DOI- https://doi.org/10.31219/osf.io/yde8w || Online: 28.03.2022

Negative Emissions at Negative Cost - An Opportunity for a Scalable Niche

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Keywords: Negative emissions, Agroforestry, Sustainable agriculture, Biochar, Bioenergy, Carbon sequestration, Climate change mitigation, Food security, Income generation

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DOI- https://doi.org/10.31219/osf.io/yde8w || Online: 28.03.2022

Abstract

In the face of the rapidly dwindling carbon budgets, negative emission technologies are widely suggested as required to stabilize the earth's climate. However, finding cost-effective, socially acceptable, and politically achievable means to enable such technologies remains a challenge. We propose solutions based on negative emission technologies to facilitate wealth creation for the stakeholders while helping to mitigate climate change. This paper presents a coffee and jackfruit agroforestry-based case study with an array of technical interventions, having a special focus on bioenergy and biochar, potentially leading to "negative emissions at negative cost." The strategies for integrating food production with soil and water management, fuel production, adoption of renewable energy systems and timber management are outlined. The emphasis is on combining biological and engineering sciences to devise practically viable niche that is easy to adopt, adapt and scale up for the communities and regions to achieve net negative emissions. The concerns expressed in the recent literature on the implementation of emission reduction and negative emission technologies are briefly presented. The novel opportunities to alleviate these concerns arising from our proposed interventions are then pointed out. Finally, the global outlook for an easily adoptable nature-based approach is presented, suggesting an opportunity to implement revenue-generating negative emission technologies at the gigatonne scale. We anticipate that our approach presented in the paper results in increased attention to the development of practically viable science and technology-based interventions in order to support the speeding up of climate change mitigation efforts.

1. A new science and technology pathway for negative emissions and climate change mitigation

An unabated increase in greenhouse gases (GHGs) and other atmospheric pollutants in the earth's atmosphere have reached a threshold at which reversing the emissions appears to be the only survival strategy for humanity. A recent editorial in Nature(Why current negative-emissions strategies remain 'magical thinking,' 2018), another recent report from National Academies of Sciences, Engineering, and Medicine (NASEM) etc. have stressed the importance of "Negative Emissions" programmes and technologies in mitigating climate change (Negative Emissions Technologies and Reliable Sequestration, 2019). The pertinence of combining biological and engineering sciences based interventions to reduce emissions at a gigatonne scale is highlighted in recent literature(Majumdar and Deutch, 2018; Horton et al., 2021). However, the high costs, large land, and energy requirements and/or penalties pose a major challenge in the execution of commonly promulgated negative emission technologies such as Bioenergy Carbon Capture and Storage (BECCS) and Direct Air Carbon Capture and storage (DACCS)(Fuhrman et al., 2020; Hanssen et al., 2020). Recently Hanna et al.(Hanna and Victor, 2021) argued that identifying niche markets is an approach for opening up new pathways in the search for solutions for emissions reduction challenges.

Afforestation as a negative emission technology is gaining global significance for carbon sequestration, however, it directly competes with food production(Frank et al., 2017; Doelman et al., 2020). Similar challenges appear when various negative emission technologies are taken up separately for large-scale implementation. To this date, no systematic approach of any global appeal appears to have been proposed and empirically tested, even though local initiatives and scattered scientific efforts have been reported on negative emission technologies. A potential solution is a globally adoptable and easily implementable nature-based programme to generate food security, income, and clean energy while simultaneously removing CO_2 from the atmosphere. In this context, we propose technology transition pathways, based on ongoing regional carbon neutrality programmes with community participation, to introduce several negative emission technologies in an integrated manner. We present an approach combining agricultural sciences and engineering sciences (agroforestry, bioenergy, soil engineering, remote sensing etc.). We also suggest an array of technological extensions for intercropped agroforestry and its byproducts, biochar for soil amendment, and bioenergy. Many of these technological extensions, potentially easier to start without the infusion of too many high-end technologies, will help to achieve negative emissions and simultaneously increase farmers' income through interventions in food, water, housing, waste, energy, and climate. Further, we explain how such an approach could potentially help us to overcome several seemingly insurmountable techno-social challenges presented in recent literature and mass media (Fellmann et al., 2018; Gardezi and Arbuckle, 2020; Söderholm, 2020). Therefore, we discuss different strategies to fight climate change at a global scale by replicating the current initiative worldwide.

Climate summit discussions are often prolonged due to the very challenging goals. Further reaching agreements on emission reduction targets and the financing needed is also not easy(New Scientist, 2019; Council on Foreign Relations, 2021; Buchner et al., 2019). Additionally, farming based negative emission technologies are now suggested as integral to climate related initiatives, as assuring food security is equally important while fighting climate change(Beerling et al., 2018). Our approach, targeting food security, wealth generation and climate change mitigation at the same time may hence help to ease out the rather difficult negotiations at climate summits.

2. Where to begin?

Fleischman et al.(Fleischman et al., 2020) suggest that considering the needs of indigenous rural communities is of paramount importance for the success of any nature-based climate neutral solution. The support of stakeholders whose decisions and actions determine the long-term viability of climate-friendly initiatives is therefore critical. There are such places in Kerala, a state in India where environmentally friendly initiatives are taken up with large scale community involvement. More importantly, Kerala is considered to have one of the most developed and naturally evolved agroforestry systems in the world(Hart, 1996). This might make it easier for the stakeholders to quickly introduce innovative interventions in the state making it a niche market with potential for agro-forestry based carbon sequestration.

Ongoing Carbon Neutral Village Initiatives in Kerala and the Meenangadi Programme

Meenangadi village within the Wayanad district of Kerala has initiated several environmentally friendly initiatives in the last couple of decades, and a carbon neutrality programme recently. Environment-friendly activities are conceived and implemented as part of the “people-centric” development programmes and with the support and involvement of the local people(Meenanagadi Gramapanchayat, 2015). The ‘Grama Panchayat’, the village local self-governance institution is in the lead. Care has been taken to ensure that interventions are socially acceptable and, wherever possible, also economically beneficial to the people. The focus areas include environmental protection, biodiversity conservation, and agricultural development. Panchayat’s interventions included large scale tree planting, agroforestry practices, bamboo cultivation, use of compost for soil amendment, plastic waste for road construction, roof water harvesting, and the replacement of plastic bags with environment-friendly cloth and paper bags. Cultivating fruit trees, conserving native crop diversity, and protecting water bodies have been promoted while sand mining and quarrying have been restricted. MS Swaminathan Research Foundation played an important role in providing knowledge support for many of their activities. The panchayat started the carbon neutrality programme largely based on the above-mentioned activities. Doubling the farmers income is set as an important goal. The activities are supported by the state government(Isaac, 2016, 2018, 2020), a non-governmental organization “Thanal” which has carried the baseline assessments on Carbon Neutral Meenangadi (Jayakumar C et al., 2018), and several other organizations including the ones many of the authors are connected with(Nandakishor et al., 2022; Rajeesh et al., 2022; Vasanth et al., 2022; Vijay et al., 2021).

Tree banking and incentives for tree planting

Tree banking is a unique feature of the carbon neutral programme in Meenangadi and was recently inaugurated. The State and Local Self Governments have set up innovative tree banking schemes to incentivize tree planting in the region(The Guardian, 2020). Under this scheme, individuals are given credit-linked incentives for planting and ensuring the survival of trees. Farmers may also use trees as collateral to get bank loans. Local Self Governments provide planting materials free and bear the cost (labour) of planting and weeding for the initial years. Incentives for tree planting are critical for the success of the carbon neutral programme in two ways. First, they support the farmers to compensate for the short-term losses caused by planting trees in coffee plantations. Fear of yield loss and resultant financial loss is one of the major factors hindering tree planting. Second, they encourage farmers and local communities to participate in carbon neutral programmes. Thereby the initiatives ensure that carbon neutrality is a community movement, rather than just a government scheme.

The Mankulam Programme

Similarly, Mankulam is another village in Kerala with a history in sustainable interventions including organic farming, agroforestry, village owned renewable electricity production and a village carbon neutrality programme is recently initiated. The United Nations Development Programme, Global Environment Facility, and the government agencies support the programme (with funding a project in which several of the authors are involved). The Mankulam programme focuses on achieving carbon neutrality and increasing farmer’s income using energy, farming and agroforestry interventions (coffee, tea, cardamom, jackfruit etc.).

3. Organized agroforestry and extended engineering interventions: The Way Forward

Based on the platform of ongoing efforts focusing on tree planting and other environmentally friendly initiatives, we propose the introduction of organized agroforestry together with new and renewable energy technologies, soil and water management practices, sustainable construction and an array of related science and technology-based interventions to achieve carbon neutrality and or negative emission futures while creating wealth and building climate resilience. Our suggested science and technology interventions include, among others, pyrolysis for energy and biochar (as an early step with potentially other bioenergy technologies to be eventually introduced), soil amendment, plant breeding, ICT based remote and embedded sensing technologies for monitoring

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the water availability, agricultural productivity, and tree growth.

Agroforestry is a unique land use practice where farmers integrate trees with crops and/or livestock(Unasylva - No. 154). It has gained prominence in the context of climate change programmes(FAO, 2013) after the Kyoto protocol. As an interface between agriculture and forestry it is a sustainable land use practice in many developing countries. Agroforestry allows farmers to produce food, fodder, fuel, timber, and other forest resources from their farmlands(Jose, 2009). Improved agricultural practices and afforestation are, therefore potent measures to reduce GHG emission(Rose et al., 2012; Smith et al., 2013).

Agroforestry can significantly mitigate tropical deforestation by offering alternate sources for wood products, thereby reducing the pressure on these forests. The tree-rich farming systems also reduce the need for chemical fertilizers to improve soil quality, maintaining the nutritional balance and fertility(Shi et al., 2013). Trees in the croplands can thus improve the productivity of farming systems and also provide opportunities to create carbon sinks(Nair, 1993; Dixon et al., 1994; Dixon, 1995). Additionally, they could also offer benefits such as increased slope stability in hilly areas(Cohen and Schwarz, 2017).

Fig. 1| (A) Coffee Plantations without shade trees (B) with shade trees (C) Fruit bearing jackfruit tree

a) (Image Credit J. Stephen Conn is licensed under CC BY-NC 2.0) b) (Image Credit Nathan Darpen is licensed under CC BY-NC-SA 2.0) c) (Image Credit: Balaram Mahalder is licensed under CC BY-SA 3.0)

4. Negative Emissions at Negative Costs

An agroforestry-based case study is presented. The case is based on the potential opportunities at Meenangadi village. Coffee is of prime importance in Meenangadi as it accounts for the largest area under cultivation in the village (more than 3000 hectares(Jayakumar C et al., 2018)). Coffee gardens are selected because they can accommodate a large number of shade trees (Fig.1(b)) if accompanied by agro-ecological interventions to reduce the competition for inputs like nutrients, water, and sunlight between plants and trees. More importantly, coffee production is expected to be severely affected by global warming(Climate & Coffee | NOAA Climate.gov; Time, 2018), and the cooling effect brought in by the shade trees is suggested as a local and natural climate change mitigation approach A study on the impact of climate change on coffee production in Brazil indicated a 60% decline in the area suitable for coffee cultivation in unshaded plantations under projected climate change by 2050. However, it also suggested that agroforestry can mitigate climate change effects and maintain 75% of the area suitable for coffee cultivation due to the trees bringing in lower mean air temperatures, higher soil moistures and potentially more birds and bees, contributing towards pollination and pest control in coffee agroforestry systems(Gomes et al., 2020).In the present study, the expected revenue and the sequestration potential of Jackfruit-coffee-based agroforestry systems are calculated and presented (indicative values) to demonstrate an alternative approach to strengthen the coffee growing regions in the face of climate change (Fig. 2). The Meenangadi programme is potentially replicable in many other villages in the Wayanad district (and elsewhere), where coffee production is from 67000 hectares(Coffee board of India, 2015) mostly unshaded *Robusta Coffee*.

Food: Jackfruit - The Jack of all fruits

Jackfruit trees are suggested for coffee-jack tree agroforests as they are food-yielding and are known to have a high carbon sequestration capacity(Jithila and Prasadan, 2018). Also, the jack tree is endemic to this region and recently designated as the ‘state fruit’ for the state of Kerala(Morton, 1987; The Indian Express, 2018). It is cultivated in several hundred hectares as support for black pepper (*Piper nigrum*), whose vines can be trained on the stem. Jack trees are also recently planted along with a wide variety of tree species as part of the larger tree planting efforts in Meenangadi. Promoting jackfruit cultivation in coffee farms will gain more impact by introducing an organized industry around it. Producing and distributing quality seedlings, investing in the production, processing, and marketing of value-added products derived from jackfruit which all could contribute to such organized efforts and are starting up in the region in small scales. However, science and technology supported large-scale efforts are yet to take place.

Jackfruit is a versatile tree because apart from the direct use as a fruit, it is used as a vegetable in its tender stage and its seeds are also valuable. It is primarily cultivated in Asia- Pacific region. Jack trees are also grown in North and South America and Africa(Elevitch and Manner, 2006b). Countries like Vietnam, Philippines, Vietnam, Cambodia, Sri Lanka are aggressively promoting Jackfruit cultivation and its use. India is the second largest producer of the jackfruit in the world with more than 1,02,552 hectares of farm areas with jack trees, with Kerala as one of the leading cultivators in 97,000 ha annually(APAARI, 2012) . In addition to its use as a staple food, a ripened fruit and a cooked vegetable, Jackfruit can also be used to prepare value added products like chips, squash, jam, pickles, ice creams, jelly, papad etc. Currently jackfruit has a market size of around \$286 Million globally and is expected to grow at a rate of 3.2 % annually (Jackfruit Market Share, Size and Industry Growth Analysis 2021 - 2026).

Jackfruit is increasingly being accepted as a meat substitute, especially for vegan and vegetarian diets, and is a potential staple food for the future(AP News, 2020; The New Indian Express, 2020). In coffee plantations, it is advised to grow straight-growing jack tree varieties bearing fruits on the main stem (Fig. 1(c)). The suggested model will support the farming community by providing food, income, ecological services, and rural employment. Any other tree species with food and timber values can also be included as a companion crop in such a farming system.

On an average, 40 to 45 jack trees per hectare can be grown as a shade crop, based on the recommended wide spacing of 15 m x 15 m(Morton, 1987; Elevitch and Manner, 2006a). A conservative estimate shows that 10 tonne per year per hectare(APAARI, 2012; India Together, 2013; Chandrakanth Reddy et al., 2019) jackfruit yield is achievable. Taking the minimum price of a tonne of jackfruit- 100 Euro(Chandrakanth Reddy et al., 2019), a revenue of 1000 Euro per year per hectare will be generated from the jackfruit trees.

Timber

Jack tree timber is excellent for furniture and construction purposes. Approximately 2 m^3 (1.2 tonnes, considering density of timber as 600 kg/m^3) of timber per jackfruit tree(Elevitch and Manner, 2006a; Kunhamu, 2011; Pandya et al., 2013) or 80 m^3 of timber per hectare can be obtained in 40 years. Assuming the price of timber to be 300 euro per m^3 an additional revenue of 600 euro per year per hectare will be generated that could also compensate for the reduction in revenue from coffee(Beer et al., 1997). Also, we estimate that nearly 2 tonnes of CO_2 will be sequestered per year by 2 m^3 of timber(Pandya et al., 2013; Jithila and Prasadan, 2018).

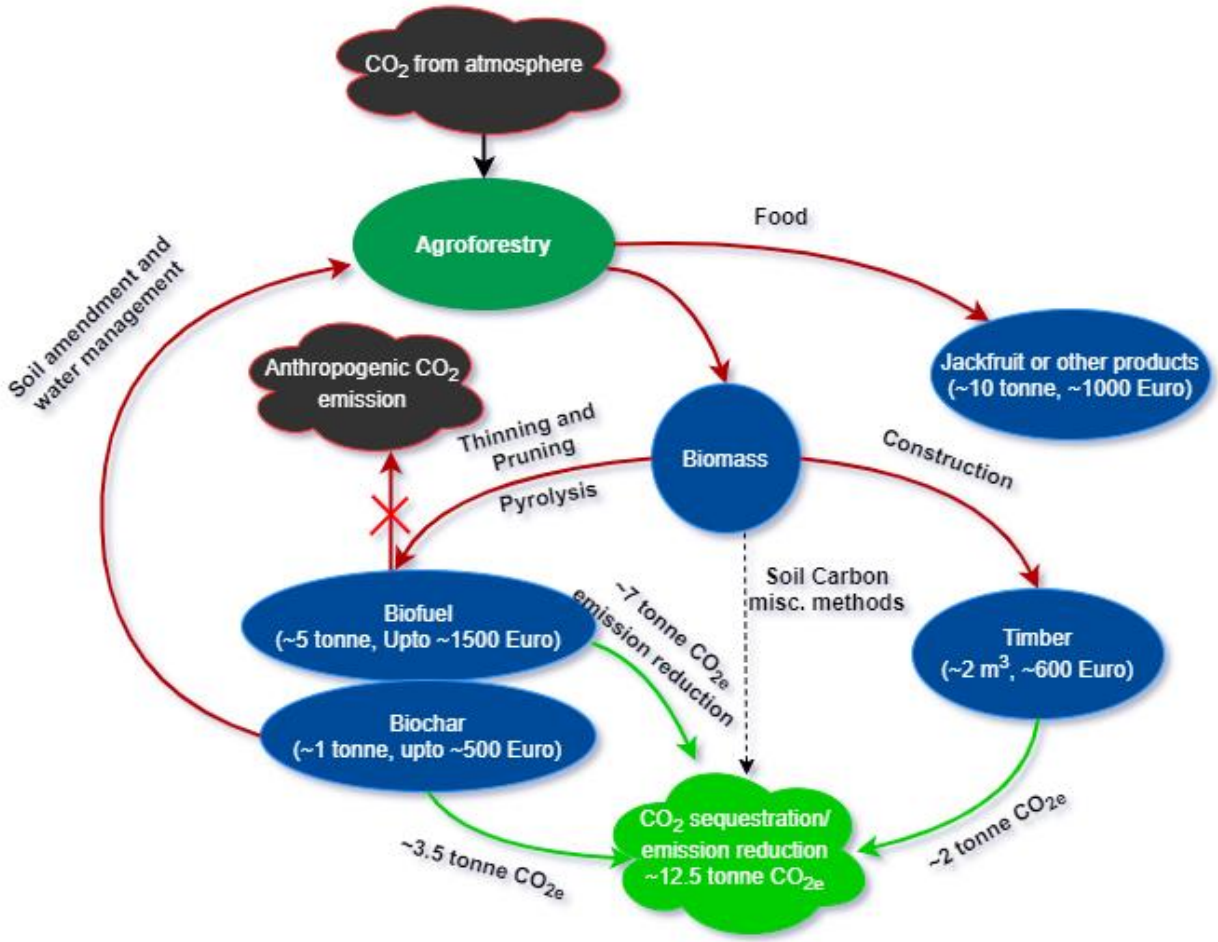

Fig. 2. Revenue generation, emission reduction, and carbon sequestration potential (per hectare per year) of the coffee-jackfruit agroforest with biochar and biofuel production.

Biofuels, biochar, and soil management

Biomass obtained from the thinning and pruning of trees can be converted into biochar and biofuel using pyrolysis. In a previous study, our extended team has extensively reviewed the literature on impact of field application of biochar on soil health and crop yield. Based on the reported literature, we found that the effect of biochar application is higher in stressed soils of tropical regions in comparison to the temperate regions(Vijay et al., 2021). Total biomass output from litter falls, and pruning from a coffee plantation with shade trees is around 10-12 tonne per hectare per year(Beer, 1988; Evizal et al., 2009). Based on the feedstock used, biochar and biofuel production rate using fast pyrolysis varies from 15-25 wt. % of solid char, 60-75 wt. % of liquid bio-oil(Mohan et al., 2006; Carrasco et al., 2017), leading to ~1 tonne biochar and ~5 tonne biofuel (bio-oil) per hectare per year. We estimate that when a tonne of biochar is used to amend soil, ~3.5 tonnes (approximately) of CO_2 is sequestered. Depending on the replaced fuel mix, ~5 tonnes of biofuel (bio-oil) lead to an emission reduction of approximately 7 tonnes CO_2 per hectare. Biochar and the biofuel produced could generate revenue up to 500 and 1500 euro per hectare per year, respectively(Campbell et al., 2018). In the case of fast pyrolysis, an internal rate of return (IRR) of above 30% is possible, if the cost of feedstock is zero and pyrolysis co-produces biochar for carbon sequestration and biofuel for transportation(Brown et al., 2011). Another extended team of ours has started early stage experiments and carried out an extensive review of literature on biochar production technologies for rural applications in the developing countries(Vasanth et al., 2022). It appears that there are easy to implement technologies such as pyrolysis or gasification stoves to start with biochar production(Birzer et al., 2014). . However, it should be noted that biochar may not directly generate income as it will be primarily used as soil enhancer in the region. Biochar is known to support the rhizosphere and productivity of agricultural land and therefore contributes to sustain the long-term productivity (Kolton et al., 2017). Together with biochar application, other soil carbon improvement methods such as composting, slurry addition, soil moisture management, legume cultivation, and zero-tillage agriculture can also significantly increase the soil carbon sequestration potential.

Appendix 1 presents the emissions and techno Economic analysis of Coffee-Jackfruit Agroforestry system when biochar producing cook stoves are employed which also results is somewhat similar emission values and income generation. Also, Appendix 2 presents a simplified life cycle assessment of the coffee jackfruit system considering the proposed interventions.

Additional benefits

There are also several other potential benefits from jack tree agroforests. They have a strong root system that could help in slope stabilization(S. Lukose Kuriakose et al., 2009; Giadrossich et al., 2019). The use of jack tree leaves for fodder is another example. The leaves are also used for a variety of applications such as mulching.

Jack trees also provide a potential opportunity for significantly increased food production. Food yield upto 80 tonnes(Balamaze et al., 2019) or perhaps more might also be feasible in certain regions with well-organized farming practices. This is probably one of the highest expected food yield per hectare from any staple food species. Fig. 3(a) indicates that the yield of food from jackfruit is significantly higher than the other edible food/crop species(FAOSTAT; Rahaman et al., 2018; Kreitzman et al., 2020)'. Additionally, shade coffee plantations, or agroforests provide agricultural waste streams spread over several seasons and months and mostly throughout the year. Fig. 3(b) shows comparison between biomass availability from shade tree plantations and wheat and paddy fields. Availability of biomass throughout the year offers the opportunity for deploying either small scale power plants or smaller storage units for producing similar amounts of bioenergy streams (electricity, biofuels) and biochar per year when compared to other highly seasonal food

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crops. This is expected to help bring down the capital costs required for installing such units and their operational costs. Appendix 3 presents the strategic planning for farmer centered and agroforestry focused emission management initiatives. Appendix 4 highlights the additional biodiversity benefits in coffee farms brought by trees in agroforestry systems.

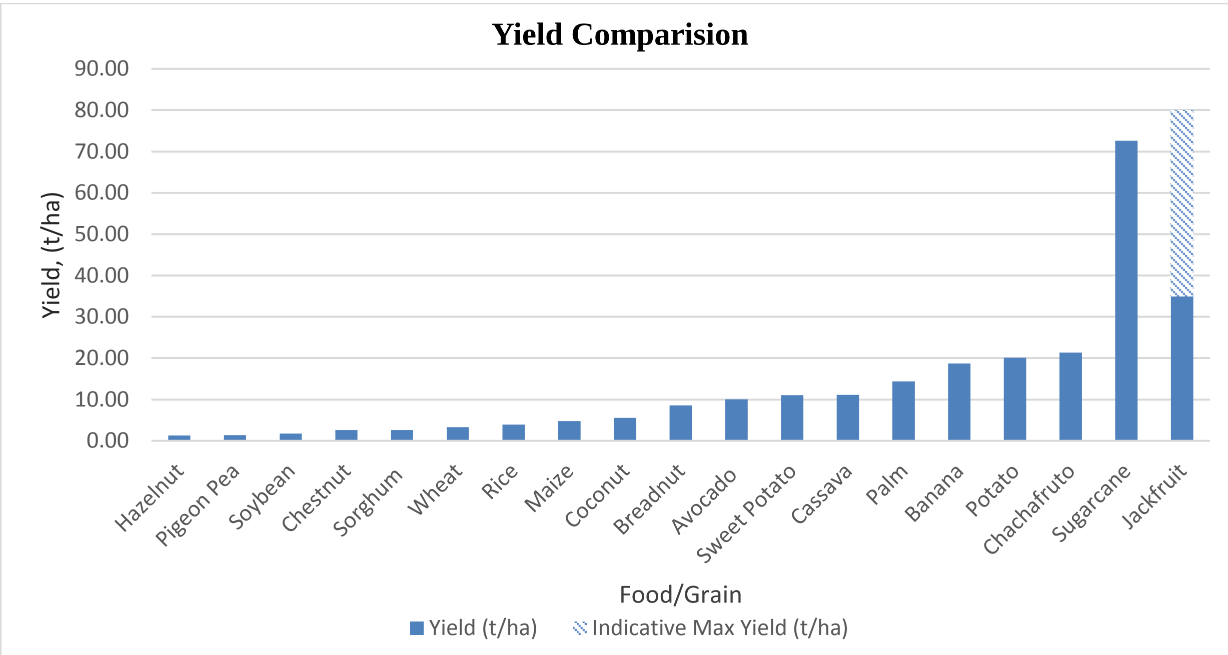

Fig. 3(A). Comparative yields of commonly grown high yielding food/grain species

Note: The yield of jackfruit per hectare in many places is reported to be upto 80 tonnes(Balamaze et al., 2019). *The shaded sections of the bars show the indicative yield ranges.*

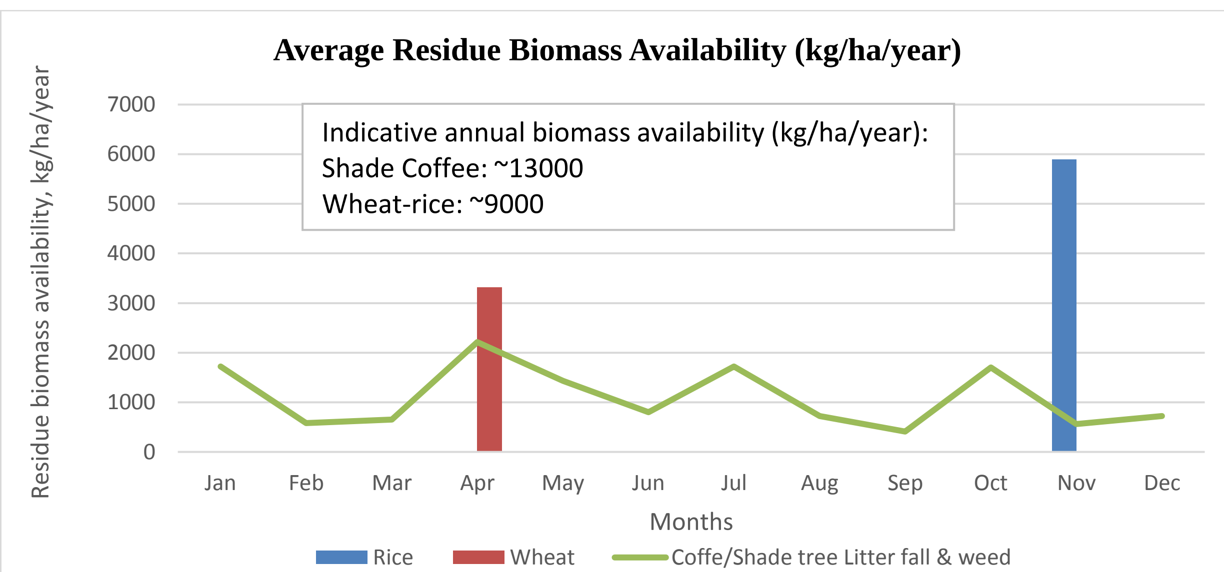

Fig. 3(B). Indicative values for residue biomass yield from rice, wheat (when rice and wheat are grown in consecutive seasons in the same field) and shaded coffee(Evizal et al., 2009).

The Meenangadi opportunity

Meenangadi certainly appears as a suitable village for early implementation of such a scheme. Appendix 5 presents the results from an opinion survey conducted by our extended team highlighting the willingness of the local community for the suggested agroforestry approaches. The detailed results are available elsewhere (Nandakishor et al., 2022). If 3000 hectares of coffee farms in Meenangadi are converted to shade coffee plantations, 6000 tonnes of CO_2 will be sequestered per year as timber. And 10000 tonnes of CO_2 will be sequestered per year as biochar (thinnings and prunings). Using biofuel for energy applications, though challenging, could help in avoiding approximately 20000 tonnes of CO_2 emissions per year. All of the above measures will sequester around 36000 tonnes of CO_2 per year, potentially making Meenangadi a carbon neutral territory (where the total calculated emissions are around 33000 tonnes (Jayakumar C et al., 2018)). Net-zero or net negative emissions could be achieved when all other interventions such as renewable energy (solar, wind, and hydro), and additional soil carbon management options mentioned above are considered. This is especially important as the renewable energy systems are rapidly becoming cost effective. The proposed interventions will generate a revenue of around 1.8 million Euro from timber, 4.5 million Euro from biofuel, and 3 million Euro from jackfruit, adding to a total revenue generation of 9.3 million Euro per year. All the above interventions may offset capital costs connected to the investments needed, any revenue drop arising from the conversion of coffee plantations to shade coffee, resulting in negative emissions at a negative cost.

Significance of integrated biofuel and biochar interventions in agroforestry initiatives

Fig. 2 shows that integrated biofuel and biochar interventions significantly increases the emission reduction and carbon sequestration potential in the selected agroforestry case. For combined soil amendment and bioenergy interventions, there are many emerging and attractive technological approaches. Easy to introduce routes could combine technologies ranging from small-scale biogas production and slurry utilization(Wasajja et al., 2021) to (solar) thermochemical approaches. Solid oxide fuel cells might help in CO_2 separation in small scale bioenergy systems while helping to achieve very high thermodynamic efficiencies(N. Jaiganesh, P. C. Kuo, T. Woudstra, R. Ajith Kumar, 2021). Small scale hydrogen production from biogas , pyrolysis, or gasification systems(Matthias Binder, Michael Kraussler, Matthias Kuba, 2018), based on simple and conventional approaches or based on cutting edge technologies such as internal reforming SOFCs(Saadabadi et al., 2021) or fuel assisted electrolysis is becoming very attractive, considering the significant momentum in the adoption of hydrogen technologies worldwide. Please refer to Appendix 6 for the details of the technologies mentioned. Hydrogen or biofuels thus produced, could also provide an early-stage entry even to negative emission transportation(Jaspers et al., 2021).

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5. Science and technology interventions for de-risking and the roadmap

The negative emission at negative cost programme, if properly de-risked, is an investment opportunity that can bring significant economic gains to the stakeholders while meeting the emissions targets. Appendix 7 presents some of the risks and mitigation strategies.

Detailed understanding in several knowledge domains, including the interaction dynamics of different intercropped species with the environment, the biochar application rate for soil amendment, technology choices for biofuels and carbon sequestration potential, is needed to come up with optimal strategies. Therefore, efforts are required to develop interlinkages between the proposed mechanisms and corresponding science and technological innovations. Biological techniques such as plant breeding are needed for developing appropriate plant varieties for agroforestry systems. Technological interventions coupled with monitoring systems in the form of Information Communication Technology (ICT) based remote and embedded sensing technologies are helpful in monitoring the water availability, agricultural productivity, and tree growth through geotagging. Remote sensing is also extremely important in developing cost-effective approaches for preserving existing forests, especially when large-scale timber programmes are conceived(Mitchell et al., 2017). Further, there are potentially rather easy to start techniques for remote sensing using mobile phones for image collection and processing(Ferster and Coops, 2016). However, advanced systems are expected to be based on drones or satellites(Tang and Shao, 2015). Fig. 4 shows our proposed technological interventions and their interlinkages. In order to get the best possible results in income-generating carbon sequestration methods, some of the basic science areas to build clarity include, among others, thermodynamics, fluid dynamics, chemical sciences, material science, data sciences, artificial intelligence, and biological sciences. Engineering practices have to be developed based on scientific advancements. A fast-paced timeline to realize these technological interventions is critical to meet the international emission reduction commitments. Once the knowledge lines are well developed, the intercropped agroforestry approaches could be replicated worldwide by considering region-specific agroforestry approaches. Many of the perennial food crops presented in Fig. 3(A), among others, are potential candidates.

While it is possible to start immediately making use of already available technologies, relevant technologies need to be developed to process and store jackfruit and other similar farm produce, biofuel and biochar production and utilization, all considering emission reduction and carbon sequestration. Further, the focus on large-scale timber-based construction technologies for carbon neutrality is new despite timber usage for construction in the past. Tailoring these technologies for achieving carbon neutrality and large-scale implementation may take a couple of years.

Advanced technologies might make these approaches even more attractive in the future (ultra-high efficiency bioenergy systems based on solid oxide fuel cells, fuel assisted electrolysers etc., as discussed before). For such technologies, one or two decades are needed for globally acceptable engineering practices and products to become widely available, if the technology development pace is comparable with the timelines of the average technology development and implementation cycles (from technology readiness level-1 to 9 and then to market(Peisen et al., 1999) With the technology pathways mentioned above, focussed efforts might result in such solutions becoming available sooner, especially since technology development is getting significantly faster(Butler, 2016). Dedicated and focused efforts are hence urgently needed.

Combining all these interventions and considering their importance, we are building multiple science and technology partnerships to involve in and contribute to such initiatives (including Meenangadi, and Mankulam). Academic institutions, government agencies, business houses and global bodies (such as UN agencies), etc. all are involved. This is well-aligned with the large-scale investments the Government of Kerala(Isaac, 2016, 2018, 2020) and the Government of India are planning(WRI India, 2021) in carbon neutrality and renewable energy programmes (worth billions of Euros).

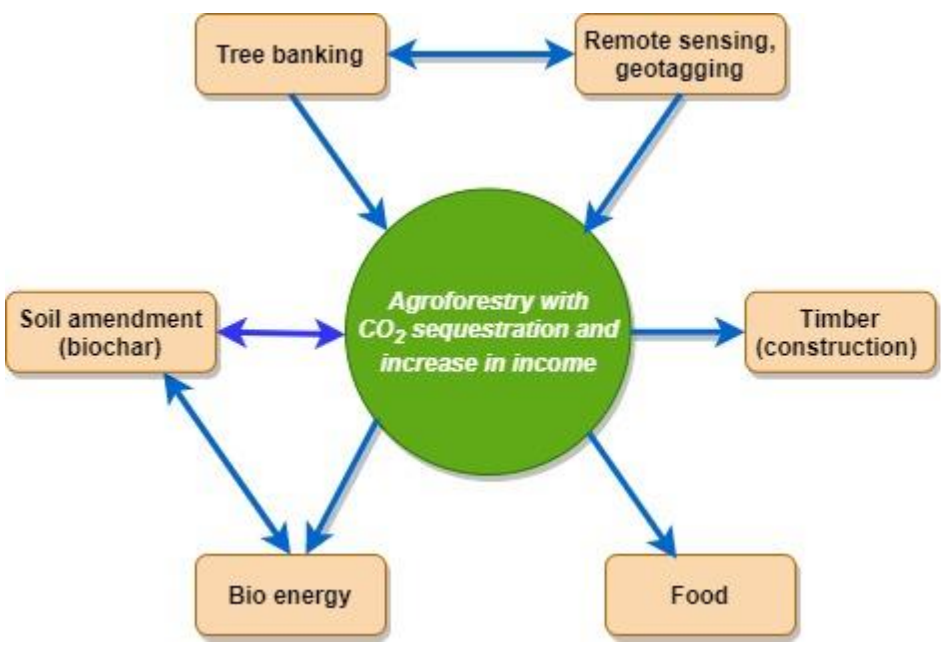

Fig. 4. Mapping of the possible science and technology interventions for CO_2 sequestration and revenue generation in agroforest

6. Our approach and answering the recently posed questions

Cox et al.(Cox et al., 2020) looked at the public perception of carbon dioxide removal technologies and concluded that tangible and near-term results are helpful in receiving public support for such efforts. Hanssen et al.(Hanssen et al., 2020) presented the potential for bioenergy with carbon capture and storage (CCS) but expressed concern over the land requirement for Bio-Energy with Carbon Capture and Storage (BECCS). A major concern with negative emission technologies like Direct Air Capture (DAC) is that they are energy-intensive and costly(Fuhrman et al., 2020). Our approach alleviates such concerns, as food production and wealth creation are suggested parallel to carbon sequestration efforts. A niche opportunity is also identified, in line with the suggestions from Hanna. et al.(Hanna and Victor, 2021). Chile's experience in afforestation through forest subsidies resulted in the expansion of exotic tree plantations and decreased the area of native forest and biodiversity without increasing total carbon stored(Heilmayr et al., 2020). Learning from the above, policymakers must ensure that afforestation/ reforestation policies are carefully developed to increase vegetation and carbon sequestration and conserve biodiversity simultaneously.

Hasegawa et al.(Hasegawa et al., 2018) stated that implementing stringent climate mitigation policies across all regions and sectors will negatively impact global hunger and food consumption by 2050. Hayek et al.(Hayek et al., 2020) points to the need for carefully designed mitigation policies for agriculture and land use to simultaneously achieve climate stabilization and food security. Similarly, based on a thorough review of literature on empirical evidence about the adoption of sustainable agricultural practices, Piñeiro et al.(Piñeiro et al., 2020) also affirmed that emission management programmes linked to short-term economic benefits have higher adoption rates than those aimed solely at providing an ecological service. Therefore, an integrated approach of food and bioenergy production should be explored. Horton et al.(Horton et al., 2021) evaluated the technologies to deliver food and climate security through agriculture, and pointed out the need for a series of new agricultural technologies in order to allow intensive agriculture to have a key role in climate change mitigation. Hepburn et al.(Hepburn et al., 2019) compared several CO_2 utilization methods and came up with several economically attractive propositions, including the land-based ones. However, they have stated that barriers to implementation remain substantial.

In a general perspective, climate change is attributed largely to increased GHG emissions. This overlooks the significant role many of the negative emission technologies play in land use, sustainable soil and water management, and consequently the hydrological cycle and the local climate(Roodari et al., 2021). The potential role of trees in forests in cooling and stabilizing local climates through moisture regeneration(Makarieva et al., 2009) may bring additional long-term benefits by mitigating the predicted reduction in growing areas due to climate change by 2050 (Climate & Coffee | NOAA Climate.gov).

Our novel approach makes bioenergy with CCS a much more attractive option avoiding concerns over the land requirement for BECCS. Our approach is also centered around agricultural practices that concurrently benefit the farmers and environment in both the short and long run and thus becomes a possible inclusive and participative solution at the community level. The solutions presented by us prioritizes food security and revenue generation along with climate stabilization, thus leading to negative emissions at a negative cost. Furthermore, we examined the possibilities of integrating climate stabilization with food production and food security, fuel production, and timber management as a well-integrated solution for the future.

It is our view that the novel integrated concepts presented here may encourage the community to forego the apprehensions and quickly start the efforts to test and deploy negative emission technologies at a large scale in the near future. These concepts also offer an opportunity to achieve environmental, economic, and social sustainability in an all-integrated manner.

Box 1. Recommendations to achieve food security with climate stabilization

1. We propose full preparations for adopting Jackfruit agroforestry as a potential solution for climate-friendly and secure staple food production (if and when needed and if the climate crisis deepens). Conversion of *robusta* coffee plantations into shade coffee plantations appears as an appealing and easy to start first step. Other possible agroforestry combinations also need to be explored.

2. Bioenergy production and replacement of fossil fuels (especially combined with biochar/bio-slurry production) appear as offering the most significant CO_2 emission reduction opportunity in agroforestry initiatives. Biohydrogen is certainly worth considering with carbon going to the soil and hydrogen used as fuel. Other methods for soil carbon management might also offer similar opportunities, but there are uncertainties(Tiefenbacher et al., 2021)**.**

3. It is important to start such agroforestry initiatives where there is demonstrated local acceptance and active community participation, for instance the Meenangadi case presented in this study.

4. To the best of our knowledge, such a unique combination of easy to introduce coffee-jackfruit agroforestry with biofuels and biochar production, with an extremely appealing set of benefits, if (and only if) the systems are engineered very carefully, is not yet presented in literature. Significant research and development efforts along these lines need to be started across the globe, in co-creation mode, considering the sharp climate changes and the global urgency.

7. Global Outlook

The proposed approach, if expanded globally, has the potential for achieving negative emissions (gigatonne scale) at negative costs. Globally, coffee is grown in around 11 Mha. Approximately 4 million hectares(Jha et al., 2014) of unshaded coffee plantations could be converted to shade coffee plantation with perennial food producing trees as shade trees. It is anticipated that a part of the approximately 3.5 million hectares of sparsely shaded coffee farms(Jha et al., 2014) could offer the opportunities for planting food yielding trees. In total this could result in a CO_2 sequestration/ emission avoidance somewhere between 40 million tonnes CO_2 to 75 million tonnes CO_2 per year.

From food production perspective, our assessment indicates that more than 10 tonnes of food can be obtained per hectare (from 40 trees) per year from coffee-jackfruit agroforestry. Intercropped-jackfruit agroforests also could be developed without coffee but with other crops (such as black pepper, cardamom, vegetables, fruits etc.) Considering 500 kg per year as the food requirement per person(Serra-Majem et al., 2003), and on an average 40 jack trees are planted per hectare in all cases ~400 million hectare of intercropped-jackfruit based agroforestry (not necessarily with coffee) or agroforestry practices based on other perennial food crops taking a few hundred million hectares more) can meet a major part of the food requirements for the current 7.8 billion world population. This estimation is in line with the detailed discussion on the advantage of perennial food crops versus annual food crops (wheat, soy and rice) that was recently presented by Kreitzman et al. (Kreitzman et al., 2020) and shows that a conversion of a fraction of the 1.29 billion Hectares of agricultural land used for annual crops into perennial crops has an underutilised potential for the global food supply of nutritious staple foods.

Timber from jackfruit trees is another highly valuable product. Presently, the cement industry emits around 8% of the world's total GHG emission(Carbon Brief, 2018). Promotion of timber-based construction can reduce the dependency on highly emission-intensive cement and steel sectors, and hence reduce the GHG emissions(Skullestad et al., 2016; Sandanayake et al., 2018). Our estimation indicates that 80 m^3 of jackfruit timber can be produced per hectare from coffee-jackfruit agroforestry in 40 years, which can be used for construction purposes. Thus, extending jack fruit, or other staple food yielding tree-based agroforestry with a variety of intercrops to ~400 million hectares and using the timber to replace a fraction of cement and steel, will offer significant emission reduction from the construction sector around the world. More details on emission reduction potential from concrete replacement with timber are presented in Appendix 8. For example, Chachafruto (Erthyrina edulis) is another appealing shade tree species with significant food (upto 85 t/km fencing) and fodder production (upto 30 t/km fencing)(Orwa C, A Mutua, Kindt R, Jamnadass R, 2009) potential that can be explored on similar lines as jackfruit in suitable agro-climatic zones globally.

Following this approach, a significant share of more than one billion hectares of the world's arable land can be used for tree planting which is otherwise used for farming to produce food. Apart from timber, biomass can be used to produce biochar, a wide range of industrial chemicals, and other bioproducts. The energy alternatives from jack tree biomass can also provide biofuels (including biohydrogen) as a substituent to fossil fuels for future transportation fuel requirements leading to negative emission transportation opportunities(Jaspers et al., 2021). Wider replication of the proposed programme with large-scale afforestation, biochar for soil carbon sequestration, and fossil fuel replacement with biofuels can help to reduce 5-10% (or more) of the current global GHG emissions. This shows the importance of bioenergy initiatives in global agroforestry based emission reduction efforts and even beyond. Biofuels, if judiciously employed, might also help the difficult to decarbonize sectors such as shipping and aviation becoming emission negative. In extremely well-designed cases this could perhaps make even aviation more environmentally friendly than riding bicycle or even walking, if one considers the well to wheel fuel production and utilization chain resulting in active removal of carbon dioxide from atmospheric air. With the emerging uncertainties in the future fuel options worldwide(Speirs et al., 2015) and the energy conversion technologies for the chosen fuels, and the wide variety of technology options cropping up in biofuel production and utilization, it is becoming imperative that the scientific and engineering communities start giving significantly increased attention to bioresource management and their efficient utilization.

The opportunities for generating wealth, could also help to foster international solidarity in finding climate solutions. Our suggested approach offers a solution for the simultaneous achievement of climate stabilization and food security. We believe that the global hunger and food consumption-related problems resulting from mitigation policies can be bypassed through the suggested interventions. Further, the increase in solar and wind production capacity indicates that a negative emission global society may not be a distant dream anymore. Such an effort will, however, need well-coordinated science and technology development programmes, accompanied with socio-technical studies. Nonetheless, taking up such initiatives is suggested as worthwhile considering the environmental challenges humanity faces.

8. Summary

Negative emission technologies are gaining global significance and the need for combining agricultural sciences and engineering sciences are critical for a cleaner and healthier future. A global programme of this nature, based on agroforestry, might lead to increased food security and income for the rural population while stabilizing climate. Our indicative analysis shows that 1 ha of coffee jackfruit agroforestry system has the potential to sequester approximately 10.5 tonnes of CO_2 per year while also presenting an income generating opportunity of the order of 3000-4000 Euro per year. Other agroforestry systems based on different perennial food crops also appear as worth considering. We have presented an empirically testable integrated approach (encompassing bioenergy systems, geo-tagging, remote sensing, soil carbon and water management, biochar application, biodiversity conservation) implementable in a rather short time period, well connected to an ongoing government programme. The energy, water, waste, food, and housing emissions nexus pointed out here brings a unique opportunity to achieve negative emission features at negative costs, with regional efforts first, eventually leading to a global effort–driven by local farmers and the governments. Ongoing and the expected future efforts include knowledge development in all the domains discussed in this manuscript and field level implementation with a participatory approach, well supported by a triple helix consortium. The success of the programme is expected to open up similar opportunities elsewhere in the world and hence is of international significance.

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Acknowledgement

Authors acknowledge the support and leadership provided by former Finance Minister of Kerala Dr. Thomas Isaac in setting up the carbon neutral Meenangadi and Wayanad initiatives. Authors also thank the President of the Meenangadi Village Panchayat, Beena Vijayan, Ajit Mathai of mByom, Executive Manager of TU Delft Climate Institute H Schoffelen, and the Director of the TU Delft Climate Institute Prof H Russchenberg for their help in setting up and contributing to the science and technology related discussions on and around the concepts presented in this paper. Authors are also thankful to Dr Nadia van Pelt, Centre for Languages and Academic Skills, TU Delft, for her help in language editing of the manuscript. The authors are grateful to the panchayat officials and the experts who have attended several work meetings and events organized in support of the initiative. We also acknowledge the early-stage activities carried out in Meenangadi by the NGO, *Thanal*. All the speakers from various organizations and countries who contributed to the science and technology related discussions during the workshop and the webinar organized in connection with the carbon neutral Wayanad programme are also thanked by the authors (one workshop organised by Kerala Government Agencies in 2019 and the webinar by TU Delft in 2020).

Author Contributions

P V Aravind conceived of the paper and drafted the first outline. Vipin Champatan, Vandit Vijay and P V Aravind finalised the manuscript. Girigan Gopi supported the Meenangadi Panchayat officials in implementing the sustainability and the carbon neutrality programmes for more than a decade. All authors contributed in developing the concepts, provided critical input on estimates, and were involved in drafting the manuscript. Additionally, all authors have read and approved the manuscript.

Competing interests

The authors declare no competing interests.

Appendices

Appendix 1: Emissions and Techno Economic Analysis of Coffee - Jackfruit Agroforestry system v/s unshaded coffee plantations

Appendix 1a: Emissions Analysis of Coffee - Jackfruit Agroforestry system v/s unshaded coffee plantations

Emissions reduction and sequestration potential from Coffee-jackfruit shade agroforestry combination is compared here with unshaded coffee plantations to present the potential benefits in emission reduction and income enhancement achievable with the suggested interventions. For biochar and bioenergy production, easier to start with biochar producing cook stove option is considered. The valuations are approximations. This means that it is the order of magnitude of the values that is relevant (the values are used in showing the trends), rather than the exact number calculated.

A coffee-jackfruit agroforestry system, from a hectare farm land, is expected to lead to the production of approximately 10-12 tonnes of agro-waste annually. Fig. 2 in the paper presents the indicative yields of biochar (1 tonne/ha), biofuel (5 tonnes/ha), and timber (2 m^3) achievable from a coffee-jackfruit agroforestry system.

For an annual average coffee production of 2 tonnes/ha (World Bank, 1982), taking 1.02 kg CO_2 emissions per kg of coffee production(Killian et al., 2013), the emissions from coffee plantation will be around 2 tonnes/ha. An unshaded coffee plantation biomass could be used to generate limited quantities of biofuel and biochar without any timber. Assuming biomass yield from coffee in unshaded systems as 50% of the coffee-agroforestry system (Evizal et al., 2009). The net CO_2 sequestration potential is ~3.25 tonnes /hectare (indicative) as shown in Table 1a.

We obtained the fertilizer requirements from the literature (Chandrakanth Reddy et al., 2019) and estimated the GHG emission from the fertilizer application, Jackfruit cultivation will lead to ~1.5 tonnes of $CO_{2\text{-eq}}$ emission per hectare considering IPCC guidelines.

When Jackfruit trees are grown in the coffee plantations with wide spacing, say, 15*15m, on an average 2 m^3 of timber could be produced per year per hectare. Considering that 1 m^3 of timber weighs 600-700 kg and carbon content of wood as approximately 50% of dry mass (Jithila and Prasadan, 2018), around 300 kg carbon is then sequestered. This corresponds to around 2 tonnes of CO_2 sequestration from 2 m^3 of wood. As mentioned before, with very conservative estimates and moderate efficiencies, from 10-12 tonnes of agro-waste, assuming that 8 tonnes biomass is feasibly collectible and is taken for cooking in biochar producing stoves, 1 tonne of biochar (or more) could be obtained. Using this for soil amendment results in around 3.5 tonnes CO_2 sequestration.

Table 1a. Emission and Sequestration from unshaded Coffee Plantations

A. Emission from Coffee Plantations
1.02 kg CO_2/kg of green coffee
Considering 2000 kg of Coffee/ha is produced, total emission from Coffee is 2 tonne of CO_2/ha

B. Sequestration from unshaded Coffee Plantation with biochar and biofuel	
Biochar	1.75 tonnes CO_2/ ha
Biofuel	Upto 3.5 tonnes of CO_2/ ha
Net Sequestration (B – A)	**~3.25 tonnes of CO_2/ ha**

Assuming that the heating value of sun-dried biomass is around 18 MJ/kg(Erol et al., 2010), and that of biochar is around 30 MJ/kg(Kosakowski et al., 2020), this leaves around 14 MJ in the gaseous combustion products for cooking (from 1 kg of biomass used in pyrolysis/gasifier stoves). 8 tonnes of biomass from one hectare will have a heating value of ~144 GJ/ha and one tonne biochar produced from the biomass will have a heating value of ~30 GJ/ha (not available for cooking). Considering the calorific values of LPG (~46 MJ/kg) and the energy available for cooking as ~114 GJ from the biomass in pyrolysis stove, a bit more than ~ 2 tonne of LPG could be saved per hectare of agroforest (assuming somewhat similar efficiencies in gaseous fuel-based cooking with concentrated flames for both the fuels). The LPG consumption reduction/avoidance is hence expected to lead to around ~7 tonnes of CO_2 reduction/avoidance (considering 0.072 kg of CO_2 emissions per MJ from LPG(Carbon emissions of different fuels - Forest Research). The following equations present the CO_2 sequestration potential with biochar amendment and LPG replacement with gaseous fuel from biomass:

$$\text{CO2 sequestration with per tonne biochar soil amendment} = \frac{Biomass\ available}{1\ hectare} \times \frac{Biochar\ produced}{1\ tonne\ biomass} \times \frac{44\ tonne\ CO2}{12\ tonne\ C}$$

Eq. 1

$$\text{CO2 emission saved by replacing LPG with gaseous fuel from biomass} = \frac{Biomass\ available}{1\ hectare} \times \frac{(Heating\ Value\ Biomass - \ Heating\ Value\ Biochar\ removed)}{1\ tonne\ biomass} \times \frac{0.072 * 1000}{1000}$$

Eq. 2

Note: 0.072 kg is the CO_2 emission factor per MJ of LPG

It is interesting to note that the emission reduction is somewhat comparable to the emission reduction with the fast pyrolysis and biofuel production route as presented in Fig. 2 in the manuscript. Therefore, the net CO_2 sequestration potential from coffee-jackfruit agroforestry system is approximately 9 tonnes /ha (Table 1b) compared to 2 tonnes of net CO_2 emission in a coffee plantation without shade trees (Fig. 1). This is due to the potential for the production of timber and significantly higher quantities of biofuel and biochar as shown in Table 1b. These are still indicative calculations and we have not yet considered the accumulation of carbon in the jack tree roots or the soil carbon increase reported in the shade coffee plantations when compared to unshaded plantations(Jha et al., 2014). Such detailed calculations are being carried out as a part of the life cycle analysis and material analysis efforts.

Table 1b. Emission and Sequestration from Coffee - Jackfruit Agroforestry

A. Emission from Shade Coffee Plantations	
1.02 kg CO_2/kg of green coffee	
Considering 2000 kg of Coffee/ha is produced total emission from Coffee is 2 tonne of CO_2/ha	
Emission from jackfruit fertilization is estimated to be 1.5 tonnes of $CO_{2\text{-eq}}$	
B. Sequestration from Coffee - Jackfruit Agroforestry with timber, biochar and biofuel	
Timber	2 tonnes CO_2/ ha
Biochar	3.5 tonnes CO_2/ ha
Biofuel	(up to) 7 tonnes CO_2/ ha
Net Sequestration (B – A)	**~9 tonnes of CO_2/ha**

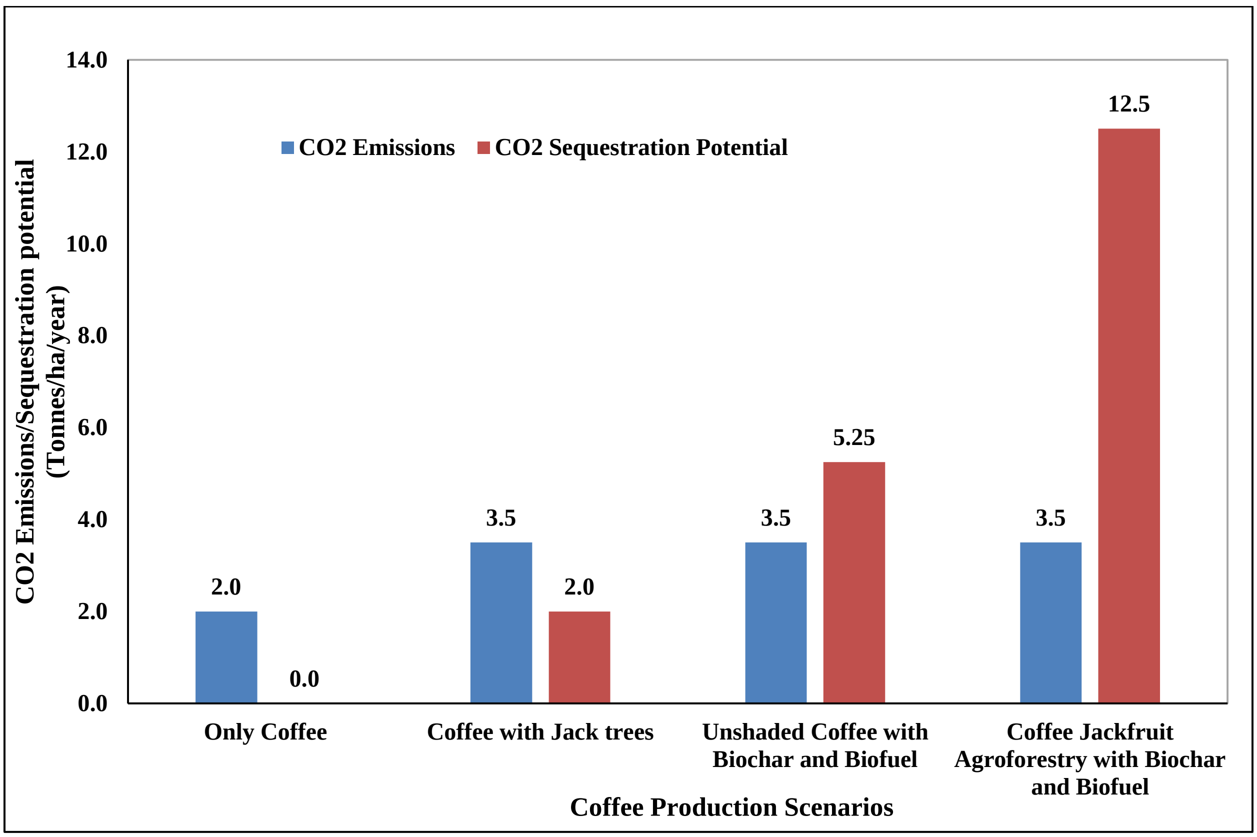

Fig. 1. Variation in CO_2 sequestration with different coffee production scenarios (indicative).

Fig.1 shows the potential for achieving the negative emission in coffee jackfruit agroforestry. It also shows an opportunity for achieving the negative emission even at the beginning of the program by introducing the biochar and bio energy technologies using the agrowaste streams. Eventually the carbon sequestration would increase as the jack trees grow up and agrowaste streams from the plantations increase.

Appendix 1b: Techno-economic analysis of Coffee - Jackfruit Agroforestry system v/s unshaded coffee plantations

For cost benefit calculations, we consider a simple pyrolysis/gasifier cook stove route which results in replacement/avoidance of LPG consumption. As mentioned before, with very conservative estimates and moderate efficiencies, 1 tonne of biochar from 10-12 tonnes of agro-waste (considering 8 tonnes of agrowaste is collected from this for biochar and bioenergy production), can be obtained. Considering the calorific values of LPG (~46 MJ/kg) the remaining biomass used gas mode cooking (considering that biochar is not burned) could replace ~ 2 tonne of LPG (assuming similar efficiencies in gaseous fuel-based cooking for both the fuels). LPG cost in India is around 0.80 Euro/kg. ~2 tonnes of LPG replacement/avoidance could save around 1600 Euro. Additionally, 2 m^3 of timber is also expected to be produced.

The income generation shown is also in line with the economic returns from a gasifier fuel cell integrated power plant with biochar co-production as presented in another manuscript from our group (N. Jaiganesh, Po-Chih Kuo, Vipin Champatan, Girigan Gopi, R. Ajith Kumar, 2022), where the net cash flow per hectare per year comes as around ~2000-2500 Euro. Similarly, with the fast pyrolysis and biofuel route as given in Fig. 2, the income from the fuel is also around 1500 Euro. Hence, we assume that the assumptions taken with the pyrolysis/gasifier stove are reasonable and the values are in an acceptable range. The following tables present the estimated income potentials from the different coffee plantation scenarios.

Table 2a. Estimated income and expenses- Unshaded Coffee plantations only

Income from Unshaded Coffee plantations	
2 tonnes of Coffee/ ha/ year#	2500 Euro
Expenditure in Coffee Plantations	
Coffee farming cost/ha/year*	1600 Euro
Net income	**~ 900 Euro**

#(Thanuja and Singh, 2017)

*Compared to our previous work(Nandakishor et al., 2022), the coffee production cost considered here is higher. We have considered higher coffee yield here often needing intensive farming

DOI- https://doi.org/10.31219/osf.io/yde8w || Online: 28.03.2022

methods (irrigation etc.) (Joy, 2004). However, it appears that the net profits are in similar ranges in both the cases.

Table 2b. Estimated income and expenses- Unshaded Coffee plantations with biochar and biofuel generation from biomass available in the farm

Income from Unshaded Coffee plantations	
2 tonnes of Coffee/ ha/ year	2500 Euro
Biochar (0.5 tonne/ha/year)	250 Euro
Biofuel (~ 1 tonne of LPG replacement)	800 Euro
Expenditure in Coffee Plantations	
Coffee farming cost/ha/year	1600 Euro
Biomass Collection and processing cost ha/year	20-200 Euro
Pyrolysis/gasifier Stove Cost: (as one time investment). We have considered it as a negligible annual investment.	40-100 Euro
Net income	**~ 1400-1900** Euro**

Table 2c. Estimated income and expenses- Coffee-Jackfruit Agroforestry

Income from Coffee Plantations	
2 tonnes of coffee/ha/year	2500 Euro
Income from agroforestry based suggested interventions	
Jackfruit	1000 Euro
Jackfruit Timber	600 Euro
Total Income	**~4100 Euro**
Expenditure in Coffee plantations	
Coffee farming cost/ha/year	1600 Euro
Increase in farming cost with Jackfruit introduction*/ha/year	300 Euro
Total Expenditure	**~1900 Euro**
Net income upon introducing the Jackfruit as shade trees	**~ 2000-2300**Euro**

*(Chandrakanth Reddy et al., 2019)

Table 2d. Estimated income and expenses- Coffee-Jackfruit Agroforestry with biochar and biofuel

Income from Coffee Plantations	
2 tonnes of coffee/ha/year	2500 Euro
Income from agroforestry based suggested interventions	
Jackfruit	1000 Euro
Jackfruit Timber	600 Euro
Biochar# (may or may not be included in the total income per hectare)	500 Euro
Biofuel (~ 2 tonnes of LPG replacement)	1600 Euro
Total Income	**~6000-6200 Euro**
Expenditure in Coffee plantations	
Coffee farming cost/ha/year	1600 Euro
Biomass Collection and processing cost ha/year	20-200 Euro
Increase in farming cost with Jackfruit introduction*/ha/year	300 Euro
Pyrolysis/gasifier Stove Cost: (as one time investment).	40-100 Euro
Total Expenditure	**~2000-2200 Euro**
Net income upon introducing the Jackfruit as shade trees	**~3000-4000** Euro**

*(Chandrakanth Reddy et al., 2019)

Considering that biochar could be used in the farm itself for soil amendment.

**As we have given indicative calculations, we present a range for the net income.

It is estimated that conversion of unshaded coffee plantations into coffee-jackfruit agroforestry system, with additional expenses in the range of 300-500 Euro will lead to an annual net income increase of approximately 2500-3000 Euro from timber, biofuel and biochar. Hence, we consider that this effort is leading to negative emissions at a negative cost.

Appendix 2: Simplified LCA for Coffee-jackfruit agroforestry system

This section presents a "system model" for the coffee and jackfruit agroforestry-based case study from a life cycle thinking perspective, following the conceptual guidelines of the LCA methodology and its four steps: 1. Goal and Scope definition, 2. Life Cycle Inventory, 3. Impact Assessment, and 4. Interpretation:

2.1 Goal and Scope definition:

Goal: Get an estimate on the potential of the coffee and jackfruit agroforestry-based case study to reach negative greenhouse gas (GHG) emissions, using the 100-year Global Warming Potential (100 GWP) perspective.

Function: Efficient use of coffee plantations to promote negative emissions systems and local economic opportunities through co-production of jackfruit, timber, and heat & biochar (via pyrolysis).

DOI- https://doi.org/10.31219/osf.io/yde8w || Online: 28.03.2022

Functional unit: 1 ha-year of coffee plantation co-producing jackfruit, timber, heat, and biochar.

System boundaries: Production of coffee and jackfruit, and processing of residual biomass (see Fig. 2.a), from a cradle-to-gate perspective.

Background system: Coffee and jackfruit production.

Foreground system: Residual biomass processing into timber, and heat & biochar (via pyrolysis).

Multifunctionality: Coffee and jackfruit production are considered independent productive systems where the full LCA GHG emissions are assigned to their respective products. In consequence, waste biomass is free of any LCA GHG emissions burden. Additionally, heat is accounted for as credits through system expansion, while biochar and timber are considered carbon sinks. Timber is considered to be used as a construction material with a lifetime of over 100 years(Smith and Snow, 2008; Ayanleye et al., 2022). This approach is applicable for the "system model" since it considers the product basket as a whole.

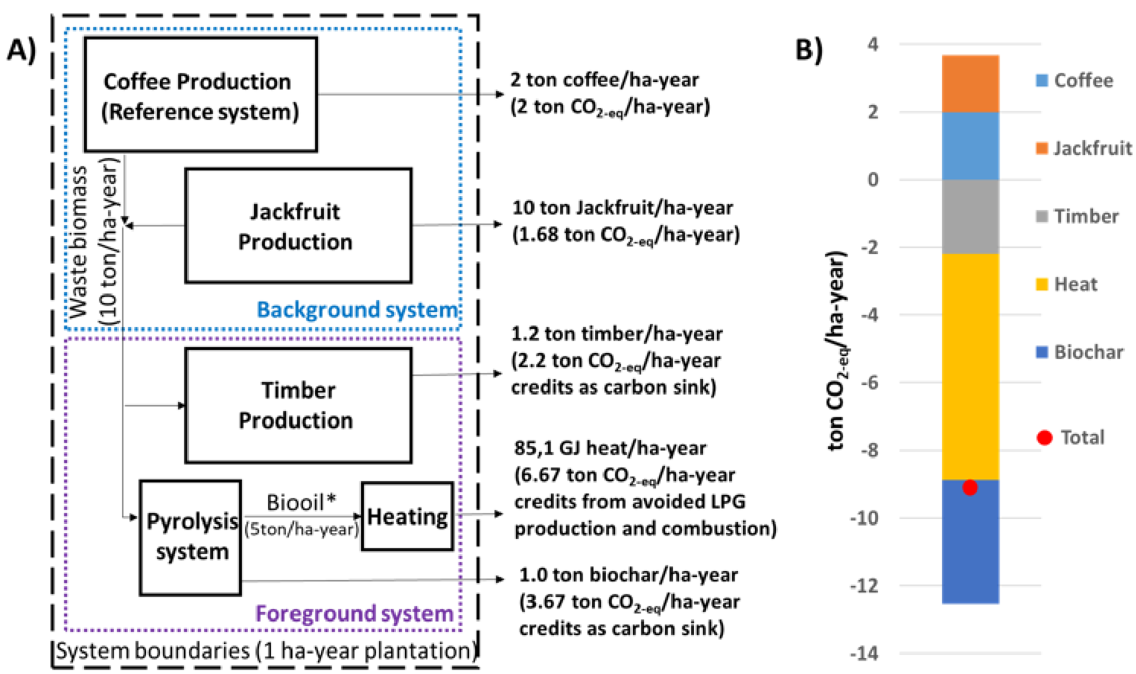

Fig. 2 A. Representation of "system model" with system boundaries, background and foreground systems, product flows, and related LCA GHG emissions; and B) contributions to LCA GHG emissions and aggregated results. (*Combustion of Bio oil results in biogenic CO_2 emissions.)

Assumptions: For the sake of simplicity, no additional material/energy inputs have been considered for timber production (e.g. power) or avoided emissions from concrete replacement, the pyrolysis system (incl. gas, solid, and liquid separation), and heating. Bio-oil combustion considers that only biogenic CO_2 is generated.

2.2 Life Cycle inventory

Background system: The coffee production system is based on (World Bank, 1982; Killian et al., 2013; Usva et al., 2020) and the jackfruit production system is based on (Elevitch and Manner, 2006; APAARI, 2012), productivities are given in Fig. 2A accordingly to the respective literature sources.

Foreground system: The coffee and jackfruit agroforestry produce 1.2 tonnes of timber per hectare per year. Upon pyrolysis, the 10-tonne waste biomass thinning and pruning (Evizal et al., 2009) per hectare per year produces 5-tonne bio-oil and 1-ton biochar. Bio-oil (with a calorific value of 17 MJ/kg) is then used for cooking heat which aims to substitute fossil-based heat produced with liquefied petroleum gas (LPG) (46 MJ/kg). No additional material/energy inputs are considered for timber, pyrolysis, and heating, as indicated above.

2.3 Impact Assessment

The LCA GHG emissions for coffee is assumed to be 2 tonnes $CO_{2\text{-eq}}$/ha-year (Killian et al., 2013; Usva et al., 2020). Farm level emission from the application of synthetic fertilizers is considered for jackfruit cultivation and estimated as per IPCC 2006 guidelines to be 1.68 tonnes of $CO_{2\text{-eq}}$/ ha-year. Fertilizer requirements are taken from literature sources. (Chandrakanth Reddy et al., 2019).

As indicated above for multifunctionality, heat is accounted for as credits through system expansion; and biochar and timber as carbon sinks. Heat is aimed to replace LPG-based heat whose LCA GHG emissions from production are 0.3 kg $CO_{2\text{-eq}}$/per kg of LPG (Shahrier et al., 2020) and from its combustion are 0.072 kg CO_2/ MJ of LPG (IPCC Guidelines for National Greenhouse Gas Inventories, 2006). For timber, as indicated in Appendix 1, 1 m^3 (density 600 kg/m^3) sequestrates 1.1 tonnes $CO_{2\text{-eq}}$/ m^3 of timber (assuming 50% of dry mass is Carbon); while biochar has the capacity for carbon capture of 3.67 tonnes $CO_{2\text{-eq}}$/ton biochar.

The resulting contributions to the LCA GHG emissions are shown in Fig. 2B.

2.4 Interpretation

LCA GHG emissions from coffee and jackfruit production are here considered as background emissions since they would be produced anyway if coffee and jackfruit were produced elsewhere in separate productive systems. Furthermore, independent productive systems for coffee and jackfruit would lead to additional land use (doubled according to the FU of 1 ha-year) -not considered here-. Hence, this "system model" focuses primarily on the potential to reach negative emissions through the additional production of timber, heat, and biochar.

Heat production has the largest contribution for potential negative emissions (6.67 tonnes CO_{2-eq}/ha-year) due to the replacement of fossil LPG with bio-oil. Heat production through LPG combustion leads to fossil-based emissions of CO_2 while combustion of bio-oil would lead to only biogenic emissions. Hence, those fossil-based emissions are avoided (6.12 tonnes CO_{2-eq}/ha-year). Furthermore, the LCA GHG emissions associated with the LPG production are also avoided 0.55 tonnes CO_{2-eq}/ha-year).

Biochar and timber combined, as carbon sinks, have a similar contribution to negative emissions (5.87 tonnes CO_{2-eq}/ha-year) of that from heat production, where biochar has a larger potential for carbon sequestration (3.67 tonnes CO_{2-eq}/ha-year) in comparison to timber (2.2 tonnes CO_{2-eq}/ha-year).

Hence, the total potential for negative greenhouse gas (GHG) emissions of the coffee and jackfruit agroforestry-based case study, with co-production of heat, timber, and biochar, is 12.54 tonnes CO_{2-eq}/ha-year. If emissions from coffee and jackfruit are considered as part of the overall system, the net potential for negative emissions would be 8.66 tonnes CO_{2-eq}/ha-year or a sequestration of 4.43 kg CO_{2-eq}/kg of green coffee produced.

Disclaimer: Limitations of limited LCA

The goal of this LCA was to demonstrate the negative emission potential of the intercropping between coffee and jackfruit, would result in net negative emissions. It should however be stated, that tree aging and changes in productivity have not been specified per year nor per geographic location. Also, only a base scenario has been considered for the substitution of timber and heat by products of this specific Robusta coffee jackfruit agroforest.

Appendix 3: Strategic planning for farmer centered and agroforestry focussed negative emission/emission management initiatives

Based on the experience built up with our initiatives till now, we propose the following strategy for taking up similar efforts elsewhere. The proposed strategy is based on the triple helix concept with the knowledge organizations, government agencies and the industry working together in building up such initiatives. The strategy is presented from an academic viewpoint and is not yet a fully adopted government policy/programme. However, several of the elements presented in this manuscript are already in the government programmes. Policy support around the suggested interventions in the future will be critical for the successful implementation of such strategies.

1) Knowledge leadership: Knowledge leadership is very helpful in bringing in new ideas when there is a receptive community. In the case of Meenangadi, the support role played by MS Swaminathan Research Foundation (MSSRF) from 2005 onwards to the environmentally friendly initiatives in the panchayat appears as playing a significant role. Framing the carbon neutrality concepts around the environmentally friendly initiatives became easier with the knowledge support and leadership provided by Dr. Thomas Isaac, the then finance minister of Kerala with the additional support of Thanal, an NGO, which carried out the baseline assessment for the carbon neutrality effort in the panchayat. The Meenangadi leadership appeared also as finding comfort in the technical and scientific support provided by the academic network involving the organizations to which the authors of this manuscript are affiliated with, all with the Centre for Energy and Environment at Govt. Engineering College Kannur, jointly with MSSRF, playing the role of a local connecting hub.

2) The Government agencies: The village governing council, the Panchayat, played an important role with the support of Kerala state government. The main features of this intervention and its future impacts were discussed in 'Grama Sabhas', conventions of people in the Panchayath for finalising the developmental interventions of the Grama Panchayath, since the approval of Grama Sabha is vital for undertaking projects and programmes for both development and environmental protection. Farmers' concerns over such interventions were discussed which helped to gain peoples' support for Carbon neutrality focussed interventions. Building up an international knowledge support system became possible when the government officials and the embassy officials played a supporting role. This became possible mainly with the involvement of the officials in the international workshops and webinars organized to support the program.
3) Industry: The industry started showing enthusiasm when the opportunities to contribute became visible. Large scale and small scale industrial and business organizations are actively contributing to the discussions in developing the concepts further.

All together 25 organizations have signed up in setting up the platform for initiating similar efforts in multiple places. Extending to a Quadruple helix approach, might also help, especially in places where participatory governance structures are not in place. A good example for a triple consortium supporting a large scale energy initiative is the New Energy Coalition (Hydrogen Valley - New Energy Coalition) in Groningen. Groningen is in North Netherlands and North Netherlands is the first Hydrogen Valley of Europe(Hydrogen Valley - New Energy Coalition). Groningen is also the largest natural gas field of Europe, where natural gas production is being stopped and instead, an hydrogen based economy is being built.

Appendix 4: Potential biodiversity enhancement with shade trees in agroforestry systems

In the present global scenario, staple food production largely happens in mono-cropped farms and without agroforestry, unshaded coffee plantations are similar to such mono-cropped farms (Nair, 2011; Jose, 2012; Bavec and Bavec, 2015). Introduction of jackfruit trees in coffee plantations is expected to enhance the biodiversity potential of such mono-cropped farms while also providing food products. Previous investigations in biodiversity rich rainforest regions indicate that shaded coffee agroforestry maintained substantial biodiversity (Harvey and González Villalobos, 2007; Bhagwat et al., 2008), especially the diversity of indigenous tree species (Nesper et al., 2017). Changes in biodiversity with introduction of multi-species agroforestry needs to be further explored locally with scientific research.

The trade-offs between conserving biodiversity and economic returns from shaded coffee, is a matter of debate for coffee agroforestry systems (Jezeer et al., 2017). Gomes et al. have reported that shade levels below 40-50% in coffee plantations do not compromise with the coffee yield (Gomes et al., 2020). Durian tree having characteristics similar to jackfruit in height and canopy providing around 14% shade with 46 Durian trees per hectare (Long et al., 2015). Similarly, the coffee-jackfruit agroforestry system can also be expected to have less than 20% shade with the suggested tree density of around 40 trees per hectare. This brings in an opportunity to plant a variety of indigenous tree species sustainably increasing the local biodiversity. Further, careful selection of shade trees and tailored pruning management may limit the competition between coffee crop and shade trees. The incorporation of shade trees in coffee systems may positively influence the productivity of coffee plants due to reduced temperatures under shade that slow down the fruit maturation, resulting in larger coffee beans of better quality(Muschler, 2001; Bote and Struik, 2011). Additionally, the presence of trees in coffee systems can lead to more birds and bees, contributing towards pollination and pest control(Chain-Guadarrama et al., 2019).

Coffee based agroforestry, apart from contributing towards conserving biodiversity (Moguel and Toledo, 1999; Bhagwat et al., 2008) can also provide several ecosystem services allowing the farmers to produce food, fodder, fuel, timber, and other forest resources from their farmlands (Jose, 2009). It also provides suitable measures to increase soil organic carbon for the enhanced growth of coffee and diverse indigenous trees. Thus, tropical agroforestry needs to be revisualized and promoted as an approach to reconcile biodiversity conservation, enhancing farm income and capturing CO_2 from atmosphere.

Appendix 5: The Meenangadi opportunity

Meenangadi certainly appears as a suitable village for early implementation of such a scheme. We have conducted an opinion survey in 100 households in Meenangadi. The detailed results are available elsewhere (Nandakishor et al., 2022). The objective of the survey was to check the awareness and interest of local population on climate change and its mitigation and to find out farm forestry strategies appealing to the local population. We found that 93% of the individuals feel that there is climate change and 86% of the population believes climate change could be mitigated. Out of this, 95% find planting trees as an acceptable way to mitigate climate change. Those who were interviewed have largely shown willingness in planting shade trees in their farms especially when there are incentive schemes such as the proposed tree banking program. More than 50% of individuals said that they would prefer to plant timber yielding trees or fruit trees. Our findings indicate that the individuals are ready to plant both native and non-native tree species in the region. The response we have obtained alleys several of the concerns expressed in literature (Nandakishor et al., 2022) on the acceptability of tree planting initiatives among the farmers and other inhabitants in rural areas.

Appendix 6: Advanced Biofuel Technologies

Here we present some of the advanced bio fuel technologies discussed in the manuscript.

1. Hydrogen production from biogas - This is often done with reforming methane (in biogas) followed by water gas shift reactors and hydrogen purifiers(Gao et al., 2018).

2. Hydrogen production from biomass - This is often done with gasification followed by water gas shift reactors and hydrogen purifiers(Levin and Chahine, 2010).

3. Internal reforming solid oxide fuel cells (SOFCs) - The presence of nickel catalyst, high temperature, local steam production due to the electrochemical oxidation of hydrogen and local heat production within SOFCs help with internal reforming of methane inside SOFCs, making it possible to produce both electricity and hydrogen at the same time. Additionally, the electrolyte of the SOFCs allows the oxide ions to travel to the fuel electrode from the air electrode while preventing the movement of nitrogen to the fuel electrode. This makes it easier to separate CO_2 from the outlet gas from the fuel electrode(van Biert et al., 2019).

4. Fuel assisted electrolysis - Steam or CO_2 is fed to one electrode and the electrolyser allows oxygen ions to move to the other electrode and reacts with the fuel (such as methane or syngas) provided, leaving hydrogen and or CO leaving the steam or CO_2 fed electrode(Cinti et al., 2016).

Appendix 7: Risk and mitigation strategies

Some of the major risks associated with the suggested interventions and possible mitigation strategies are presented below.

Risk	Mitigation Strategy
Acceptability problems with biofuels technologies	Starting with easy to implement technologies (biogas, easy to use but advanced cook stoves etc.) and co-creation of advanced systems resulting in the development of acceptable solutions.
Timber trade leading to deforestation in nearby areas	Development of appropriate governance strategies including the development of tracking mechanisms such as remote sensing and geo-tagging.
Biodiversity concerns	Focus on the conversion of existing mono cropped farm lands and not in the development of new farming areas. Promoting intercropping as much as possible.
Adoption rate is not high	Large scale awareness building (even this paper is a part of such efforts) create an enabling policy environment
Unexpected science, technology or organizational problems arising during the implementation stage	Development of a sufficiently large community and environment around in order to come up with solutions faster as and when problems arise
Risk of Reversal	Appropriate and well managed farming practices with the help of advanced technologies including remote sensing can help in mitigating the reversal risks. It is also important to note that agroforestry combined with bioenergy minimizes the risks associated with forest fires due to the lower tree density and also the usage of local biomass for bioenergy generation and biochar production.
Risk of Economic Leakage	Economic calculations giving an indicative range and considering conservative values. Presenting a range for economic returns is expected to cover the risks of economic leakage (As done in this study).

Appendix 8: Emission reduction potential from concrete replacement with timber

Around 8% of the world's total GHG emissions are from the cement industry(Carbon Brief, 2018). The promotion of timber-based construction can reduce the dependency on cement and steel, and hence reduce GHG emissions. Studies show that by using wood, instead of concrete, emissions could be reduced considerably(Skullestad et al., 2016; Sandanayake et al., 2018). A life cycle assessment (LCA) study using the 'cradle to gate' approach in Korea showed that 250-350 kg CO_{2-eq}/m^3 is emitted in concrete manufacturing (Kim et al., 2016) and another case study revealed that using timber along with concrete can reduce the emission around 15 kg CO_{2-eq} per square meter (Sandanayake et al., 2018).

Considering the density of wood as 0.7 g/cc and 50% of the dry mass as Carbon, 1 m^3 of wood can approximately store 300-350 kg of Carbon or 1-1.2 tonnes of Carbon dioxide. Replacing concrete with timber wherever feasible can help in storing and locking the carbon in wooden structures along with a reduction in the amount of concrete usage. As per the Bureau of Energy Efficiency (BEE) India, the per capita cement consumption in India in 2019 is around 195 kg (Cement | Bureau of Energy Efficiency). Adopting wooden building construction technology like cross-laminated timber (CLT) in Meenangadi, can significantly reduce construction-based emissions along with the promotion of sustainable infrastructure. The total coffee plantation in Meenangadi is around 3000 hectares, offering a potential for producing 6000 m^3 of timber per year and corresponding emission reduction in construction sector annually. Assuming that this timber could replace around 6000 m^3 of concrete, and considering 250-350 kg CO_2/m^3 emissions from concrete, there is a potential for emission reduction of approximately 1500-2100 tonnes CO_2 per year with timber. Additionally, considering that 1 m^3 of timber can sequester around 1 tonnes of CO_2, it can sequester 6000 tonnes CO_2, resulting in a net reduction of 7500-8100 tonnes CO_2 per year from the atmosphere.

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