REVIEW ARTICLE

Steering restoration of coal mining degraded ecosystem to achieve sustainable development goal-13 (climate action): United Nations decade of ecosystem restoration (2021–2030)

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Abstract

For millennium, mining sector is a source not only of mineral extraction for industrialization, economic expansion, and urban sprawling, but also of socio-environmental concern. It, therefore, has been the central attention of the business and public policy sustainable development scheme for several years. Thus, gradually, mining industries are getting involved with the concerns such as carbon emissions mitigation and carbon accounting to govern a rhetorical shift towards "sustainable mining". However, there is scarce knowledge about how the emergence of a "green and self-sustaining" forestry reclamation strategy coupled with potential carbon sequestration capacity in degraded mining areas will be an impeccable option for achieving sustainable development goal-13 (SDG-13: climate action) and ecosystem services during United Nation decade of ecosystem restoration. This paper reviews the extent to which reforestation and sustainable land management practices that employed to enhance ecosystem carbon pool and atmospheric CO_2 sequestration capacity to offset CO_2 emission and SOC (soil organic carbon) losses, as consequences of coal mining, to partially mitigate global climate crisis. Moreover, future research is required on mining innovation concepts and its challenges for designing an SDG impact framework, so that it not only synergies amongst SDGs, but also trade-offs between each individual "politically legitimized post-2015 development agenda" (i.e. UNSDGs) could be depicted in a systematic way. In a developing country like India, it is also an utmost need to assess the environmental impact and economic performance of such technological innovation and its possible synergistic effect.

Keywords Coal mine restoration · Carbon sequestration · Sustainable mining · Sustainable development goal-13 (climate action) · Ecosystem goods and services (EGS)

Abbreviations

ACC	Anthropogenic climate change
AGB	Aboveground biomass
AMF	Arbuscular mycorrhizal fungi
BGB	Belowground biomass
BMP	Best management practices
BNF	Biological nitrogen fixation
BT	Billion tons
C:N	Carbon:nitrogen
CCL	Central coalfield limited
CDM	Clean development mechanism
CEC	Cation exchange capacity
CI	Carbon input
CL	Carbon loss
CO_2	Carbon dioxide
COP	Conference of parties
CSR	Corporate social responsibility
EC	Electrical conductivity

Highlights

- Trends in forestry reclamation strategy with respect to carbon sequestration potentials of reclaimed ecosystem are reviewed.
- Development of carbon sequestration capacity in reclaimed mine site (RMS) towards achieving sustainable development goal-13 (climate action) and ecosystem goods and services (EGS) has been briefly discussed.
- Application of glomalin related soil protein (GRSP) to enhance carbon sequestration potentials is also summarized.
- Implementation of market-based carbon trading approach and regeneration of EGS in reclaimed ecosystem could be a cost-effective way to achieve UNSDG-13 (climate action).

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ECB	Ecosystem carbon budget	TEV	Total economic value
EGS	Ecosystem goods and services	Tg	Teragrams (=10^9 kg)
ES	Ecosystem services	TOC	Total organic carbon
FAO	Food and Agriculture Organization	UNDP	United Nations Development Programme
FLR	Forest landscape restoration	UNEP	United Nations Environment Programme
FRA	Forest restoration approach	UNFCC	United Nations Framework Convention on Climate Change
FRP	Forestry reclamation project		
GDP	Gross domestic product	UNSDG	United Nations Sustainable Development Goals
GHG	Greenhouse gas		
GRSP	Glomalin-related soil protein	USA	United States of America
Ha	Hectare	USD	United States dollar
ICMM	International Council on Mining and Minerals	WCED	World Commission on Environment and Development
IPBES	Intergovernmental Platform on Biodiversity and Ecosystem Services		
		WEF	World Economic Forum
		WoS	Web of Science
IPCC	Intergovernmental Panel on Climate Change		
ITPS	Intergovernmental Technical Panel on Soils		
K	Potassium		
LB	Litter biomass		
LULC	Land use land cover		
MEA	Millennium Ecosystem Assessment		
Mg	Megagram (=1 tonne)		
Mha	Million hectare		
MRT	Mean residence time		
NBS	Nature-based solutions		
NDC	Nationally determined contributions		
NEP	Net ecosystem production		
NPP	Net primary productivity		
NPV	Net present value		
NWFP	Non-wood forest products		
OB	Overburden		
OCP	Opencast project		
P	Phosphorus		
PAH	Polycyclic aromatic hydrocarbon		
PES	Payment for ecosystem services		
Pg	Petagrams (= 10^{12} kg)		
PME	Post-mining ecosystem		
POM	Particulate organic matter		
REDD	Reducing emissions from deforestation and forest degradation		
RMP	Recommended management practices		
RMS	Reclaimed mine site		
SDG	Sustainable development goal		
SERI	Society of restoration ecology international		
SIC	Soil inorganic carbon		
SLM	Sustainable land management		
SMB	Soil microbial biomass		
SMCRA	Surface Mining Control and Reclamation Act		
SOC	Soil organic carbon		
SOM	Soil organic matter		
SRC	Short rotation coppices		
T-GRSP	Total GRSP		
TEEB	The Economics of Ecosystems and Biodiversity		

Introduction

Background

Since the genesis of industrial revolution and urbanization, the emission of carbon di-oxide (CO_2) accounts for about 76% to global GHG emissions (IPCC 2014a, b). The atmospheric concentration of CO_2 exceeded 419 ppm in 2021 — way above the pre-industrial level of 278 ppm as a consequence of fossil fuel combustion and deforestation, predicting 2021 to be the first year on record that exhibits CO_2 levels of more than 50% above pre-industrial levels in the last 35 years (https://www.co2.earth, https://www.downtoearth.org.in/news/climate-change, accessed on 20.05.2021). In this context, the Paris Agreement, signed by 196 nations to reduce their CO_2 emissions by nationally determined contributions (NDCs), aims to keep global warming below 2 °C by 2100, with 1.5 °C as a target (UNFCC 2015). Furthermore, to accelerate the action towards the goals of the Paris Agreement and UNFCC, the UK hosted the 26th UN climate change COP 26 in Glasgow (Glasgow Climate Pact 2021), which intends to secure global emission to net zero by 2030 and keep 1.5 °C within reach. The COP 26 produced new "building blocks" to advance implementation of the Paris Agreement through actions that can lead the world to a more sustainable and low carbon pathway forward. Moreover, being the top three coal-producing country, China aims to reduce CO_2 emissions by 60–65%, India by 35%, and the USA by 28% per unit of GDP by 2030 (Yang et al. 2019; Ramseur 2017).

Amongst conventional fossil fuels, coal, the second largest source of primary energy, accounts for 30% of total energy consumption globally. As of 2018, the world recoverable coal reserves were estimated about 1055 billion tons (BT), out of which about 75% are located in five countries (the USA, Russia, Australia, China, India) (https://www.mining-technology.com/features/feature-the-worlds-bigge

st-coal-reserves-by-country/, accessed on 20.05.2021). Though in 2020, global coal demand experienced its largest drop (falling 5% from 2019 levels) since the Second World War due to Covid-19 crisis, it can be forecasted based on the presumption of a global economic recovery in 2021 that a rebound in global coal demand of 2.6% will be dominated by China, India, and Southeast Asia (https://www.iea.org/reports/coal-2020, accessed on 20.05.2021). About 8 BT of coal combustion occurred annually worldwide for electricity generation that is responsible for being second largest share (approximately 62%) of the world's CO_2 emissions (https://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions, accessed on 20.05.2021) and concerned as a contributor to global warming. Such anthropogenic perturbations of atmospheric carbon cycle directly affect ecosystem sustainability and global climate dynamics. Despite of having different pros and cons, coal mining industry is indispensable worldwide for socio-economic development. Additionally, European Union Member States have emphasized the significance of the mining industry to fulfil the minerals need for consumer products, besides a successful transformation towards achieving the United Nations Sustainable Development Goals (UNSDGs); therefore, gradually, mining industries are getting involved with the related issues of carbon accounting and carbon emission mitigation (Pellegrino and Lodhia 2012). Incorporation of carbon trading approach ("cap and trade" or "emission trading system") could provide substantial, environmental, social, and economic co-benefits such as sustainable ecosystem (SDG-12), improved resource efficiency (SDG-9), ensured energy security (SDG-7), and certified employment (SDG-8) in mining sector. Hence, enhancing soil carbon stocks and atmospheric CO_2 sequestration capacity through proper reclamation strategies in coal mine derelict site is now the main attention of researchers, scientists, and policy makers. The emergence of such "green and self-sustaining" approaches to regulate carbon emissions from land-use change provides a prospect for mining sectors to exacerbate their sustainability credentials through carbon finance (Hirons et al. 2014). Enhancing carbon sequestration in terrestrial ecosystems could be a potential approach to offset rising atmospheric CO_2 levels. Carbon sequestration potential is linked to not only global climate change, but also changes in other ecosystem processes that are significant to human welfare. Therefore, development of potential carbon sequestration capacity in degraded mining areas is an impeccable option for achieving sustainable development goal-13 (SDG-13: climate action) during the UN decade of ecosystem restoration.

Surface mining, the most common coal mining technique worldwide, causes extreme perturbation to the soil profile that leads to loss of soil fertility, carbon stock, disruption of carbon equilibrium, destruction of carbon sink, carbon deficit in natural soil, and reduced ability to provide ecosystem services (ES) (Ličina et al. 2017). Complete destruction of forest cover, removal of topsoil, generation of overburden (OB) dumps (used for backfilling of mine voids), and land use changes due to mining operations (enhanced mineralization, erosion, and leaching) cause depletion in global biodiversity, carbon cycle, visual aesthetics, and augmentation of GHG emissions (del Mar Montiel-Rozas et al. 2016; Feng et al. 2019). Moreover, the carbon content in world's soils is around three times that of the vegetation and twice that of the atmosphere (Tan et al. 2014; Scharlemann et al. 2014; Averill et al. 2014). Therefore, it is an urgent need to formulate green strategies to enhance carbon storage, carbon sequestration capacity, and rate of CO_2 flux in post-mining terrestrial ecosystems (Lal 2003; Pandey et al. 2016). Hence, revegetation is inevitable for accelerating the post-mining ecosystem (PME) recovery, geotechnical stabilization of the waste dump (through the development of extensive root systems), generation of ecosystem goods and services (EGS), sustainable land use land cover (LULC), and partially combating global warming by enhancing CO_2 sequestration (Tripathi et al. 2012).

In several countries, post-mining degraded landscape was restored through fast-growing exotic vegetation species. In the USA and other European countries, perennial vegetation has been applied on degraded land to boost up the SOC content and to limit soil erosion (Cortina et al. 2011; Munson et al. 2012). Besides, over the last decade, more emphasis has been centralized on three-tier vegetation (i.e. grasses, understory vegetation, and trees), five-tier plantation (trees, shrubs, herbs, grass–legumes, climber), and indigenous and diverse species composition that could influence carbon dynamics and soil quality, improve genetic diversity, and accelerate the recovery to a self-sustainable ecosystem (Yuan et al. 2020). The regenerated carbon sinks play critical role to offset CO_2 emission and SOC losses from coal mining (Shrestha and Lal 2009). In comparison to the young trees and herb or shrub species, matured woody trees have more carbon sequestration potential due to higher concentration of aliphatic root suberin, glycerides, waxes, tannins, and lignin (Tripathi et al. 2014). Reforested mine soils, thus, could be an important sink for atmospheric CO_2 through soil organic matter (SOM) formation and biomass production (Shrestha and Lal 2009). Therefore, proper restoration of mine spoil is a significant approach to sequester large amount of atmospheric carbon to a stable state towards achieving UNSDGs.

Formulation of research gap

Loss of biodiversity, climate change (in reference to CO_2 emission), and reduced ability to provide EGS due to mining operation can significantly reverse the progress towards sustainable future and global socio-economic development. Under this paradigm, concerns are

increasingly dominated by one of the most significant challenges of the twenty-first century "to take urgent action to combat climate change and its impacts" (Stern and Stern 2007). Hence, there is an urgent need to stabilize atmospheric CO_2 to reduce the GHG effect. Carbon sequestration is one of the significant adaptation strategies that have the capabilities to capture GHGs from the atmosphere and sink it through terrestrial sequestration. Although, the efficacy of carbon sequestration is affected by climate variability, post-disturbance land use dynamics, biophysical factors, and degree of land degradation. The chronological and spatio-temporal variation of carbon sequestration in post-mining degraded ecosystem and its effectiveness towards achieving UNSDGs should be monitored so that the contribution of carbon sequestration can be predicted in terms of mitigation of GHG emission and formation of sustainable management system to reinstatement of pre-mining ecosystem and capsulize the gap between carbon emission and carbon sink.

To date, restoration of post-mining degraded landscape confined to the evaluation of reclamation success by indexing, remote sensing, and modelling. The importance of restoration science in understanding environmental moderation through carbon sequestration potential and ecosystem service generation cannot be overemphasized. Recovery trajectory of post-mining ecosystem (PME) becomes more explicit with the multi-story vegetation approach and its impact on carbon dynamics. Achieving UNSDGs by steering up PME restoration is not mostly incorporated. Hence, this review deals to address these research gaps to develop a cost-effective, self-sustaining mitigative strategy to combat the global climate and biodiversity crisis as well as to regenerate ecosystem goods and services.

Research question

How could the sustainable management (restoration) of post-mining ecosystem be essential for achieving the target of post-2020 framework of UNSDGs (SDG-13)?

How could this target relate with the sustainable mining during UN decade of ecosystem restoration (2021–2030)?

Objectives

The carbon sequestration accounts to reverse adverse impact of land degradation in the tropics and sub-tropics through revegetation approach, a green and sustainable technology, which affords win–win effects in terms of environmental and economic sustainability, higher biodiversity, and enhanced environmental management to empower global environment conservation framework.

The present study aims to review (1) the potentiality of post-mining ecosystem (PME) restoration towards achieving UNSDGs (SDG-13) during 2021–2030, (2) the factors affecting carbon sequestration potential in PME, (3) the global potential of carbon sequestration in RMS, (4) the carbon budget for PME, and (5) probable benefits of carbon sequestration towards achieving the SDG-13 target (6) to propose sustainable land management (SLM) in PME to partially mitigate global climate change.

Review methodology

The literature review was performed using the Web of Science (WoS) Core Collection to derive research statistics relating to the potentiality of carbon sequestration in reclaimed coal mine site to achieve sustainable development goals (UNSDGs). Despite of having several databases such as Google Scholar, Scopus, and ScienceDirect, WoS core collection is considered for the present study as it is a repository for a wide range of scientific articles (SCIE, SCI, SSCI). The present study considered the period of 2001–2021, and the data was collected on 2 July 2021. The present study focuses exclusively on the potentiality of carbon sequestration in reclaimed coal mine sites to achieve sustainable development goal. "TS = ((restoration OR restored OR reclamation OR reclaimed OR reforested OR revegetation OR reforestation) AND (soil carbon sequestration OR soil carbon stock OR soil carbon pool OR soil carbon storage OR atmospheric carbon di-oxide sequestration) AND (coal mine spoil* OR coal mine tailing* OR technosol OR anthrosol OR reclaimed mine soil))" was entered in the basic search option of WoS core collection for obtaining data for the present study.

Publications over the years and countries

This review was mainly based on the number of published research articles over the period of 2001–2021 in different countries that aid to comprehend the evolution occurred in the subject area. The trends illustrate that there is no such substantial growth in publications in this particular field till 2014; from 2015, there has been a significant increase in research publications. The publications' statistics followed a linear trend ($R^2 = 0.6799$) as exemplified in Fig. 1. The country-wise global hotspots for the research publications in this field were estimated through the analysis of the WoS database. As presented in Fig. 2, the USA is the

Fig. 1 The number of publications during the period 2001–2021 on the carbon sequestration potential in reclaimed coal mine site to achieve sustainable development goals (UNSDGs) (data is up to July 2021)
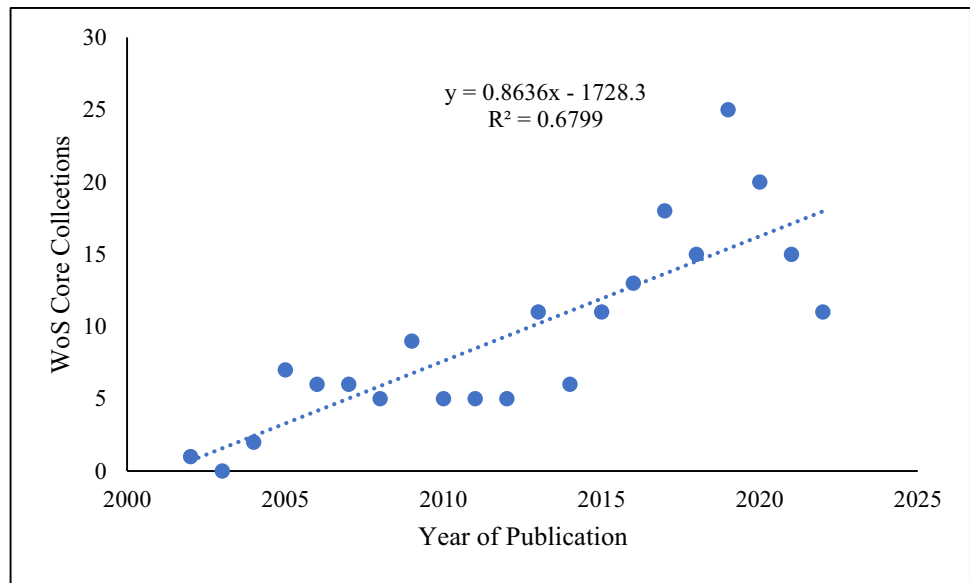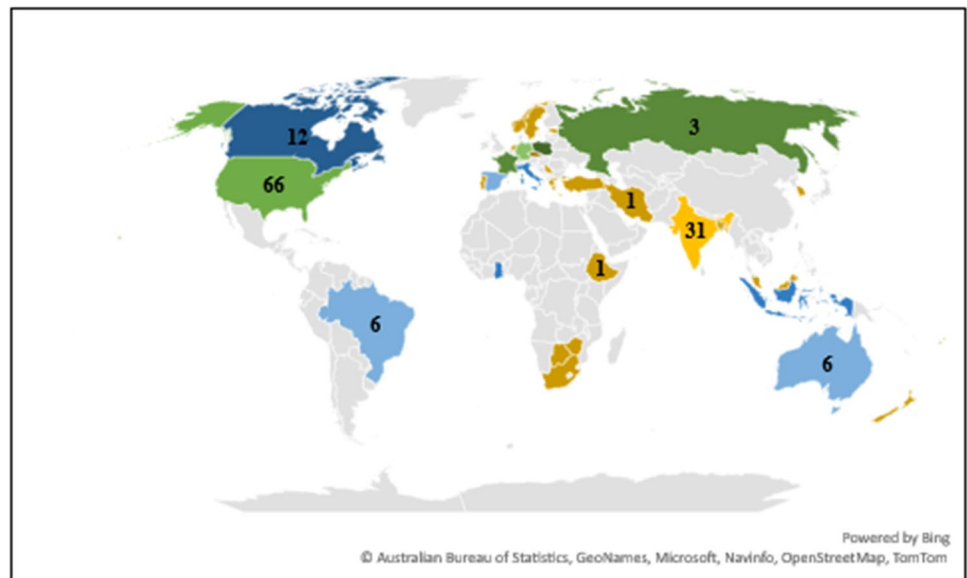

Fig. 2 Country-wise distribution of published research articles on the carbon sequestration potential in reclaimed coal mine site to achieve sustainable development goals (UNSDGs)

highest contributing country followed by China, India, and Poland.

Restoring mine degraded ecosystem for more than to achieve reclamation success

SDG-based environmental management

Generation of huge OB dump and voids during surface mining cause severe landscape disruption and significant disturbances in pedospheric ecosystem. Before the twenty-first century, the aim of PME restoration was mainly confined to "Ecological Restoration v 1.0", i.e. "the process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed" (SER 2004). With the evolution of the restoration ecology domain in the twenty-first century, the aim is modified to "Ecological Restoration v 2.0", i.e. "the process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed to reflect ecosystem value and to provide ecosystem goods and services (EGS) for socio-economic well-being". Therefore, in recent decades, the focus of global research has shifted from evaluating reclamation success in afforested PME to providing EGS for a clean, sustainable environment by accelerating CO_2 offset potential and regaining carbon dynamics in the vegetation-soil-atmosphere C cycle.

An effective and successful phyto-management (revegetation or afforestation) approach for PME restoration,

towards achieving the goals of Paris Agreement and UNSDG-13, depends on the availability of appropriate growing substratum for vegetation establishment which will act as a "Cradle for nature" on RMS (Haigh 2018). In this context, application of topsoil (either stockpile or concurrent manner) as a blanketing material over slope of unreclaimed OB dump for at least 40 to 60 cm depth is broadly acknowledged as one of the critical steps for assuring vegetation establishment (Maiti 2013; Tripathi et al. 2014). In some instances, inoculation of beneficial soil microbes (i.e. nitrogen fixing, phosphorus solubilizing bacteria) during mixing of topsoil (grading of OB dump) can enhance the quality of growth substratum that positively reflect biomass growth and pedogenesis. Mine spoil composition can influence the rate of carbon sequestration through the interaction between spoil and vegetation biomass (aboveground: AGB and belowground: BGB) production and affinity of PME to stabilize carbon inputs into SOM pools. Carbon dynamics reflect a long-term balance between terrestrial carbon input (photosynthesis, litterfall, root exudates, root turnover) and losses (respiration, decomposition, erosion, leaching) in reclaimed ecosystem. Decomposition of SOM facilitates the soil-atmosphere carbon cycle by emitting a part of SOC to the atmosphere as CO_2, whereas a portion is sequestered in soil humus. As SOM decomposition rate is proportional to SOM content in soil, stabilization in carbon dynamics at a steady-state level could be achieved over chronosequence age and under relatively similar environmental circumstances through the equilibrium between the rates of C emission and sequestration. The recent research interest in carbon sequestration potential of reclaimed ecosystem is centralized on improving its natural capability to enhance the rate of SOM input with a long residence time so that derelict mine spoil accumulates carbon through the development of soil horizons to off-set fossil fuel emissions. Therefore, carbon pool formation in reclaimed coal mine sites, both in live tree biomass (AGB, BGB) and in soils, with longer residence time, making PME conversion to forest ecosystem with larger sink of CO_2.

EGS-based environmental management

The development and survival of global population depend directly or indirectly on overexploitation of abundant ecosystem resources. As per the FAO and UNEP (2020), the natural forest ecosystem continues to get reduce by 420 million hectares during last three decades (1990–2020) at unprecedented rates due to massive anthropogenic land-use changes to support urbanization and the industrial revolution (IPCC 2014a, b). In a nutshell, forest ecosystems have the potential to provide a wide range of ecological functions, ecosystem goods and services, societal and environmental profits such as carbon sequestration, climate regulation, water purification, biomass production, nutrient cycling, habitat provision, cultural and aesthetic benefits that are currently subjected to strong pressure due to mining activities, other infrastructure explosion, and agricultural expansion (Carrasco et al. 2014; Margono et al. 2014).

Ecosystem degradation and biodiversity loss jeopardize ecosystem function, resilience, and its ability to provide a continual flow of ecosystem services to present and future generations. The novel concept of ecosystem services can be defined as "the direct and indirect contributions of ecosystems to human welfare and subsistence" (MEA 2005; TEEB 2011; IPBES 2014), which is of current interest due to its potential to integrate the ecological, economic and social beneficial aspects (Bouwma et al. 2018). Evaluation of the economic value of EGS due to deforestation is thus obligatory to support proper LULC decision-making policies for restoration of coal mine degraded land that can comprehend the trade-off among ecosystem services (ES) provision, biodiversity conservation, carbon sequestration, and mine restoration. Hence, the revegetation approach to coal mine degraded sites would provide a range of EGS, depending on site-specific socio-economic conditions, and bio-physico-chemical characteristics (de Groot et al. 2012).

Economic valuation of EGS for sustainable development

Ecosystem goods and services are a significant contributor to sustainable human welfare. Due to massive anthropogenic land use changes, the global value of EGS has reduced by approx. USD 20 trillion/year between 1997 and 2011 (Kubiszewski et al. 2017; Costanza et al. 2014). For the maintenance and amplification of multiple ecosystem services (ES) from afforested ecosystem in reclaimed coal mine site or planted forest, the researchers and policy makers must be proficient in thorough qualitative and quantitative assessment, monetary valuation, and documentation of ES. The economic valuation of ES is a significant tool that not only promotes awareness and explains the relative importance of biodiversity to policy makers and company stakeholders (Baral et al. 2016), but also enables more efficient utilization of limited funds through recognizing where restoration is economically most significant (de Groot et al. 2012). But there are some additional ambiguities with the economic valuation of ES due to continuous anthropogenic LULC changes, overexploitation of natural resources, and subsequent climate changes at local to global scale (Sannigrahi et al. 2019; Song and Deng 2017; Liu et al. 2017). However, it is difficult to precisely measure the bio-physical economic values of EGS due to

under/overestimation and double counting of many indirect ES (Sannigrahi et al. 2019). Recently, several methods have been implemented to gross estimate "total economic value (TEV)" and "total economic value (NPV)" of EGS including "market price" and "benefit transfer" approach (de Groot et al. 2012; Sannigrahi et al. 2019). The valuation methods are as follows: hedonic pricing, contingent valuation, production approach, conjoint analysis, and spatial biophysical modelling (de Groot et al. 2012; Costanza et al. 2017). From the report of the Indian Institute of Forest Management, Bhopal (Nov 2014) (supported by the Ministry of Environment, Forest & Climate Change, Govt. of India), it can be hypothesized that the EGS expected from reclaimed mine ecosystem could be evaluated from the given parameters such as timber/wood production, bamboo production, fodder production, NWFPs (non-wood forest products), fuel wood, carbon sequestration, gene pool conservation, pollination and seed dispersal, soil conservation, water recharge, carbon storage, and water purification. The economic valuation (TEV, NPV) of EGS due to deforestation (loss of forest ecosystem due to anthropogenic LULC change) is listed in supplementary table 1. The framework for the development of the inter-relationship between sustainable mine restoration and EGS with respect to carbon sequestration is illustrated in Fig. 3.

Sustainable mining and SDG-13 frameworks

From socio-environmental perspective, sustainable mining is an oxymoron: Exploitation of finite natural resources is integrally unsustainable. Mining sector, on the other hand, affords a variety of minerals essential for social welfare. Being a multi-dimensional concept, sustainable mining accompanied with a consolidative approach combines institutional and socio-economic development with environmental upliftment. But, for the implementation of such a strategic concept, it is necessary to build integrated and holistic sustainable development frameworks and action recommendations. Since the commencement of sustainable development, many international organizations such as International Council on Mining and Minerals (ICMM), World Economic Forum (WEF), and United Nations Development Programme (UNDP) have endeavoured to illustrate the concept in the context of the mining industry (Sethi and Emelianova 2011; Buxton 2012;
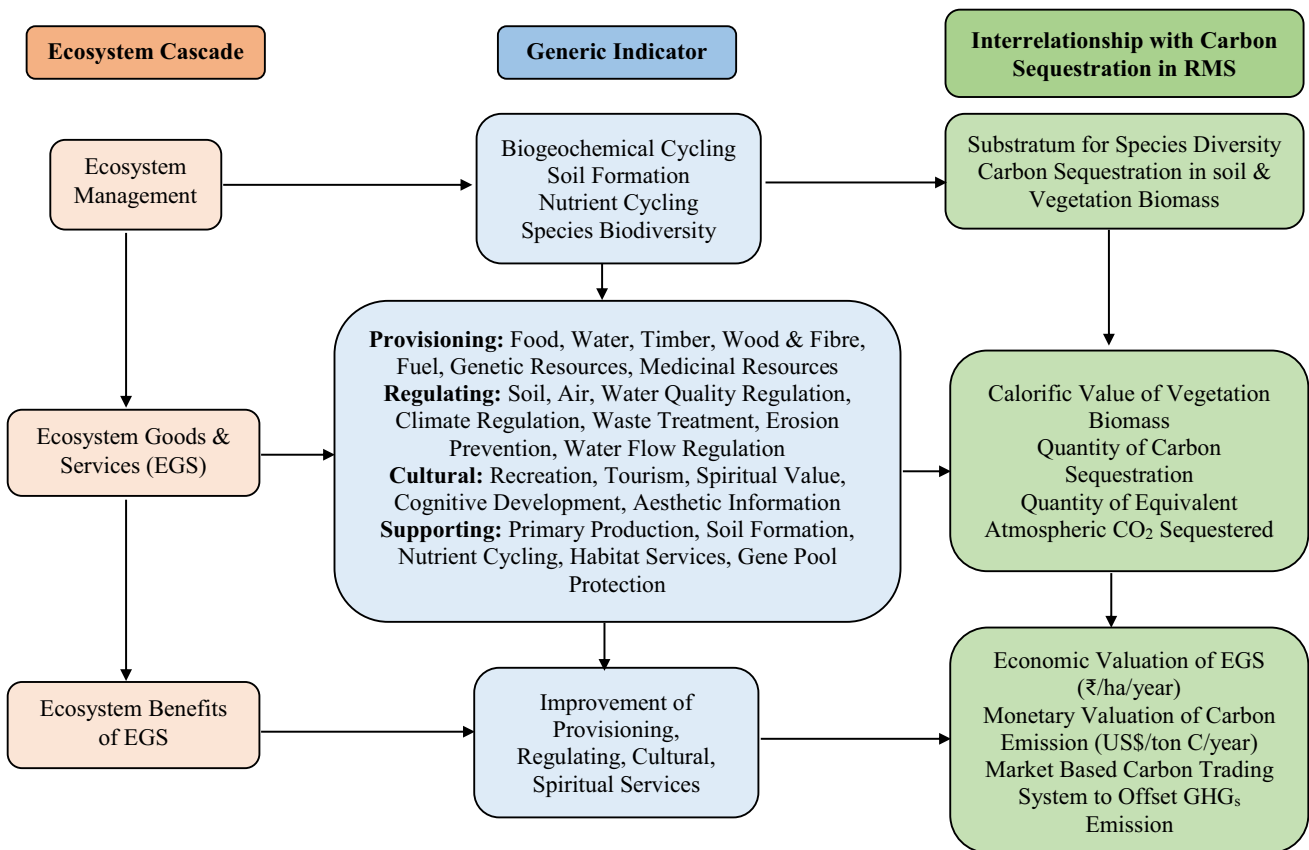

Fig. 3 The framework for the development of inter-relationship between sustainable mine restoration and EGS in respect of carbon sequestration

Sonesson et al. 2016) to present a widely acknowledged framework for disciplinary action. These guidelines (Sonesson et al. 2016) provide insight on what factors establish sustainability in the mining industry and practical suggestions for its stakeholders on how to procure it. In accordance with Starke (2016), a broadly accepted, future-oriented, and politically legitimised approach, the SDGs, would be a breakthrough for mining sector to incorporate its operations within a broader sustainable development framework. In response to extensive criticism, the mining sector has adopted a range of legitimized policies to functionalise a rhetorical transition towards "sustainable mining". Corporate social responsibility (CSR) programs are at the foreground of these sustainable approaches. Gilberthorpe and Banks (2012) emphasized the rationale for the acceptance of CSR towards providing a guideline to attain sustainable development. With the increasing significance of global climate change in the SDG scenario, the mining sector has gradually started to involve with this issue (Grist 2008). The documentations on climate and mining by ICMM demonstrate the compliance of the mining industry to play "a constructive and pragmatic role in climate change policy discussions", which could be a positive symptomatic shift towards attaining the SDGs (Hirons et al. 2014). In accordance with the ICMM climate report, "The role of Mining and Metals in Land-Use and Adaptation" recommends the collaboration of the mining sector with REDD +, but there seems to be little discussion regarding why and how mining industries might involve with land use–based carbon finance initiatives. Schemes, which are primarily considered as a carbon offset alternative, should be materialized by now (ICMM 2013). Payment for ecosystem service (PES) schemes based on the carbon market have proliferated under this paradigm (Olsen et al. 2011), enabling government, private companies, and non-governmental organizations to pay for carbon storage and sequestration (Hirons et al. 2014). There are several examples of carbon-based PES schemes, including the reducing emissions from deforestation and degradation (REDD +), clean development mechanism (CDM), and voluntary carbon market. Forest-based legacies, the potential of which has received limited attention, could be a direct link between mining operations and carbon markets. Under such schemes, mine derelict land could be restored to a forest ecosystem and subsequently returned to local communities so that benefits could be derived through payments for carbon sequestration (Hirons et al. 2014). These initiatives might theoretically intensify CSR agendas by contributing to climate change mitigation and local development. However, no explicit consideration has been given to the possibility of carbon-based PES schemes in a development context at mine-out sites. Miners can help by planning investments,

identifying hazards, designing possibilities, and disseminating transparent report to mitigate the effects of climate change, particularly by monitoring the mine land of different microclimatic conditions so that decision-makers can take steps to do the needful. Furthermore, a collaboration between industry, government, and stakeholders is required to synchronize corporate strategies worldwide to combat climate change.

Phytoremediation — a nature-based solution (NBS) for mine restoration

With the industrial revolution, extensive mining of coal and other natural resources has led to contaminated environment worldwide (Maiti 2013; Ahirwal and Maiti 2018). A variety of conventional remediation technologies are used for environmental decontamination, and new innovative methods are constantly being developed (Zhang et al. 2017; O'Connor et al. 2018; Souza et al. 2020; Gao et al. 2022). However, these technologies frequently rely on the practice of chemical compounds, fossil fuels, and grid-supplied electricity, associated with environmental footprint (Hou et al. 2018). Nowadays, adopting nature-based solutions (NBSs) as a strategy of resource efficient clean-up and enhancing remediation resilience to global environmental change are emerging trends (O'Connor et al. 2019). Compared to conventional methods, NBS approaches to remediation, such as phytoremediation, offer several environmental, social, and economic benefits also. Plant-assisted restoration (phytoremediation) of those abandoned post mining ecosystems is thus an effective option to prevent soil erosion, fix toxic compounds (i.e. heavy metal, PAH), and recover soil fertility and vegetation structure (Ahirwal and Pandey 2021). The phytoremediation approach should not only consider the accumulation of toxic compounds but also often coupled with natural attenuation to achieve recovery trajectory in native climate condition (Arreghini et al. 2017; Maiti 2013). Therefore, native plants species are often selected to obtain the most efficient growth and also the metal accumulating properties because of their adaptability to the conditions and are sometimes required by local regulatory agencies due to concerns over invasive species.

Plant-assisted bioremediation or rhizoremediation refers to the interaction between the rhizosphere and soil microbes resulting in transformation of pollutants into less hazardous compounds (Wei et al. 2021). The rhizospheric microbial diversity is stimulated by the plant roots through substrates (glucose, fructose), soil aeration, exozyme secretion, and nutrient and mineral uptake via root exudation. By fixing nitrogen, mobilizing and solubilizing phosphorus (nutrients), producing growth regulatory compounds, reducing stress hormones, and protecting plants against pathogenic

organisms, these microbes promote the plant growth (Upadhyay et al. 2017; Vishwakarma et al. 2018). Due to the tendency to inhabit internal plant tissue naturally, endophytic bacteria have been included into a recently developed method to boost phytoremediation capacity and to detoxify the contaminants (Khare et al. 2018). Furthermore, carbon storage associated with plant growth and microbial population contributed ex situ carbon sequestration in vegetation biomass of phytoremediator species that partially mitigate global climate change (O'Connell and Hou 2015; O'Connor et al. 2019).

Carbon stabilization — prerequisite for carbon sequestration

Surface mining activities disrupt the carbon equilibrium state in PME, while proper restoration practices promote soil development and associated recuperation of carbon dynamics. With revegetation age, the enhanced potential of carbon equilibrium in reclaimed ecosystem enables carbon stabilization at a constant, near steady-state level. The carbon stabilization, an integral part of carbon sequestration in reclaimed ecosystem for a long-term basis, is determined by technosol properties (physico-chemical and biological), microclimate, prevailing management system, and sustainable land use planning. The mechanisms that are responsible for carbon stabilization in reclaimed ecosystem may be categorized as follows: (a) physical stability or protection, (b) chemical stabilization, (c) biochemical recalcitrance, and (d) thermal stability (Ussiri and Lal 2005; Christensen 1996). The nature, location, and distribution of different organo-mineral associations within soil aggregates determine the extent of physical protection that have the ability to resist microbial population to cause decompose. Complex organo-mineral compounds slow down microbial degradation and contribute recalcitrant soil carbon that persist in soil for years. The microaggregates are more efficient than macro-aggregates for physical stabilization of soil carbon as it is not generally affected by tillage operation, protect soil carbon against decomposition, and more permanent in nature, resulting in longer residence time for soil carbon. Soil aggregate formation is mainly affected by moisture percentage, minerology, clay content, and quality of soil organic matter. Aggregate stability of technosol increases with a combination of improved management practices such as application of organic amendments and reduced tillage. The association between soil minerals and decomposable/recalcitrance organic compounds (e.g. organic carbon trapped between clay layers, i.e. clay-humus complex or adsorbed to clay surfaces through polyvalent cation bridges, hydrogen bonding, Van der Waals forces) is responsible for chemical stabilization that can limit microbial decay to organic inputs. The

biochemical recalcitrance is allied to the chemical composition (stable microaggregates and non-hydrolysable compounds) and degradability of substrate (e.g. lignin and its derivatives such as quinone, polyphenol, and fungal melanin are resistant to microbial decomposition) (Ussiri and Lal 2005). Microorganisms and soil faunal communities promote aggregation by forming binding agents while root exudates flocculate colloids to stabilize aggregates (Shrestha and Lal 2006). Microaggregates (formed due to cementing effects of root exudates, faunal mucus, and microbial cell), which are combined with macroaggregates through enmeshment of larger fragments of particulate organic matter (POM), fine roots, and fungal hyphae, lead to secondary recalcitrance (Lal et al. 2015). The thermal stabilization of soil carbon is interlinked to temperature-driven biochemical degradation. With the increase in soil temperature, the rate of decomposition of soil carbon increases; hence, the degree of stabilization decreases.

Factors affecting carbon sequestration potential of reclaimed ecosystem

Different influencing factors such as soil compaction level, spoil depth, aboveground (AGB) and belowground (BGB) biomass, the presence of N-fixers, and spoil type affect the carbon sequestration potential in PME. The management processes that can influence the rate of accumulation of SOC in aggrading terrestrial ecosystems are as follows: (a) input rates of SOM, (b) decomposability of SOM, (c) incorporation of SOM in deeper soil depth, and (d) enhanced physical protection by intra-aggregate or organo-mineral complexes (Ussiri and Lal 2005). Factors affecting soil properties, SOC dynamics, microbial activity, soil aggregate stability, nutrient availability, soil fertility, and soil horizon development must be incorporated for better understanding the possible interventions for good biomass production and potential sequestration of atmospheric CO_2 towards achieving self-sustainable post-mining ecosystems.

Soil microbial biomass (SMB)

Soil microbial biomass (SMB) is an influential indicator that could provide rapid and accurate statistics of revegetated soil quality and productivity (Xiao et al. 2015; Baqir et al. 2018). Soil microbial community assists to maintain SOC dynamics and nutrient cycling in reclaimed ecosystems (Song et al. 2016). It exhibits large extent of metabolic flexibility and high adaptability to the low nutrient dynamics and adversative characteristics of mine spoil. Microbial processes are mainly influenced by such factors, i.e. temperature, pH, moisture, aeration, and nutrient availability in PME (Mukhopadhyay et al. 2016; Józefowska et al. 2017). Previously,

the development and perseverance of SOC were assumed to be dependent on the chemical "recalcitrance" of plant inputs to decomposition, but recent research suggests microbial necromass as primary contributor of stable SOM fractions in reclaimed ecosystems (Kallenbach et al. 2016; Clayton et al. 2021). Presently, it is hypothesized that after microbial death, a fraction of microbial necromass is stabilized by soil matrix with each iterative microbial community turnover, resulting in a progressive accumulation of SOC (Liang et al. 2017). The stability of a restored ecosystem is determined by evaluating soil microbial populations and their metabolic activity. Microbial biomass is positively correlated to total plant biomass (AGB, BGB, litterfall) of the revegetated mine spoil over time (Tripathi and Singh 2008). With revegetation age, due to improvement in soil aggregation, infiltration, and horizon redevelopment, Singh et al. (2004) reported a continuous increase in microbial biomass in Singrauli coal mine spoils of India. However, more extensive management and understanding of SMB are required to enhance SOC stock and carbon sequestration potential in reclaimed ecosystems (Fang et al. 2020).

Root biomass

Root production and turnover in revegetated mine ecosystems have a direct influence on the biogeochemical carbon cycle of terrestrial ecosystems as plant roots provide a path for energy and carbon movement to the deeper mineral horizon. It is essential to relate the belowground mechanism with aboveground process for understanding the formation of revegetated ecosystem carbon pool. The belowground transmission of carbon by plant roots could be a leading source of SOC (Ussiri and Lal 2005). Recent studies have also exhibited that the interaction between root biomass and rhizo-microorganisms can influence SOC content in revegetated ecosystems (Cheng et al. 2014; Treseder and Holden 2013; Ouyang et al. 2017). Root biomass contributes to SOC pool either as organic debris through plant death or as rhizodeposit exudates (composing of soluble compounds, lysates, secretions, dead fine roots, gases like CO_2, ethylene) through plant growth. Root biomass–driven carbon, an important flux in terrestrial carbon cycle, is critical for ecosystem function, soil health and carbon sequestration (Song et al. 2020; Pausch and Kuzyakov 2018). The contribution of root biomass carbon to the ecosystem carbon pool and carbon sequestration is mainly influenced by vegetation type, root productivity, exudation of organic substances, soil properties (such as moisture, temperature, pH, phosphorus, and nitrogen concentration) (Song et al. 2018; Cheng et al. 2014), turnover rates, and association between root and mycorrhizal colonization (such as symbiosis, competition) (Morriën et al. 2017; Bardgett and van der Putten 2014; Kuzyakov and Xu 2013). Hence, deep-rooted plant species

have the ability to enhance SOC sequestration by transferring SOM into deeper mineral horizons (Tefs and Gleixner 2012; Tripathi et al. 2014), accelerating or decelerating the SOC turnover rate (Kuzyakov 2010), and modulating SOC from microbial secretion and biomass (Clemmensen et al. 2013). For instance, under the alder (*Alnus* spp.) plantation growing on reclaimed technosols, Świątek et al. (2019) analysed the development of fine root biomass and associated carbon pool. They reported the development of carbon pool (108.89–377 g m^{-2} year^{-1}) in technosols through balanced circulation between nutrient deficit condition and decomposition of OM, influenced by the increment of fine root biomass (301–1319 g m^{-2} year^{-1}). Pietrzykowski et al. (2021) estimated carbon sink allocation in BGB of a 12-year-old willow coppice plantation on fluvisol soil in Southern Poland and found the accumulation in coarse roots and fine roots at 1.5 Mg C ha^{-1} year^{-1} and 1.2 Mg C ha^{-1} year^{-1} respectively that mitigate the effects of high CO_2 concentration over a short time span. In similar climatic condition, Świątek and Pietrzykowski (2021) conducted a study to determine the soil factors that increase fine root biomass under pine (*Pinus sylvestris*), birch (*Betula pendula*), and larch (*Larix decidua*) plantation in reconstructed (PME) forest ecosystems. The findings of this study confirmed the significance of fine root biomass to evaluate the soil regeneration and pedogenesis dynamics in reconstructed ecosystems. In another study, Świątek and Pietrzykowski (2022) determined the decomposition rate of fine root and leaf litter on carbon accumulation in different reconstructed forest ecosystems including PME. Over a year of the experimental process, they found that the root decomposition (15–16%) released less carbon compared to leaf litter (27–36%) which proves the importance of fine root input to the soil carbon and nutrient (N, P) pool and their significance for CO_2 sequestration in reconstructed terrestrial ecosystems. However, future research is still required to assess the responses of rhizo-microorganisms to root exudates and their efficacy in enhancing carbon sequestration potential in PME.

Species selection and revegetation age

Since the enactment of the Surface Mining Control and Reclamation Act in 1977, reclamation is practiced to re-establish landscape similar to its pre-mining morphology. To mitigate the adverse impact of mining and initiate ecosystem recovery, self-sustainable revegetation or forestry reclamation strategy is a significant PME management option (Pietrzykowski 2014; Józefowska et al. 2017). But due to unfavourable mine spoil characteristics such as low nutrients and carbon content, low SOM content, poor plant available water reserve, high acidity, electrical conductivity, bulk density, and coarse fraction, the establishment of vegetation restoration is a little bit difficult. In this regard, proper

land use management strategies in reconstructed mine soil (technosol) play a decisive role in recuperating soil properties, ecosystem carbon pool and partially mitigating global climate crisis over chronosequence reclamation age (Frouz 2017). Different technosol properties such as soil structure (aggregate stability, compaction, texture), nutrient dynamics (C:N ratio, NPK inputs), and microbial activity (rhizobacterial interaction, glomalin secretion) accelerate the decomposition rate of SOM and hence affect carbon accretion in PME. Thus, proper species selection and management could enhance the potential of C sequestration in PME through recuperating vegetation biomass (AGB, BGB) production, litter decomposition, rooting depth, and faunal interactions.

For instance, Chatterjee et al. (2009) reported significant increase (from 9.1 to 29.7 Mg ha^{-1}) in soil carbon storage of a restored grassland ecosystem after 30 years of revegetation in China. In similar climatic condition (the Loess Plateau, China), Yuan et al. (2017) reported accumulation of soil carbon at an average rate of 0.94 Mg ha^{-1} year^{-1} in reclaimed forest after 17 years. Reclamation success with enhanced carbon sequestration potential in PME mainly depends upon proper selection of vegetation species, adequate plant growth, and biomass productivity (Shrestha and Lal 2006; Woś and Pietrzykowski 2015; Bandyopadhyay et al. 2020). Selection of proper vegetation species and their diversity has a great impact on soil carbon storage and CO_2 sequestration potential due to litter production and decomposition dynamics, root turnover, rhizospheric carbon input, and soil microbial populations (Lange et al. 2015; Yan et al. 2020; Frouz et al. 2009; Cong et al. 2014). According to previous research, the rates of soil carbon accumulation vary with vegetation species establishment on the postmining lands (Bandyopadhyay et al. 2020; Yuan et al. 2017). In China (RMS of Malan coal mine), Yan et al. (2020) reported accumulation of soil carbon stock at an average rate of 0.46 Mg C ha^{-1} year^{-1} and 0.6 Mg C ha^{-1} year^{-1} under *Rhus typhina* and *Platycladus orientalis* respectively. Precisely, vegetation diversity has been regarded as a significant index to indicate recovery of soil carbon pool in mine degraded area. In another study, after 20 years of reclamation, Lei et al. (2016) exhibited the improvement of Shannon–Wiener index from 0.39 to 2.09 which positively associated to soil carbon content. Moreover, mixed plantation with functionally diverse species could improve nutrient retention, carbon dynamics, and resource utilization efficiency and strengthen the resilience of technosol ecosystem (Ahirwal and maiti 2018). In Indian dry tropical climate (Rohini OCP, CCL), Ahirwal and Maiti (2017) estimated total ecosystem C sequestered increased from 8 to 90 Mg C ha^{-1} (30–333 Mg CO_2 ha^{-1}) after 2–14 years of revegetation (6.4 Mg C ha^{-1} year^{-1}) under mixed plantation such as *Acacia auriculiformis*, *Leucaena leucocephala*, *Dalbergia sissoo*, *Heterophragma adenophyllum*, *and Ficus racemose*. Under the similar climatic

condition, Ahirwal et al. (2018) reported an increase in ecosystem C pool at the rate of 5.38 Mg C ha^{-1} year^{-1} after 15 years of revegetation in which AGB, BGB, and SOC contribute 66%, 16%, and 0.09% respectively.

Application of amendments

The physico-chemical and biological constraints (high pH, bulk density, heavy metals; low fertility, SOM concentration, soil fraction, water holding capacity, microbial population; poor aggregate stability) of PME for efficient revegetation could be ameliorated by the application of different organic amendments that initiate nutrient cycling, soil productivity, and microbial activity, improve soil water retention capacity, and enhance SOM concentration and carbon sequestration. Organic amendments address these limitations through different mechanisms, such as capturing organic carbon in SOC pool, stabilization of heavy metals, directly or indirectly accelerating nutrient release, improvement of soil structure and fertility, moisture properties, and SOM pool. Application of amendments to PME enhances reclamation success (in terms of ecosystem recovery) towards formation of the self-sustaining ecosystem. Organic soil amendments which are commonly used include mulching, grass–legume seeding, and fossil fuel combustion by-products (fly ash). Organic materials can either be used as amendments into surface or subsurface derelict soil or as surface modifier mulch.

Mulching

Mulches are inorganic or organic materials applied on soil as temporary surface cover and soil conditioner for surface stabilization and improvement of soil microclimatic condition for vegetation establishment. Agricultural crop residues (i.e. hay, straw, saw dust, plant residues) and wood residues with high C:N/C:P ratio are often applied as mulch on disturbed land for reclamation purposes (Maiti 2013; Tripathi et al. 2014). The primary roles of surface mulches in reclamation of mine spoils (after seeding of desired vegetation species) include the following: (a) minimization of soil water loss through improvements in infiltration rate, soil moisture holding capacity, surface wetness, and reduction in evaporation; (b) enhancement of soil stabilization by reducing surface soil erosion by wind, water, and raindrop effect; (c) increase in SOM content and SOC stock; (d) reducing soil surface temperature; (e) improvement of soil structural stability and permeability in technosol; (f) reducing weed germination and improving microclimate conditions for desired species used for revegetation and increases plant stand; (g) serving as substrate for beneficial soil microbial organisms; (h) increases soil nutrient dynamics (N, P, K) and CEC; and (i) minimization of surface crust formation (Ussiri and Lal

2005). Additionally, it inhibits the growth of herbaceous plants and thus eliminates competition between undesirable weeds and trees (Maiti 2013). As it is environmentally benign, labour–efficient, and releases nutrients after microbial decomposition, organic mulching has been frequently recommended. This results in SOM input to derelict ecosystem that concurrently augments the soil C and N pools (Frouz 2018; Zhang et al. 2019). Under temperate condition, Singh et al. (2004) reported greater plant growth as well as replenishment of soil carbon from high quality litter fall and root turnover of leguminous plants growing on revegetated mine spoils. In another study, Kumari et al. (2022) reported an 145% increase of much density (Mg ha^{-1}) in reclaimed waste dump under subtropical climatic conditions over 5 years of revegetation with grass–legume seeding that substantially enhanced the soil fertility with organic matter input. Previous literature has also recommended that improving SOM using high-quality biomass residue is the key to manage soil C sequestration (Farooqi et al. 2018; Semenov et al. 2019).

Grass–legume seeding

Numerous issues affect the sequestration and preservation of soil organic carbon (SOC), some of which are driven by human-induced activity, such as the low adoption rate of sustainable soil management techniques (FAO and ITPS 2015; Kumar et al. 2018a, b). Agroforestry, eco-restoration parks, and fruit orchards are the most often used postmining land uses in India (Ahirwal and Maiti 2016). To re-establish the characteristics of a natural ecosystem, it is crucial to restore the degraded areas. In recent years, the applications of grass–legume seeding as a reclamation strategy have gained momentum for the improvement of nutrient-deficient mine spoil. Leguminous species contribute to the N supply in abandoned sites during the early stages of reclamation, so it is crucial to study the early interactions between the impoverished mine spoil and the development of pioneer species (grasses and legumes) in a degraded ecosystem in order to monitor the recovery trajectory. Legume species are one of the significant options for soil C sequestration in PME and plays a critical role to mitigate climate change (Lal 2015). SOC has an impact on soil properties that are related to aggregate stability and soil aggregation (Six et al. 2002). The management of legume residues affects soil aggregation, hence influencing soil C sequestration (Franzluebbers 2002). Naturally, the legume species fix nitrogen (N) through biological nitrogen fixation (BNF) which, in turn, contributes to C sequestration with an average rate of 0.88 Mg ha^{-1} year^{-1} (Diekow et al. 2005; Martins et al. 2012). The extent of soil C sequestration differs among various leguminous species in accordance with total biomass production, decomposition rates, and conversion of liable

C to soil recalcitrant C (Lal 2004a, b; Benbi and Brar 2009; Benbi et al. 2015; Maiti 2013).

Revegetation with grass and legume species as a restoration strategy has been widely used, but a sustained mixture of grass and legume species is rare; instead, the majority of studies reported either legumes or grass species alone. For instance, in Indian scenario, Kumari and Maiti (2019) showed the rate of SOC accumulation and soil respiration were higher under legume *Stylosanthes hamata* (1.57 Mg C ha^{-1} year^{-1} and 2.34 μmol CO$_2$ m^{-2} s^{-1}) than grass *Cenchrus ciliaris* (1.27 Mg C ha^{-1} year^{-1} and 2.17 μmol CO$_2$ m^{-2} s^{-1}). Another study, conducted by Kumari et al. (2022), aimed to evaluate the potential of grass (*Pennisetum pedicellatum*) and legume (*Stylosanthes hamata*) revegetation to restore the soil fertility of an industrial solid waste dump in central India. The study reported an increase of 1.61% of SOM and 1.03% of SOC at a 5-year-old revegetated site, concluding that the direct seeding of grass–legume mixture possibly restores the soil fertility and enhances biomass production that helps to prevent land degradation and achieve UN sustainable development goals such as SDG-13 (climate action).

Fossil-fuel combustion by products

Application of fossil-fuel combustion by-products as soil amendments in restoration of mine degraded ecosystems achieves global attention due to its environmental, societal, and ecological benefits as well as the potential to enhance carbon sequestration by developing mine soil productivity (Ram and Masto 2014; Yao et al. 2015). Fly ash is the major fossil-fuel combustion by-products that can be advantageous for PME reclamation to promote carbon sequestration. Fly ash, a coal combustion residue, is an amorphous aluminosilicate composition comparable to soil with minor content of unburnt coal carbon with quartz, hematite, mullite, and magnetite (Ussiri and Lal 2005). Fly ash, being a source of trace nutrients for plants, can be used to modify soil texture and increase porosity, water retention capacity, phosphate solubilizing bacteria, N$_2$-fixing bacteria, pH, EC, CEC, dissolved CO$_3^{2-}$, SO$_4^{2-}$, Cl$^-$, and other basic cations (Ussiri and Lal 2005; Shrestha and Lal 2006). The potential application of coal combustion by-products to enhance physicochemical properties and carbon sequestration in PME could be accelerated in combination with organic amendments like mulch or grass–legume seeding or biosolids or sludge or manure (Ussiri and Lal 2005; Palumbo et al. 2004). In addition, fly ash promotes flocculation between soil particles and stabilizes soil structure through cation bridging with Ca^{2+} and other divalent cations, while in organic amendments, OM adsorbs to the soil minerals to form more reactive network for nutrient and water interaction on soil that can be enhanced by Ca^{2+}. Hence, the addition of fossil fuel

Table 1 The role of GRSP in C sequestration in revegetated ecosystem (GRSP-C = Glomalin related soil protein-carbon)

Study area	T-GRSP (g kg^{-1})	TOC (g kg^{-1})	GRSP-C (g kg^{-1})	Reference
Reclaimed coal mine dump, India	5.4	15.89	1.82	Kumar et al. (2018a, b)
Forest ecosystem, China	0.17–6.12	0.47–5.07	-	Li et al. (2020)
Planted tropical forest, SE China	2.63	-	19.5	Zhang et al. (2017)

combustion by-products with organic amendments would provide synergistic profits to soil development and carbon sequestration potential in the reclaimed mine ecosystem. Despite of having certain benefits, there are crucial research gaps on the appropriate proportion of both materials (fly ash and organic amendments) to be added, application procedures, management required, and optimal strategies for rapid improvement of carbon sequestration in PME.

Microbial inoculation

Soil microbial community plays a significant role to enhance carbon sequestration by varied mechanisms such as forming recalcitrant vegetative tissue and stable soil aggregates and possessing metabolic activities that capture atmospheric CO_2. Soil carbon pool could be affected by mycorrhizal and rhizobacterial population independently that is far more than the effects of temperature, precipitation, and net primary production (Averill et al. 2014). For instance, arbuscular mycorrhizal fungi (AMF), which obligate plant symbionts, are associated with more than 80% of plant roots that significantly accelerate long-term mine site reclamation success. Due to having large surface area of arbuscules, the symbionts can trade nutrients; hence, AMF acquires carbon from plant with an additional supply of phosphorus (as phosphate) to plants. The direct contribution of mycorrhiza to C accumulation in soil can be categorised in three groups: (i) formation and deposition of mycorrhizal residues; (ii) oxidative and hydrolytic enzyme secretion by mycorrhiza facilitating the decomposition of plant, microbial residues, and SOM as well; and (iii) plant growth stimulation (Agnihotri 2022). AMF enhances the plant growth which, in turn, increased above- and belowground biomass, hence the C input in the soil (especially through roots and rhizodeposition) (Zhou et al. 2020). Intensive studies have focused on the role of the external mycelia (Verbruggen et al. 2016; Soudzilovskaia et al. 2015) and soil aggregation (Daynes et al. 2013; Vogel et al. 2014) in SOC sequestration. Previous studies on how AMF facilitates SOC accumulation have considered the production of glycoprotein (glomalin-related soil protein; GRSP) by external mycelia that can promote the soil aggregation (Rillig et al. 2002; Dai et al. 2015; Xie et al. 2015). Compared with our understanding about the effects of hyphal biomass and soil aggregates on SOC sequestration,

knowledge of how GRSP promoted SOC accumulation is deficient especially for coal mine restoration (Table 1).

Glomalin-related soil protein (GRSP), an insoluble hydrophobic glycoprotein produced from hyphae and spore of mycorrhizal fungi, affects carbon sequestration by means of two ways, viz., (i) assisting soil aggregate formation and (ii) recalcitrant nature that makes it stable in soil environment for long term, subsequently affecting carbon sequestration (Peng et al. 2013; Qian et al. 2012). The estimation of indirect contribution of GRSP on SOC sequestration is critical as it operates mainly through soil aggregation. The formation and stabilization of soil aggregates increase C sequestration through (i) physical protection, (ii) plant growth, (iii) deeper root growth, (iv) increased microbial activity (Subramanian et al. 2019; Wright and Upadhyaya 1998), and (v) increased soil moisture (Carminati et al. 2011). Fungal populations contribute to the atmosphere–soil–vegetation carbon dynamics not only through fungal metabolites production (glomalin) but also via fungal necromass degradation. Fungal necromass is the primary microbial source of stable SOM; hence, mycelial necromass could be a significant source of soil carbon storage. Fungal mycelia could grow into stable soil forms like soil aggregates which would be resistant to deterioration for a long period. Thus, the more fungal necromass remains protected, the more carbon will be sequestered in soils (Agnihotri et al. 2022).

Carbon accretion/sequestration in revegetated mine soil

Globally, different research institutions, ministry projects, non-governmental organizations, state reforestation programmes, and federal agencies are involved in enhancing C sequestration potential in RMS through the revegetation approach with or without amendments that can offset CO_2 emissions due to mining to some extent. The potential of C sequestration in PME can be enhanced through (a) sustainable land-use management and (b) soil and vegetation management. Sustainable land use refers to "the rational development, use, and protection of land resources based on specific space–time conditions and adopting appropriate means and organizational forms". Forest landscape play a critical role in partially mitigating climate change through C sequestration and provide a broad range of

ecosystem services. Forest landscape restoration (FLR) is a long-term process to regain ecological functionality, enhance human well-being in deforested or degraded landscapes, and deliver a broad range of goods and services for a wide range of stakeholders and across different land uses. Moreover, judicious management of soil and vegetation properties resulted in high biomass accumulation, soil health recuperation and balance between input and output of SOC storage that enhance C sequestration potential of PME (Table 2). As estimated by office of surface mining (2003), in the USA, there are about 3.2 Mha of degraded mine spoil that has the carbon sequestration potential at the rate of about 0.5–1 Mg C ha^{-1} year^{-1} through reclamation approaches; therefore, sequestering 1.6–3.2 Tg C year^{-1} into soil and off-setting 5.8–11.7 Tg CO_2 year^{-1} emitted by fossil fuel activities. A chronosequence approach could be a better option to estimate the recovery of PME in terms of carbon stock (both in soil and vegetation species), C sequestration, and its equivalent CO_2 stabilization. Moreover, this approach is highly efficient to overcome the estimation error caused by the initial heterogeneity in fossil C content among sites.

The efficiency of C sequestration of afforested PME is assumed to increase as development of community structure, pedogenesis via proper stand establishment and management. Pietrzykowski and Daniels (2014) assessed the reclamation potential of *Pinus sylvestris* L. for C sequestration in PME and associated interrelationship between soil and vegetation C sequestration, indicating significant potential for development of total ecosystem C stocks of about 50 Mg C ha^{-1} and equivalent increase rate of annual C sequestration of about 1.6–5.6 Mg C ha^{-1} year^{-1} in RMS, Poland. Apart

from that, Quinkenstein and Jochheim (2016) proposed short rotation coppices (SRC) system for the production of woody biomass that could potentially sequestered CO_2 in RMS within soil and biomass. They validated the proposed approach through assessing carbon cycle of *Populus suaveolens* (Poplar) and *Robinia pseudoacacia* (Black locust) with SHORTCAR (carbon model) and found SOC stock of about 8.9 Mg C ha^{-1} and 64.5 Mg C ha^{-1} under Poplar and Black locust respectively over a period of 36 years.

Land-use policy and land-use conversions are key influencing factors of SOC dynamics and its equivalent CO_2 sequestration in PME. Ussiri et al. (2006a, b) conducted a study to evaluate the effects of converting pastureland to *Casuarina* spp. and *Robinia pseudoacacia* L. forest in RMS of south-eastern Ohio and found the development of SOC pool by 6 Mg C ha^{-1} (11%) and 24 Mg C ha^{-1} (42%) respectively in 10 years. Similarly, after 24 years of management practices under different land-use effects (meadow, hay, grazing, grazing-feeding) in RMS of south-eastern Ohio, Ussiri et al. (2006a, b) observed SOC dynamics in order of grazing-feeding (89 mg ha^{-1}) > hay (76 mg ha^{-1}) > grazing (70 mg ha^{-1}) > meadow (64 mg ha^{-1}). In similar environmental conditions, Shrestha and Lal (2010) reported improvement of ecosystem carbon pool at the rate of about 5.1 Mg C ha^{-1} year^{-1} after 25 years of reclamation under forest and pasture ecosystem in Ohio, USA. Moreover, under different land-use conversions, Ahirwal et al. (2021) showed 84% and 50% reduction in soil CO_2 sequestration in reclaimed mine soil and agricultural soil respectively compared to natural forest sites.

Table 2 Comparative analysis of carbon sequestration rate in reclaimed mine soil

Ecosystem	Revegetation age (years)	C sequestration rate (Mg C ha^{-1} year^{-1})	References
Reclaimed mine soil, Ohio, USA	25	0.2–2.6	Akala and Lal (2000)
Reclaimed mine soil, Ohio, USA	0–21	1.64	Akala and Lal (2001)
Reclaimed forest Singrauli, India	5	0.1–3.2	Singh et al. (2006)
Reclaimed forest, Czech Republic	22–32	0.1–1.2	Frouz et al. (2009)
Reclaimed mine soil, Ohio, USA	25	1.5	Shrestha and Lal (2010)
Reclaimed coal mine, Singrauli	19	3.64	Singh et al. (2012)
Reclaimed coal mine, West Virginia	22	2	Chaudhuri et al. (2013)
Reclaimed coal mine, India	19	1.21	Tripathi et al. (2014)
Reclaimed coal mine dump, Czech Republic	11	0.9	Bartuska and Frouz (2015)
Reclaimed mine soil, USA	21	2.78	Avera et al. (2015)
Reclaimed coal mine, India	19	3.65	Tripathi et al. (2016)
Pingshuo opencast coal mine, ChinaReclaimed coal mine, Singrauli	25	3.58	Yuan et al. (2017)
Reclaimed coalmine, Rohini OCP, India	11	1.7	Ahirwal et al. (2017)
Reclaimed coal mine, Singrauli, India	25	6.2	Bandyopadhyay et al. (2020)
Xishan coal mine, China	12	0.99	Yan et al. (2020)

Carbon budget for reclaimed post mining ecosystem

Carbon sequestration shows the removal of CO_2 from atmosphere by the way of equivalent CO_2 out of the total carbon sequestered to the reclaimed ecosystem. Therefore, an evaluation of carbon budget over a chronosequence is very essential to identify sustainable management options for improved C sequestration potential in PME. The carbon budget is defined as "the net ecosystem production (difference of C absorption by plants and C release by soil in RMS), which includes carbon pools, CO_2 flux for the ecosystem and the net C exchange between atmosphere and RMS" (Shrestha and Lal 2006). Carbon input of RMS ecosystem includes AGB, BGB, amendments (such as manure, microbial inoculation, mulch), and precipitation. Likewise, carbon output includes carbon loss from the ecosystem by respiration, leaching, and erosion. There are very few published literatures on carbon budget in RMS ecosystem.

Different methodologies (carbon balance model including Sim-CYCLE model, CENTURY model, FORCARB2 model, InTEC model, and CBM–CFS2 model; eddy covariance; mass balance model) at (a) terrestrial or regional or national scale and (b) ecosystem or farm scale are adopted for the estimation of carbon budget in other ecosystems are mentioned in Table 3.

The carbon budget of degraded ecosystems like PME needs to be improved for achieving optimum reclamation success trajectory so that it can be concluded that whether a degraded mine ecosystem is a C sink (positive NEP) or a source (negative NEP). The proposed equation for ECB calculation is as follows (Paustian et al. 1990):

$$\text{Carbon Budget} = \sum C_{INPUT} - \sum C_{OUTPUT}$$

From India, Singh et al. (2012) estimated an annual carbon budget of about 8.40 t C ha^{-1} year^{-1} in 19-year-old revegetated mine spoil in Singrauli coalfield out of which 2.14 t ha^{-1} was allocated in AGB, 2.88 t ha^{-1} in

Table 3 Carbon budget (g C m^{-2} year^{-1}) of different types of ecosystem

Ecosystem type	Country	ECB method	C Budget (g C m^{-2} year^{-1})	Reference
Forest				
Pinus sylvestris (40 years old)	South Finland	Eddy covariance	$+228$	Kolari et al. (2004)
Pinus pinaster	Les Landes, France	Eddy covariance	-200 to -340	Kowalski et al. (2003)
Boreal and temperate forest	Ontario, Canada	CBM-CFS2 model	-40	Liu et al. (2002)
Forest ecosystem	Ontario, Canada	CBM-CFS2 model	-43	Peng et al. (2000)
Native forest	New Zealand	Mass balance and modelling	-136	Tate et al. (2000)
Agriculture				
Mixed crops agriculture	Denmark	Eddy covariance	-31	Soegaard et al. (2003)
Corn crop	Ohio, USA	Cropland ecosystem model	$+26$	Evrendilek and Wali (2004)
No tillage — corn-soybean mixed crop	North Central USA	Eddy covariance	$+90$	Hollinger et al. (2005)
Chisel ploughed, fertilized — corn crop	Wisconsin, USA	Difference method	-90 to $+590$	Brye et al. (2002)
No tillage, fertilized — corn crop	Wisconsin, USA	Difference method	-210 to $+430$	Brye et al. (2002)
Grassland				
Miscanthus sinensis	Nagano, Japan	Ecological method	-100 to -56	Yazaki et al. (2004)
Pasture	New Zealand	Mass balance and modelling	-414	Tate et al. (2000)
Grassland	Cork, Ireland	Eddy covariance	$+236$	Leahy et al. (2004)
Tall grass prairie	Oklahoma, USA	Eddy covariance	-8	Suyker and Verma (2001)
Tall grass prairie	Wisconsin, USA	Difference method	-410 to $+70$	Brye et al. (2002)
Mixed grass prairie	North Dakota, USA	Soil flux	$+31$	Frank and Dugas (2001)
Moist mixed prairie	Alberta, Canada	Eddy covariance	-18 to $+21$	Flanagan et al. (2002)
Reclaimed mine site				
Revegetated mine spoil (19 years old)	Singrauli, India	Ecological method	8.40 (t C ha^{-1} year^{-1})	Singh et al. (2012)
Revegetated mine spoil (19 years old)	Singrauli, India	Ecological method	354.79	Tripathi et al. (2014)
Afforested mine soil (7 years old)	Jharkhand, India	Ecological method	-6.44	Ahirwal et al. (2021)

litter biomass, 0.31 t ha^{-1} in BGB, and 1.35 t ha^{-1} in soil. Likewise, in revegetated mine wasteland from dry tropical ecosystem, India, Tripathi et al. (2014) estimated the carbon budget as about 354.79 g C m^{-1} year^{-1} through ecological method (revegetation).

Carbon dynamics in reclaimed mine ecosystem

Generally, soil carbon pool is extremely in dynamic equilibrium with its ecosystem because, at one end, it acts as energy source for all microbial population and faunal community in soil environment, and on the other hand, due to having low density, it is preferentially removed by erosional process. The magnitude of change in SOC pool depends on the balance between carbon input (Eq. 1) and output (Eq. 2).

$$\text{Carbon Input}(CI) = AGB + BGB + LB + AM \tag{1}$$

where AGB = aboveground input, BGB = belowground input including root exudates, LB = litter biomass input, and AM is the amendments related input of biomass-C including compost, crop/animal residues, etc.

$$\text{Carbon Loss}(CL) = M + E + L \tag{2}$$

where M = mineralization, E = erosion, and L = leaching. The magnitude of change in SOC pool, by natural or anthropogenic factors, depends on the balance between I and L (Eqs. (3) and (4)).

$$\text{Carbon Sequestration or Accretion} : CI > CL \tag{3}$$

$$\text{Carbon Degradation or Depletion} : CI < CL \tag{4}$$

Only if the erosion-induced loss is successfully controlled and leaching losses (dissolved organic carbon) are insignificant, the SOC pool can reach a new equilibrium with changes in land use and management practices. As a result, the aim of management strategies is to keep the positive SOC budget by strategically boosting CI and reducing CL. Site-specific recommended management practices (RMPs) to generate a positive SOC budget include chronosequence reclamation with properly selected vegetation species and judicious application of amendments (mulching, liming, microbial inoculation, manure/compost). But, all of these RMPs have trade-offs that must be critically assessed under site-specific conditions.

CO$_2$ offset to mitigate climate change from reclaimed mine ecosystem

Mining and associated activities cause severe perturbation of terrestrial ecosystem, resulting in severe land degradation and global climate crisis. Soil restoration strategies in mine spoils can reverse the degradation trends, resulting in ecosystem development and enhanced SOC sequestration. Mine spoil reclamation helps to develop soil horizons relatively fast, hence, enhance sequestration potential of C, and thus reclaimed soil represents a large sink for atmospheric CO$_2$. Though, the initial SOC content of RMS, when compared to undisturbed soils, is relatively very low, but with the revegetation age, it gradually increases. The rate of carbon sequestration is determined by the productivity of land uses established on reclaimed sites and technosol qualities. Hence, mine soils have a substantial potential to boost their C capital. The ability of a soil to sequester carbon is determined by accretion and the present level of carbon in the soil. Due to the challenges (such as presence of coal particles, coal dust and carbonates) of accurate analytical quantification of carbon fraction sequestered to soil through biological processes, the rate and the degree by which RMS capture CO$_2$ and sequestered carbon in degraded terrestrial ecosystems are still obscure. The PME under sustainable land use planning (forestry reclamation) that improve carbon sequestration potential have a comparatively large capacity to off-set CO$_2$ emissions from mining. Therefore, trading of carbon credits for RMSs requires careful consideration for encouraging mining sectors or stakeholders to adopt reclamation practices and self-sustaining land uses that maximise carbon sequestration. For instance, as estimated by Shrestha and Lal (2009), "the 3.2 million ha of reclaimed forest mine soil can offset 30 teragrams (Tg) of CO$_2$ each year and on the above basis the revegetated mine spoils in the United States could offset approximately 1.5 Petagrams (Pg) of CO$_2$ produced by coal combustion over 50 years". On the other hand, soil microbial activity strongly controls ecosystem net primary production and most of the nutrient requirements of terrestrial plant species through the mineralization of soil organic nutrients. Due to their strong tolerance for stress conditions, microbial populations assist in C sequestration in mine spoils. Microbes have physiological systems to survive and to stay active in stressful situations, and they acclimatize to stress by shifting resource allocation from growth to survival mechanisms, unless the stress is too severe. It has, however, been employed to a lesser extent as a measure of RMS's potential for carbon turnover.

Sustainable land management (SLM) towards carbon sequestration and mitigation of climate change

A sustainable land management (SLM) system is defined as "a knowledge-based combination of technologies, policies, and practices that integrate land, water, biodiversity, and environmental factors to meet rising food and fibre demands, while sustaining ecosystem services and livelihood" (Lal et al. 2011). Moreover, the United Nations defines sustainable land management (SLM) as "the use of land resources, including soils, water, animals and plants, for the production of goods to meet changing human needs, while simultaneously ensuring the long-term productive potential of these resources and the maintenance of their environmental functions" (available at https://www.fao.org/land-water/land/sustainable-land-manag ement/en/). Globally, mining and associated alteration in land use land cover (LULC) are major contributor of soil carbon loss and GHG emission. In other words, sustainable mining practices and proper PME management offer significant mitigation potential for global climate crisis (Xie et al. 2020). Thus, SLM, in terms of introducing forest restoration approach (FRA), forest and landscape reclamation (FLR), and Miyawaki afforestation approach, could be one of the recognised options for restoring ecological functionality, soil carbon loss, and carbon sequestration potential due to deforestation or forest degradation during mining. Through the implementation of SLM, such as soil redevelopment, vegetation reconstruction, land remodelling, the PME will be progressively transformed from "carbon source" to "carbon sink". During the planning for SLM, attention should be paid to the selection of plant species with high adaptability (with adverse physico-chemical and climatic condition), nitrogen fixing capacity (like legumes), good growth rate of root system, high survival rate, potential to produce huge organic waste (like litter fall, dead leaf, stem), and economic value. In order to reconstruct a technically feasible, environmentally sustainable, and economically viable ecosystem, stakeholders and policy makers need to understand the carbon sequestration dynamics of mining areas and take decisions on future mining activities (Maraseni and Mitchell 2016).

The post-mining LULC planning should be favourably as forestland, grassland or cultivable land having strong carbon sequestration capacity to compensate large quantity of carbon emission through mining operations. Carbon sequestration of RMS has huge carbon emission mitigation potential with a broad range of synergies such as enhanced ecosystem productivity and soil health. The advancement of a SLM-based ecological restoration plan should include following approach:

Forestry reclamation approach (FRA)

In the USA, a five-stage method is being used to promote high-yielding forest areas on coal-mining soils under the SMCRA 1977 (Surface Mining Control and Reclamation Act), which is directed by the U.S. Department of the Interior Ministry of Surface Mining Reclamation and Enforcement (Adams 2017; Burger et al. 2005; Burger and Zipper 2011). This method is known as the forestry reclamation approach. Two of the five phases are technological remediation, and three are biological remediation. Such steps are as follows:

Build an effective rooting platform for productive plant growth

Thickness of rooting medium for good tree growth is key to the success of FRA approach, which should be greater than 1.22 m (4 feet) deep and comprised the best available soil forming material. The selection of the best growth medium will depend on local environment conditions and best available soil material. Topsoil is precious resource, and it should be conserved and reuse concurrently whenever possible.

Ensure a noncompacted surface

Excessive soil compaction can have a major negative effect on tree survival and growth. Even if a soil's chemical and nutritional properties are ideal, excessive compaction will create a compacted soil which will be poorly suitable for trees. To re-establish a healthy and productive forest in backfilled areas, final grading does such a way that it must minimize surface compaction.

Use ground vegetation covers

For slopes, soil cover vegetation must be used to prevent erosion and stability. Ground vegetation should include grasses and legumes which are rapid growing, have straggling developmental patterns, tolerant to wide range of environmental condition, and enhance nutrients and moisture contents.

Planting of tree species

Crop trees: economically important, indigenous, woody crop species.

Nursery trees/wildlife trees: Trees and shrubs which can fix nitrogen and/or attract wildlife, including birds. Nursery trees are grown to support the crop trees by improving the nitrogen status, organic matter of soil and enhancing soil physical properties.

Using appropriate tree plantation strategies to ensure a high rate of seedling survival

There are several options available for the development of vegetation cover on mine spoils. Few important methods are:

(i)   Planting of seedlings
(ii) Transplanting
(iii) Habitat transfer
(iv) Natural recolonization

Forest landscape restoration (FLR) approach

Forest and landscape restoration addresses landscape restoration, frequently involving some ecosystems and land uses, as a means of permitting users to attain trade-offs between contradictory interests and harmonizing social, cultural, economic, and environmental benefits. Forest landscape restoration (FLR) is a continuous procedure of restoring ecological functionality and improving human well-being across degraded forest landscapes. FLR is more than just implanting trees, restoring the entire ecosystem to meet present and prospective needs and providing numerous benefits and land usage over time. Successful FLR is progressive, centralized on improving environment resilience and providing potential opportunities for adapting and further optimizing ecosystem goods and services as community demands alter or new challenges emerge. It combines a variety of guiding principles, including:

(a) Special emphasis on landforms — FLR generally occurs within and across the whole ecosystems, not individual locations, rather reflecting mosaics of dynamic land use and management processes under different tenures and governance structures. It is aimed at the stage that ecological, societal, and financial interests can be harmonized.
(b) Encourage shareholders and promote collaborative governance — FLR dynamically involves shareholders on a variety of ranges, like, in land use planning and policymaking, restoration aims and approaches, execution approaches, benefit allocation, monitoring, and review procedures.
(c) Customize to the specific context using a wide range of perspectives — FLR utilizes a variety of strategies that are tailored to social, local, economic, ecological, and cultural values, requirements and ecosystem history. It is mainly based on the modern science, best practice, conventional and primitive knowledge, and application of this information in the circumstances of local capacity and recent or existing governance systems.

(d) Restore various roles to additional benefits — The objective of FLR is to restore various social, ecological, and financial activities across the ecosystem and to create a variety of EGS (ecosystem goods and services) that support several stakeholders.
(e) Dynamically regulate enduring resilience — FLR aims to improve the sustainability of the environment and its shareholders in the long and medium term. Reclamation strategies should improve genetic and species diversity and be balanced over time to represent climate change and other environmental factors, experience, capacity, needs of shareholder and social values. As reclamation improves, information from monitoring operations, analysis, and shareholder advice should be incorporated into administration plans.

Miyawaki method

Miyawaki is a method invented by Japanese botanist Akira Miyawaki which aims to develop dense native forests. The idea of sustainable afforestation has been revolutionized by transforming polluted land into mini-forests. This approach involves planting trees (only native species) as close as possible to the area, which not only redeems space, but also encourages each other to grow (self-sustainable) and prevents sunlight from entering the soil, thus mitigating weed growth. The concept behind this approach is grounded on the assumption that indigenous or conventional trees in a specific local area are more capable of maintaining a healthy and self-sustaining ecosystem than the exotic and foreign plants that are artificially grown in that particular region. The strategy is intended to certify that plant growth is 10 times faster, and the resulting cultivation is 30 times denser than usual. The Miyawaki method will help to form a forest in only 20 to 30 years, while traditional methods would take anywhere from 200 to 300 years (Ranjan et al. 2015). This method includes following steps:

(a) The indigenous plant species of the area are acknowledged and separated into four layers: shrubs, sub-tree, tree, and canopy.
(b) The analysed soil quality and biomass which would help to improve the perforation capacity, water retention capacity, and nutrient in it.
(c) A mound is built with the soil, and the seeds are planted at a very high density — 3 to 5 saplings m^{-2}.
(d) The ground is enclosed with a thick layer of mulch.

Native or traditional trees of a particular area have more capability of creating a good and self-sustained ecosystem than the exotic and foreign species which are grown artificially on that particular area. The advantages of this

method are as follows: faster result, cost-effective, self-sustained ecosystem, and no special care is required as native plant species are used.

Potential benefits of carbon sequestration towards achieving the SDG target

After the oceanic and geogenic carbon pool, terrestrial ecosystems are the 3rd largest global carbon pool. Carbon sequestration is defined as, "process of transferring CO_2 from the atmosphere into the soil of a land unit through unit plants, plant residues and other organic solids, which are stored and retained in the unit as part of the soil organic matter (humus)" (Lal et al. 2015). Generically, carbon (C) sequestration in soil refers to "capture and secure by storage of atmospheric CO2 with pedosphere in a manner that also increases its mean residence time (MRT) and minimizes sinks of re-emission" (Lal 2007). The primary aim of carbon sequestration are as follows:

(a) Off-setting anthropogenic emission of GHG by fossil fuel combustion, industrial process, and deforestation
(b) Reduction in net increase of atmospheric CO_2 concentration and carbon pool
(c) Improving SOC pool in degraded ecosystem
(d) Development of soil quality and associated ecosystem goods and services (EGS)
(e) Improving nutrient (N, P, K) and water retention capacity
(f) Reduction in risk of soil erosion and non-point source pollution
(g) Increasing sustainable productivity and ecological security

The Clean Development Mechanism (CDM) under the Kyoto Protocol recognizes the significant potential of carbon sequestration through forestry reclamation as a way forward to mitigate global warming and to offset carbon emission by developing countries through investing in forestry reclamation project (FRP). The benefits of carbon sequestration in terms of improved carbon management at different scale are as follows:

Sustainable development

The concept of sustainable development has been incorporated in various socio-academic domain since its commencement through the World Commission on Environment and Development (WCED) on the international political agenda in 1987. Sustainable development is defined by the Brundtland Commission as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs". The concept of sustainable development has been embraced by the mining industry through initiating "reclamation approach" in post-mining degraded landscape to meet societal needs. Besides being the most important support system for socio-economic infrastructure, mining industry also fulfils community needs by re-establishing "ecosystem services" on PME. Therefore, development of potential carbon sequestration capacity in degraded mining areas through revegetation strategy could be a significant step towards achieving sustainable mining as well as SDG-13 during 2021–2030. As estimated by Lal et al. (2018), the global potential of terrestrial carbon sequestration would be about 333 Pg C that equivalent to atmospheric CO_2 capture of about 156 ppm by the end of the twenty-first century. Such a potential of reclaimed ecosystems possesses different co-benefits that strongly support UNSDGs, such as "zero hunger" (SDG-2), "life on land" (SDG-15), and most importantly "climate action" (SDG-13).

Ecological restoration

Ecological restoration of post-mining degraded sites is a "green and sustainable strategy" to achieve climate change mitigation, socio-economic benefits, biodiversity conservation, soil and hydrological stability, and other ecosystem goods and services. The recovery efficiency of carbon capital in RMS is significant, as, compared to undisturbed control soil (natural forest), the carbon percentage in mine spoil is typically very low. Improvement in carbon sequestration potential in RMS corresponds to the increase in soil fractions, SOM, litter decomposition, and development of soil horizon and hence indicates initiation of pedogenesis process and effective ecological restoration. Thus, proper management plans in restored sites are required to recover SOC and increase carbon sequestration potential to combat partially with global climate crisis. It is the high time to implement sustainable restorative land use policy and soil carbon management systems to reinforce (i) provisioning of ecosystem goods and services (e.g. food and nutritional security, climate change mitigation, and water security) and (ii) the UNSDGs by recarbonization of the terrestrial biosphere. The process involves a two-pronged approach: (i) restoration of mine degraded ecosystems and (ii) adoption of best management practises (BMPs) after restoration to increase (i) the net primary productivity (NPP) of degraded and restored ecosystem and (ii) mean residence time (MRT) of the carbon sequestered in NPP by transformation into stable SOC protected against decomposition

either by translocation into the subsoil or other edaphic mechanisms (Lal et al. 2018).

Enhancement of soil health

The aftermath of surface mining led to deterioration in soil health and loss of nutrients due to complete destruction of natural vegetation and topsoil cover. Reclamation of PME with proper land use policy and management could able to reinstatement of pre-mining ecosystem in all structural and functional aspects. According to Pietrzykowski and Krzaklewski (2010), forestry reclamation approach plays a pivotal role in carbon sequestration in soil, vegetation biomass and equivalent absorption of carbon dioxide (CO_2) from atmosphere. Forest ecosystems, by accumulating carbon in vegetation biomass, also play an important role in global carbon recycling (Pietrzykowski and Daniels 2014). The long-term carbon retention capacity of soil depends upon the adequate land management practices such as application of grass–legumes; the conversion of PME to perennial vegetation (grass or trees) decreases the amount of fallow land and planting of shrubs and trees such as windbreaks.

Balancing global carbon cycle

Terrestrial ecosystems, comprising soil and vegetation, have a large impact on the global carbon (C) cycle and act as a sink for atmospheric carbon dioxide (CO_2) and methane (CH_4) under natural conditions. Conversion of natural to managed ecosystems (such as urban lands, agroecosystems, and mining lands) deteriorates ecosystem carbon stocks, exacerbates gaseous emissions, and aggravates radiative forcing. Thus, the advent of industrial evolution apparently altered these sinks into sources of greenhouse gases (GHGs), primarily CO_2, CH_4, and nitrous oxide (N_2O), depleting terrestrial C stocks (soil, vegetation, and peatlands). Because of the relationship between SOC stock and atmospheric CO_2 concentration, recarbonization of the terrestrial biosphere (soil and vegetation) could be an essential technique to minimize anthropogenic climate change (ACC) and boost other ecosystem services. Recarbonization of the terrestrial biosphere refers to the formation of positive carbon budget in soil and vegetation through conversion of degraded ecosystems to a restorative land use and adoption of best management practices (BMPs) (Smith 2016). In this context, French government in UNFCCCOP-21 (The Paris Climate Agreement, December 2015) recommended a voluntary plan of "4 Per Thousand" (4PT) to sequester carbon in world soils at the rate of 0.4% annually to 0.4 m (1.3 ft) depth (UNFCC 2015) to offset anthropogenic emissions. Soil acts as the greatest terrestrial carbon sink globally, storing round about 2157–2293 Pg of carbon to a depth of 1 m (Batjes 2014). Both organic and inorganic carbon stored in soils and vegetation comprise the terrestrial carbon pool. The SIC pool primarily consists of carbonate minerals such as $MgCO_3$, $CaCO_3$, and elemental carbon, whereas the SOC pool mostly includes plant-derived carbon and highly active humus. In terrestrial ecosystems, carbon recycling is primarily achieved by photoautotrophs, which utilize solar energy to transform atmospheric CO_2 into more complex carbon molecule and organic matter. Bound C molecules disintegrate during plant respiration, and the monomeric units are transported to the mineral soil as rhizodeposits, released CO_2 into the atmosphere. Hence, soil serves as both a sink and a source for carbon in the terrestrial environment. Soils, through respiration, emit 94.3 Pg C year^{-1}, which is the second greatest C flow after gross primary productivity (Xu and Shang 2016). The global C cycle is balanced by these C fluxes in the terrestrial biosphere. However, natural or anthropogenic activities, i.e. LULC change, fossil fuel combustion, and other variables, have had a considerable impact on these fluxes over the last century, reducing soil C sequestration and increasing atmospheric CO_2 emission.

Conclusion and future recommendations

Global climate change has off-centre considerations in mining industry, but nowadays, nascent efforts to involve with the carbon-based PES scheme to adopt self-sustainable ecosystem have highlighted the potential of forestry reclamation approaches to provide ecosystem goods and services. The 17 sustainable development goals (SDGs) appeared as guidelines for an action plan designed for pursuing an environmentally sustainable future accompanied by economic growth and societal well-being. In order to achieve UNSDG-13 (climate action) during UN decade of ecosystem restoration (2021–2030), mining companies need to pay attention towards formation of sustainable mining strategies by harnessing carbon sequestration potential through forestry-based reclamation. Reforestation in PME boosts up the carbon storage recovery both in plant biomass (AGB, BGB, Litterfall, root biomass) and soil (SOC, MBC) by developing technosol quality parameters coupled with improvement of ecosystem functions. Hence, mine spoil could be considered as a significant sink for atmospheric CO_2 through establishment of vegetation and ecosystem structure. Through the research in the scientific literatures, it is evident that mining sectors have the potential to combat global climate crisis and to evaluate carbon budget with the implementation of sustainable land management (such as forestry reclamation

approach, forest landscape restoration approach, Miyawaki method of afforestation) through collaboration among miners, government and local communities in practical way over a longer period of time. Moreover, future research is required on mining innovation concepts and its challenges for designing an SDG impact framework so that not only synergies amongst SDGs, but also trade-offs between each individual politically legitimised post-2015 development agenda (i.e. UNSDGs) could be depicted in a systematic way. In a developing country like India, it is also an utmost need to assess environmental impact and economic performance of such technological innovation and its possible synergistic effect.

Declarations

Ethics approval The manuscript has not been submitted to more than one journal for simultaneous consideration.

Consent to participate This study has not directly/indirectly involved human and/or animals.

Consent for publication The manuscript was reviewed, and all authors consented to publish.

Competing interests The authors declare no competing interests.

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