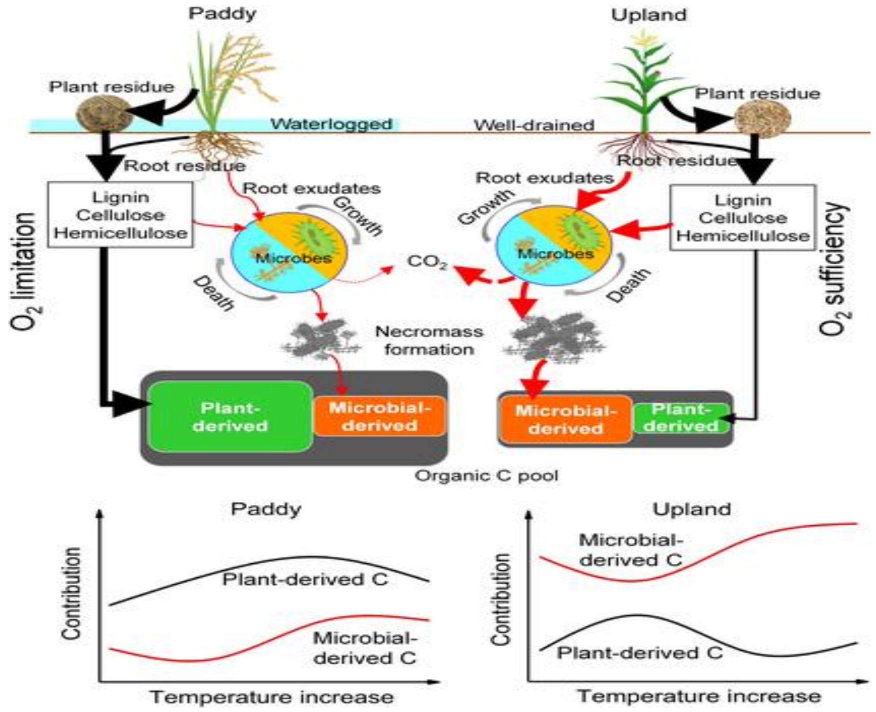

Fig. 2. Contrasting pathways of carbon sequestration in paddy and upland soils (Diagram adapted from Chen et al., 2021)

4.1 Evolution of CO_2 in Low Land Paddy Soils (CO_2-LLPS)

Carbon mineralization and carbon dioxide (CO_2) evolution have huge impact on the global carbon cycle (GCC) and function of global bionetworks [51] (IPCC, 2001). Soil respiration is more rapid with an increase in temperature from lower (5°C) than from mean (15°C) temperature [73]. CO_2 evolution under intermittent drainage has certain process that may cause CO_2 progress in lowland soils. Rice crop residues incorporated into soils with optimum conditions decomposed rapidly [74], and led to an increase in CO_2 evolution. Rice plants elevated CO_2 under Open Top Chamber (OTCs) conditions and indicated that methane emissions were significantly higher under CO_2 of 750 µmol mol^{-1} by 33 to 54 percent over the ambient CO_2 of 380 µmol mol^{-1}. These facts suggest that an alarming increase in atmospheric CO_2 may further increase the methane emission from rice fields [75]. For instance cumulative evolution of carbon dioxide flux was higher in cow dung (854 mg kg^{-1}) compared to cow dung + Rice Straw (828 mg kg^{-1}) and Cow dung + lime treatments (780 mg kg^{-1}). This fact signifies that amendments which encourages rapid decomposition and increases the CO_2 level that progressively lead to increase methane production in low lands. A considerable higher yield-scaled global warming potential (GWP) emerged with Indica rice varieties (1101.72 kg CO_2 equiv. Mg^{-1}) than japonica rice varieties (711.38 kg CO_2 equiv. Mg^{-1}) reported by Naher *et al.* [76]. And the addition of 75 percent N + *Cyanobacteria* significantly increased CO_2 evolution (185.36 mg CO_2 g^{-1} dry^{-1}) compared to control Abbas *et al.* (2015). Further, the maximum rice yield enhancement was observed on 600-699 ppm CO_2 than lower or higher elevated CO_2 levels [77]; [78].Therefore, from the above facts and reports it is understood that residue decomposition, amendments and rice varieties too influences the carbon dioxide evolution consequently methane then in lowland paddy soils. Hence, there is concern in managing rice productivity via carbon and water foot prints and or life cycle analysis of lowland rice production systems for effective carbon neutral path in said cropping systems.

4.2 Evolution of CH_4 in Low Land Paddy Soils (CH_4-LLPS)

Paddy soils accounts for 10 % of the global atmospheric methane [79]. Flooding tend to trim down C mineralization and augment methane (CH_4) fabrication; and CH_4 production may be affected in an anaerobic soil environment when flux in temperature. For instance methane evolution from plot treated with urea ranged from < 30 g ha^{-l} day^{-1} in early growing season to 12.04 kg ha^{-1} day^{-1} 63 days and the daily rate over the 77th day of sampling period was 4.6 kg CH_4 emitted ha^{-1} day $^{-1}$ (Lindau *et al*. [80] and CH_4 emissions ranged from 4 to 26 mg of C m^{-2} h^{-1} in a rice paddy [81]. Both reports opined that fertilization to paddy fields influenced the carbon mineralization and CH_4 production under submerged conditions. Further, rising atmospheric emissions straightly associate with soil sand content of 18.8% to 32.5%, that influences the seasonal methane emissions ranging from 15.1 g m $^{-2}$ to 36.3 g m^{-2} [82]. Evidences showed that CH_4 from rice fields of 3.32 Tg CH_4 (2.49 Tg CH_4-C) each year contributes about 3.4 percent to the global methane budget due to rice cultivation. Rice cultivars showed a difference in CH_4 emission, such as, the average seasonal methane emission was 22.8 g CH_4 m^{-2}, for higher-emitting cultivars and it was ranging from 8.0 to 41.0 g CH_4 m^{-2} and 17.7 g CH_4 m^{-2}, for lower-emitting cultivars it was ranging from 1.7 to 28.4 g CH_4 m^{-2}, respectively [83]. Here, the reported results proved that apart from fertilization and soil solids, rice cultivars also affect the methane flux in lowland paddy soils. Where, breaking mono-cropping can reduce the CH_4 evolution i.e. after certain period of planting vegetables, the CH_4 emissions from a single early growth rice paddy field in Guangzhou were as low as 0.21 mg CH_4 m^{-2} h^{-1}; Lu *et al.* [84]compared to rice mono cropping. Low land paddy soil hourly emission ranged from 0.65 to 1.12 mg of C m^{-2} h^{-1} and average emission values approximately 21.4 g of C m^{-2}, as influenced by plant variety and growth environment was reported by Mitra *et al*. (1999)[85]. Dise and Verry [86] reported that methane emission from the NH_4 and NO_3- N amended fields (mean of 256 mg CH_4 m^{-2} d^{-1}) were not much differed from that of controls measured on the same day (mean of 225 mg CH_4 m^{-2} d^{-1}); this report rise a question of criticism whether fertilization have influence on mehanogenesis or not? Since many research reports opined that fertilization did.

Methane flux have connection with water management i.e. the maximum seasonal emission from continuous flooding (35.81g m^{-2}) and the minimum from multiple aerations (intermittent irrigation) (16.91g m^{-2}), which is only half of the continuously flooded fields [87]. Decline in CH_4 evolution rates at harvest was due to the obstruction of conduits in CH_4 evolution through rice plants not due to the decrease in CH_4 evolution in soil [88]. The Taiku region emitted an equivalent of 5.7 Tg C from 2.3 M ha^{-1} of paddy rice fields during 1982-2000, with an average CH_4 flux ranging from 114 to 138 kg C ha^{-1} y^{-1} [89]. Khosa *et al.* (2010)[90] observed that the methane flux was low in bare soil (0.04 and 0.93 mg m^{-2} hr^{-1}) and transplanting of rice doubled the rate of methane emission (0.07 to 2.06 mg m^{-2} hr^{-1}) in control plots with no organic amendments. CH_4 emission from natural wetlands in mainland china is 2.35 Tg CH_4 yr^{-} (ranging from 2.12 to 2.86 Tg CH_4 yr^{-}) with 2.16 Tg CH_4 emitted during the growing season and 0.19 Tg CH_4 during the non-growing season [91]. Nungkat *et al*. (2015)[[92] reported that the methane emission due to the application of organic manure @ 10 t ha^{-1} and Azolla @ 2 t ha^{-1} to paddy fields was arrayed from 509.82 to 791.34 kg CH_4 per hectare. Further, organic fertilization have effects on soil mineral nutrition and functional microorganisms and steer mitigating GHG emissions from paddy soils [93]. Further, the evolution of carbon dioxide and methane was well detailed by Debusk et al. (2001)[94] in wetland ecosystems. In wetlands, the role of integrating nutrient supply thorough various organic and inorganic sources and cultivation practices plays a vital work in carbon mineralization potential. C dynamics or progression under aerobic and anaerobic situations influenced by the bio-fertilizers and mineral fertilizers in accordance with site factors inconsequence affects carbon accumulation and or methanogenesis. However, the progression of carbon under wet and dry conditions too differs with both soil and atmospheric temperatures. In addition to that biogeochemical cycles of nutrient elements affect the microbial biomass carbon, energy levels and end products of its own. Thus cyclic processes of nutrients directly and indirectly make a flux in carbon genesis under different soil environments. Hence, carbon accrual need to be explored with different soil-water –plant atmospheric continuum processes.

4.3 Carbon Dynamics (CarDy) in Low Land Paddy Soils (LLPS) and Cultural and Nutrient Management Practices (NMPs)

Land use and nutrient management practices have great impact on soil properties mainly by regulating organic pool (nature and amounts of organic matter) in the soil. Certain soil physical properties determined by the soil organic matter along with soil texture classes. SOC circulations within different pools are as important as understanding its dynamics and diverse role in different ecosystems. Soil organic carbon content reveals sizeable spatial variability, both parallel according to land use and perpendicularly within the soil profile. It shrinks with depth in spite of of vegetation, soil texture, and clay particle size [95]. Continuous application of manures, especially FYM over a period increased the organic carbon content of the soil [96]. Pascal *et al*. [97] reported that the addition of organic materials and off-farm sources like municipal solid waste, sewage sludge significantly increased the values of biomass carbon, basal respiration biomass C / total organic C ratio, and metabolic quotient (q CO_2) indicating the activation of soil microorganisms. Carbon is continuously incorporated into the microbial cells (assimilation) range from 20-40 % under anaerobic conditions and the rest is mineralized. Here the gap between assimilation and mineralization decided by microbial groups. As aerobic bacterial assimilation is only 5-10 % but fungi may assimilate 30-40 %. Hence, the soil microbial biomass is a sensitive indicator of soil fertility than the soil organic matter since it responds readily to change in the soil physicochemical environments as it is responds quickly to changes in soil management practices [98] and it is often used as an indicator of soil quality [99].

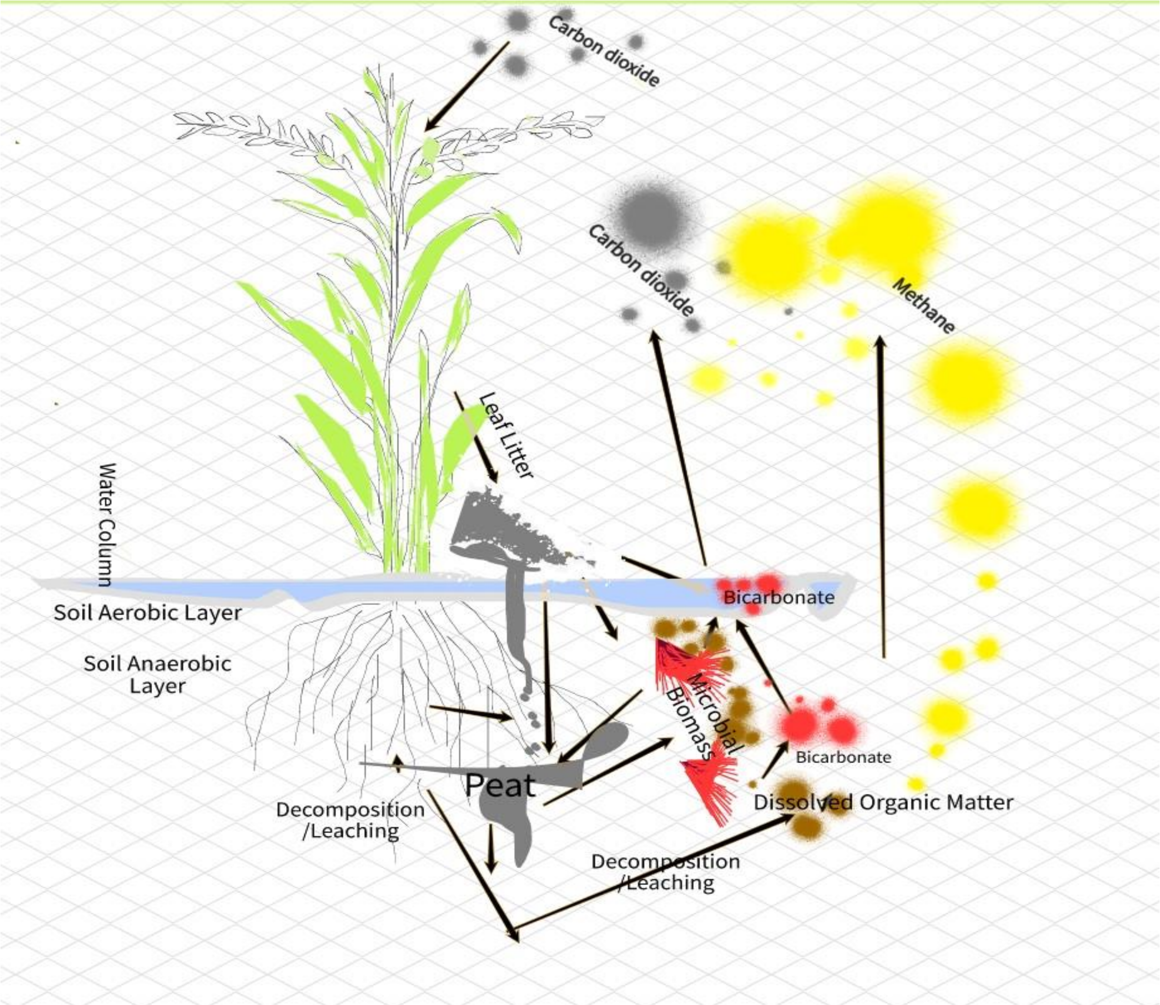

Fig. 3. Carbon progression in wetlands

Significant increase in the organic carbon content of sandy clay loam soil from 0.61 to 0.92 percent due to the addition of FYM along with nitrogenous fertilizers [100]. Microbial biomass carbon decreased with plant growth and there was no difference between planted and unplanted soils in flooded conditions[101]. Further, dissolved organic carbon (DOC) in root zone soil was significantly enriched by organic carbon released from rice roots [96]and raise in DOC with plant growth point up the increase in C substrate which was readily available for microorganisms [102,103] . Integrated use of organics via FYM and crop residues enhanced the organic carbon content of soil (Kanchikerimath and Singh [104] and Zinati *et al* [105] observed that the combined application of chemical fertilizers and compost increased the biologically active soil organic carbon such as microbial biomass carbon (MBC), and mineralizable carbon (MC) and microbial biomass C (MBC) increased with plant growth and with an increase in air CO_2 concentration [106]; [107]. Kharub *et al*.[108] stated that green manure alone or in combination with straw incorporation could effective in increasing the carbon content by 13.6 and 26.7 percent. Bhattacharaya [109] revealed that the application of 50% NPK plus FYM @ 10 t ha^{-1} increased the organic carbon content of the soil. Ramesh and Chandrasekaran [110] studied the green manure (GM) crop (*Sesbania rostrata Berm)* in a double rice cropping system per year and found that the trials with GM resulted in maximum SOC content of 10.63% increase compared to control for two years. Labile carbon pools of soil carbon are key progress as they fuel the soil food web and therefore greatly influence nutrient cycling for maintaining soil quality [111]. Banwasi and Bajpai[112] stated that the application of 50% NPK + 50% N through green manuring increased the organic carbon content of the soil. Chalwade *et al*. [113] identified that organic manures application alone and or in combination with inorganic fertilizers resulted a boost up in organic carbon content from 0.53 to 0.65 percent in soil. Soil organic carbon content in fertilized plots as compared to unfertilized plots due to C addition through the roots and crop residues had higher humification rate constant and lower decay rate Kundu *et al*. ([114] and Mandal et al [115] perceived a decline in soil organic carbon (SOC) in the control treatment, whereas balanced fertilization with NPK maintain SOC, significantly. Abid and Lal [116a] also showed a higher concentration of C and N in macro-aggregates compared to those in micro aggregates.

Role of time and fertilizer application and their function on the SOC content from a long-term study involving 36 cropping seasons of double rice cropping in India [115]. And their results identified that applying NPK fertilizers, and NPK + compost increased the total C content in the soil by 33.5 % and 54.9 % compared to the control of 28.5 Mg C ha $^{-1}$. To understand these processes TOC can separated into the "labile (or actively cycling) and stable (resistant or recalcitrant) pool". The labile carbon pool of TOC have rapid turnover rates which affect very fast oxidation of these pools as carbon dioxide from soils to the atmosphere. The labile carbon pool of carbon has been the main source of nutrition that influences the quality and productivity of soil [116];[115]. Islam *et al*. [117] observed an insignificant increase in soil organic matter (SOM) due to the application of organic residues. However, long-term application of organic residues is expected to increase SOM in tidal flooded soil and rice fields. Application of chemical fertilizer decreased soil microbial biomass carbon (MBC) and soil water-soluble organic but significantly increased mineralizable carbon (MC). Bhabesh *et al*. [118] reported that the application of inorganic fertilizer to rice-niger cropping sequence notably improved the soil enzymes and soil microbial biomass carbon. Bruns [119] noticed in a field experiment that yard waste compost derived from shrubs and garden cutting @ 10 t ha^{-1} carbon increased the content of MBC, N and P. Kusro *et al*. [120] found that application of a recommended dose of 100 percent NPK + FYM @ 5 ton ha^{-1} gave an increase in organic carbon (0.673%) when compared to control (0.504%). Zhang *et al*. [121] observed the effect of chemical fertilizers (N, P, and K) with livestock manure, crop residues, and green manure on soil enzyme activities and microbial characteristics of paddy soil in China and reported that N, P, K + livestock manure and N, P, K + straw significantly increased the organic carbon, available P, phosphatase and microbial carbon in the soil. Cultivation practices enhanced the decomposition rates of organic carbon via microbial degradation. And also make flux in soil properties and exposure of sub soil layers etc., which also lead to increased rates SOC thereby carbon stock increased and recued carbon output was realized was evidenced from the above review. Further, nutrient additions influenced the carbon sequestration rate in paddy soils especially with N additions. In addition to that, CS more when soil is low in fertility where carbon input increased through biomass production but c decomposition decreased due to fertilizer additions. From the review reports, it was identified that soil carbon addition is not only depends on the cultivation and nutrient management practices but other key environmental factors that greatly flux the C accumulation under submerged conditions i.e. low land paddy soils. According to the studies, NPK fertilizer additions have positive effects on crop yield and thus carbon sequestration in paddy soils. Further, based on the type of soil, fertilizer source and form and nature of organic matter CS potential of paddies differed greatly i.e. Carbon accumulation may be carbon positive or negative or neutral this might be due to flux in the soil labile carbon and soil inorganic carbon (SIC)pool due to fertilizers and humus additions, respectively. Thus, Integration of organic and inorganic sources of nutrient could provide better results than sole application organic alone or inorganic alone. Because, the C input and output mechanism requires certain priming work during mineralization done by microbial consortiums (aerobic /anaerobic) present in soils. This may be positive or negative and affects the nutrient availability and also influenced the carbon accretion and decomposition in soil. So, there is need for extensive studies on nutrient additions to paddies of world soils to get clear picture of carbon foot prints i.e. crop management practices could be C positive or C negative or neutral in natural Carbon cycle.

4.4 Life Cycle Assessments (LCA) of Soil Carbon Changes

Soil carbon sequestration (SCS) is a vital key mitigate GHGs from agricultural farms. A researcher can assess and calculate the GHG (CO_2, CH_4 and N_2O) emissions by modeling and evaluation by using LCA tools such as Simapro. LCA is defined as the ‘compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle’ (ISO 2006). This includes all stages required for the creation of the material of interest through to its disposal or recycling, and it includes a variety of criteria that range from energy use to eco-toxicity. . LCA can be applied to compute or simulate energy balance and environmental impact categories, such as climate change, ozone depletion, terrestrial acidification, freshwater eutrophication, and marine eutrophication. LCA can also be applied for crop production and agricultural systems for comparative analyses and identification of the best options among different production systems, practices, technologies based on some specific economic and environmental factors; production process improvement, product development, and promotion; and strategic planning and decision support.[refer Hung et al.,2020 [122]; LCA applied to rice production and residue management; https://doi.org/10.1007/978-3-030-32373-8_10]. As per Hung’s report “ in rice science , LCA should be used comprehensively to identify best practices of sustainable rice production, postharvest management, and rice straw management. Energy balances, GHGE balances, and ecological and environmental impacts can be analyzed by using LCA and SIMAPRO. Internationally certified and reliable data for calculating energy and impacts are available in Agrifootprint, GHG protocol, Ecoinvent, etc., all incorporated in SIMAPRO. LCA studies will eventually help to reduce environmental impacts. Efficiency analysis of the rice production system including the environmental efficiency may be used to understand and benchmark the level of input as well as the output. Further, carbon emission from agricultural fields can be manage significantly through identifying definite functional structure using various life cycle inventory analysis. This type analytical results helps to make policy decision for blanket recommendations of nutrients based on agro climatic regions and seasons for paddies. Long-term studies assessing cropland soil carbon pools / offset to prepared at regional or national levels or at agro climatic zone using various models like DayCent-CR [122a] ;they reported on various crops soil carbon offset in long-term scale.

5. FUTURE RESEARCH NEEDS

Future research is needed to assess the effect of cultural and nutrient management practices on carbon sequestration in lowland paddy soils (LLPS). Studies should consider the following.

- We direct from the facts reviewed in this paper that we need to work on carbon economics through life cycle assessment of various activities that influences the carbon cycle in crop (paddy) production practices to mapping the exact foot prints.
- Global survey of paddy growing areas, practices followed, carbon accumulation by different varieties in diverse seasons, through carbon foot prints of different paddy growing of the regions of the world.

- Studies on micro biomes that run the SOM mineralization in different depth of soil in conjunction with addition of inorganic and organic sources of nutrients to paddy is essential to be explored.
- Research on mapping low land paddy soils and their GHGs emission using remote sensing and GIS should be studied for effective management to mitigate GHGs emission and to improve CS potential in different agro-climatic regions.
- Paddy soil carbon offset through various modelling studies helps to identifying climate change effects on crop productivity.

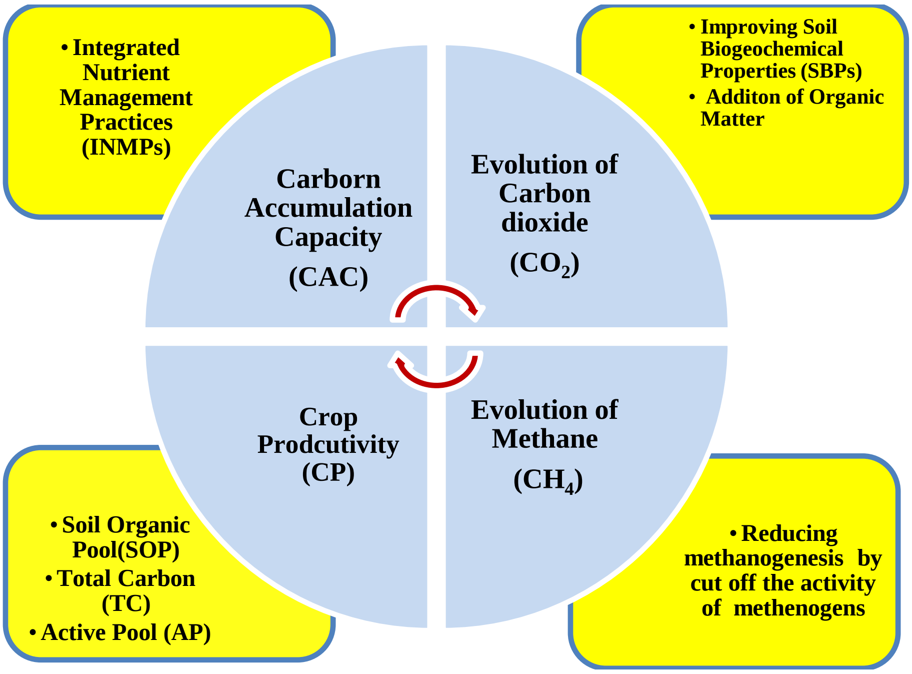

Fig. 4. Interconnection between carbon management and soil health influenced by integrated nutrient management practices (INMPs) in lowland paddy soils – a carbon-neutral path

Table 1. Key findings on carbon sequestration in paddy fields influenced by nutrient management practices

Nutrient Management Practices	**Carbon form**	**Objectives of the study**	**Remarks**	**Reference**
Biofilm Bio-fertilizers (BFBF)	SOC	BFBF on SCO,SLC,SCS , net C pool	BFBF could enhance the N C pool	Jayasekara et al. [123]
Integrated Nutrient Management	SOC	Soil Organic Carbon Stocks	Improved CS by INM	(Padbhushan et al.,[124]
Combined application of organic & inorganic fertilizers	CH_4	GHG mitigation	Conjoint applications of organic and inorganic sources cut off creditable percent of GHG emission.	(Zhao et al., [125]
Fertilizers management	SOC	C sequestration	SOC improved by fertilizer management practices through effecting CS potential of crops.	(Singh & Benbi,[126]
Organic and inorganic amendments	SOC	C sequestration	Use of organic sources would be valuable practice to increase net CO_2 sequestration in paddy soils under tropical climatic conditions	Haque et al. [122]
Fertilizers management	SOC CH_4	C sequestration & GHG mitigation	Managing fertilizer application in crop production especially in flooded crops CS could be enhanced and reduced the genesis of CH_4 significantly.	(Zhu et al., [127]
Straw incorporation	SOC CH_4	C sequestration & GHG mitigation	Significant results obtained in CS and cut down the GHG emission.	(Zhang et al., [128]

Nutrient Management Practices	**Carbon form**	**Objectives of the study**	**Remarks**	**Reference**
Cropping system + Amendments	GHG	GHG DNDC model	Cropping system and addition of various amendments helps in GHG mitigation significantly.	(Zou et al., 2018) [129]
Fertilizers management	SOC	C sequestration	Reduced inorganic application helps enhanced the CS in crops.	(Li et al., [69]
Combined application of Organic and inorganic fertilizers	TOC Stock	SOC and Nutrient management regimes	Combined use of organic and inorganic nutrient sources increased around 44 % very labile and labile carbon i.e.active carbon pool in surface soil.	(Nath et al.,[130]

6. SUMMARY AND CONCLUSIONS

The rising global population and changing climatic conditions along with their impacts on agricultural productivity have made food security questionable in most parts of the world. In this review potential impact of certain management practices on carbon accumulation in lowland paddy soils have been summarized and elaborated various facts that proper management of soil should be one of our most important tools for mitigating and adapting to the changing climatic conditions. The way we cope and preserve our present natural resources is going to have a great impact on the resources available to the next generation for combating the food security issues. Further, carbon sequestration can play a key strategy in tackling the unfavorable effects of climate change. It generally helps improve the soil carbon pools that directly and indirectly help to sustain crop productivity. In addition, the adaption of certain cultural and nutrient management practices increases biomass productivity and sink more atmospheric carbon through photosynthetic activities could help to minimize greenhouse gases emission and helps to managing the climate change in paddy growing areas significantly.

Cultivation and or nutrient management practices can play an important role in mitigating the adverse effects of climate change and decides the quantity of soil carbon sequestration in different agro-ecological systems, especially low land paddy soils. Also, integrated nutrient management practices can be a viable carbon neutral path of balancing carbon cycle both in below and above ground. However, it is evidence that these practices may increase carbon into soil and or decrease the C from the soil so soil organic carbon naturally improve over a period of time. Crop production practices increased the rate of SOC decomposition as evident from the review i.e. balance between the carbon addition and decomposition rates that decided the CS potential. Further, cultural and nutrient management practices may have C negative and or positive based on the level of carbon saturation capacity (CAC) of soil. Therefore, cultural and nutrient management practices for low land paddies could enhance the crop productivity which in turn augmentation of carbon accumulation in soil may occur, thus they have significant carbon sequestration potential as per the reports reviewed. Hence, possibility both side chances are there, C negative or positive based on the crop productivity and other lowland paddy soil environmental conditions from the these practices. So, we direct from the facts reviewed in this paper that we need to work on carbon economics through life cycle assessment of various activities that influences the carbon cycle in crop production practices to mapping the exact foot prints. Global survey of paddy growing areas, practices followed, carbon accumulation by different varieties in diverse seasons, through carbon foot prints of different paddy growing of the regions of the world through crop modelling studies.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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