Optimal Utilization of Coal Ash, Barren Land, and Application of Agrivoltaics for Sustainable Communities in the Phase-down Scenario of Coal in India

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ABSTRACT

Globally, India has one of the lowest per capita available lands for agriculture. With the increase in population, the per capita available land for agriculture has reduced by 45% over the last 30 years. About 10% of land in India is barren, while 44% is cultivated and as much as 16,684,000 hectares (ha) of land is barren, and not viable for agriculture [1]. In addition, more than 26,305 ha of land are being used for holding coal ash generated from thermal power stations, which can be put to productive and sustainable use [2]. Coal ash is a by-product of fossil fuel coal-based thermal power generation, which can be utilized in agriculture by replacing/providing the much-required topsoil in barren land.

It may be noted that out of 430 billion kWh (gigawatt-hour, GWh) electricity generated in the first quarter of 2024 in India [3] and [4], 82% came through non-renewable thermal routes, of which 74% from coal only, producing 271 million tons of ash [5 and 4]. India's 24% of coal, 85% of oil and 50% of natural gas are imported at a huge energy bill of $160 billion (USD) in the year 2023 [5]—coal import has increased to more than seven times in last two decades. For a developing economy with largest population of the world, India is talking the most crucial task of attaining overall sustainability with decarbonization of the economy, most challengingly the phasing down of coal.

This article proposes a novel approach to convert barren land for agrivoltaics i.e., the dual use of ground-mounted solar photovoltaic (SPV) projects and agriculture (Figures 1 and 2) at the underneath of the panels using ash as a base topsoil instead of soil. Preliminary results have shown successful growth of edible vegetables and flowers in an

in-situ experiment. The proposed model can serve as a sustainable model for ash utilization, judicious land use, renewable energy generation, and support to local communities for employment generation and food production. Large-scale adoption of the proposed model is expected to propel India to attain the above-mentioned benefits along with the target of achieving net zero by 2070.

Figure 1. A typical site with simultaneous use of land for agriculture and SPV power

Figure 2. A typical site with simultaneous use of land for cattle grazing and SPV power

INTRODUCTION

It is clearly stated in Chand [6] that the share of agriculture in India has shrunk drastically to even less than 15% and the reason cited is focus on growth of industrial and services sector. But the agriculture sector's importance cannot be undermined because of several reasons like food security, majority of poor people living in rural areas and dependence on rural income [7]. There is a dire need for changing current agricultural trends so that agricultural income can improve [6]. Agriculture growth is important as it helps in reducing poverty, increasing per capita income, alleviates health, nutrition and quality of life situation [6]. There is a need of creating blue collar jobs in the agriculture sector in villages so that per capita income of villagers can increase [6]. There were 16,684,000 hectares of barren land in India as of 2020-21 [1]. Due to increasing competition for land between renewable energy methods and agriculture, it would be a better solution to optimize both the scenarios by merging them. This method of agriculture using SPV systems has been termed as agrivoltaics. Here, we are going to apply this system on barren land and would use fly ash as a manure for the plants to be grown on available barren lands. Coal fired thermal power plants generate fly ash, which is a problematic waste and is a serious environmental hazard when not utilized properly [8]. 270.82 million tons of fly ash were generated in the year 2021-22 [9]. Agrivoltaics has gained considerable popularity across the world [10]. The total installed capacity of agrivoltaics was around 2.8 GW in 2020 with China leading this race with 1.9 GW of agrivoltaics systems installed [10]. Other countries at the forefront are Japan, France, Italy, France, South Korea, etc. [10]. This method of agriculture has been found to increase the yield of several crops including leafy vegetables, and medicinal plants under the shade of panels [10]. Arid and semi-arid regions that need moisture and some shade for plants have been found to be more suitable for this system of agriculture [10]. The International Institute for Sustainable Development (IIST) [10] also states that it would be a good idea to explore the potential of horticulture at the peripheries of the urban areas.

Possible Role of Agrivoltaics in Phase Down of Coal from India

India's reliance on coal for electricity generation, contributing to 74% of its total energy production, has led to significant coal ash generation and environmental challenges. In 2023 alone, over 271 million tons of coal ash were produced. Furthermore, India's high dependence on energy imports—24% of coal, 85% of oil, and 50% of natural gas—has resulted in a massive energy import bill of USD 160 billion [4] and [3].

In the transition to sustainable energy, agrivoltaics offers a promising solution. By combining solar photovoltaic (SPV) systems with agriculture, agrivoltaics optimizes land use while generating renewable energy. This system can be implemented on India's vast barren lands, especially by utilizing coal ash as a soil additive for growing crops. Even with all-out efforts already in place, a whopping 11 million tons of fly ash still remain unutilized every year in India may be utilized to cover 786 to 967 ha of barren land for agrivoltaics, the approach could reduce dependency on coal, minimize the environmental burden through scientific disposal of larger share of ash, and support local agricultural production.

Agrivoltaics can play a pivotal role in helping India achieve its net zero targets by 2070 by enabling the phase-down of coal. It aligns with the country's goal of increasing renewable energy capacity while addressing food security, generating employment, and revitalizing rural economies. By fostering the adoption of agrivoltaics systems, India can move toward a more sustainable, decarbonized energy future.

METHODOLOGY

After an assessment of potential, an investigation has been made to know the 360-degree views about the various aspects of its use, understand the problem areas and find the practical actions suitable for India in view of a few reported cases relevant to the objective of this study.

Various Aspects of the Use Coal Ash in Agrivoltaics Systems

Productivity of Vegetables (2020-21) = 18.46 MT/ha [12]

Productivity of Flowers (2020-21) = 9.25 MT/ha [12]

Productivity of Medicinal Plants (2020-21) = 1.26 MT/ha [12]

Assessment of Potential

The first target for agrivoltaics could be the land presently being used to store the huge amount of ash already generated from the various coal based thermal power stations in India now disposed at various sites totaling 26,305 ha of land. Let's assume that to attain 100% of this land being fully utilized with agrivoltaics in 10 years, 100/10 = 10% of the total land already covered with ash may be converted to agrivoltaics sites i.e., 2630 ha of land per year.

The second target could be the disposal of unutilized ash from all the coal-based thermal power plants in India to the barren land areas for agrivoltaics applications:

- Quantity of unutilized fly ash (2021-22) = 10.9588 million tonnes [9]
- Area of Barren land (2020-21) = 16,684,000 ha [1]

If we assume that 100% of undisposed coal-ash is being utilized to cover barren land, then:

- 100% of undisposed ash (2021-22) = 10.9588 million tonnes = 7,855,771 m^3, taking the average dry density of coal ash = 1.395 g/cm^3 [11]. Now, assuming required depth to be 1 m (approximately 3 feet) for fly ash, so surface area = 7,855,771 m^2 = 786 ha per year.

The third category of land would be say, 0.1% per year of 16,684,000 ha of land that is barren and not viable for agriculture could be tried with advanced agrivoltaics techniques, which means 16,684 ha land per year.

Thus, total annual potential for new area converted to agrivoltaics systems = 2630 + 786 + 16,684 ha/year = 20,100 ha/year land covered with coal-ash can be utilized for agrivoltaics.

The fourth category would be to apply agrivoltaics in existing agricultural land in a selective manner to augment the productivity of land and generation of electricity for a local microgrid, which would also help storage and processing of local agricultural produce and improve the living conditions of the local community by direct participation in establishing and maintaining the microgrid. Let's assume that 0.5% per year of the agricultural land of 367048 Ha is tactically applied with agrivoltaics without any compromise of the agricultural produce.

Four types of land would be available in India, as estimated in Table 1.

RESULTS AND DISCUSSION

We are assuming that one-third area each would be utilized by vegetables, flowers and medicinal plants.

Based on market data from 2020-21, the average price for vegetables varies significantly depending on the specific type, but a typical range can be INR 10,000 to INR 30,000 per metric ton. For a conservative estimate, the vegetable price has been assumed to be INR 10000 per metric Ton in the present study.

Table 1. An Es-ma-on of the Availability of Land in India for Agrivoltaics Use

			Agriculture			SPV
Description		Unit	Agriculture Vegetable and Flower	Agriculture Medicinal Plants	Total	50% of Agricultural Surface
1	First type (10% per year of existing ash land for 10 years)	ha	1754	877	2631	1315
2	Second type (100% of excess ash used to cover barren land till coal phase down is achieved)	ha	524	262	786	393
3	Third type (0.1% of existing barren land used for agrivoltaics, for 1000 years)	ha	111,227	55,613	166,840	83,420
4	Fourth type (0.05% of existing agricultural field covered with new SPV for 2000 years)	ha	244,699	122,349	367,048	183,524
	Total		358,203	179,101	537,304	268,652

Regarding employment generation, horticulture, particularly vegetable cultivation, tends to be labor intensive. It is estimated that about 0.03 workers are employed per ha for vegetables. Employment generation depends on the type of medicinal plants cultivated and the scale of operations. Typically, medicinal plant cultivation can generate between 1 and 3 jobs per ha [13].

Regarding market prices, the value varies by plant species and demand. For high-demand medicinal plants, prices can range significantly based on the specific plant. As an example, many popular medicinal plants like ashwagandha or aloe vera are often priced between INR 40,000 and INR 150,000 per metric ton depending on the market and regional demand [13] and [14]. For conservative estimate, the medicinal plants price has been assumed to be INR 40,000 per metric ton in the present study.

The market price of flowers varies widely depending on the type of flowers and regional demand. On average, flowers in India can be priced anywhere between INR 10,000 to INR 50,000 per metric ton, with high-demand varieties commanding even higher prices. For conservative estimates, the price of flowers has been assumed as INR 10,000 per metric ton.

In terms of employment generation, floriculture typically creates significant labor demand, with between 0.5 and 1.5 jobs per ha being common for flower farming. In the present study, a conservative estimate of 0.5 jobs per ha has been assumed [13, 14].

The amount of carbon dioxide (CO_2) absorbed by vegetable, medicinal or flower plants through photosynthesis depends on the type of plant, the growth conditions, and their photosynthetic efficiency. On average, plants absorb about 1.5 kg to 2 kg CO_2 per square meter annually. In the present study, it is assumed that plants will absorb 1.5 kg/m^2 per year or 15 ton/ha/year [13, 14]. This is an approximate calculation, as the exact rate of CO_2 absorption depends on factors like plant type, growth conditions, and climate.

If 1 ha of land is covered with a solar photovoltaic system in India, the estimated generation of electricity is 1,400,000 kWh/year. This setup can generate employment for around 4 to 5 people directly and indirectly. By utilizing solar power on this scale, it avoids the burning of approximately 1120 tons (@ 0.8 kg approximately coal required to produce 1 kWh electricity in India) of coal per year, which also leads to the avoidance of emitting 1,772 tons (at an average emission factor of 1.224 kg CO_2 per kWh) of carbon dioxide annually [15, 16].

Thus, it can easily be shown that the proposed agrivoltaics systems on coal ash in India in a phased manner, which can be the more practical way to implement, would fetch significant additional benefits to the nation every year, as shown in Table 2, for each type of land, as shown in Table 1.

India's current emission rate is 2,693MT CO_2e per year and the non-renewable electricity generation in GWh = 1374 in the year 2023-24. India's gross domestic product (GDP) of INR 173,820 billion recorded in the last year (2022-23) [17, 18].

As shown in Table 2, detailed calculations revealed that if agrivoltaics is implemented in a modest manner in the four types of land, the total outcome would be quite significant on an annual basis, as presented below:

- Total solar photovoltaic (SPV) electricity generation = 38 GWh/year, total CO_2 abatement = 287 million ton (MT) per year, total employment generation = 1,253,710/year and India's GDP would increase by INR 910 billion annually.

Considering India, total GDP = INR 173,820 per annum, total emission = 2693 MT CO_2 per annum, non-renewable electricity generation in GWh = 1374 GWh in 2023-24 and annual coal consumption is 700 MT.

Therefore, with the proposed rate of agrivoltaics, years needed to attain 100% renewable energy (RE) is 37 years and net zero in 9.4 years, coal phase down towards a halt in about 7 years and a total income generation equivalent to 1% of GDP.

SOME EXPERIENCE FROM THE FIELD

The authors have already reported in Shyam and Choudhury [19] that fly ash has been used in agriculture for winter and summer seasons vegetables. Existing areas covered with coal-ash could be the target areas for suitable agricultural use. The satellite imagery of an ash pond for better understanding has been provided in Figure 3. Several vegetables of summer and winter seasons have been grown using fly ash mixed in

Table 2. Benefits of Agrivoltaics if Implemented in Phases in India as Proposed in this Article

	CO_2 Abatement (absorption in agriculture and avoidance of coal combustion through SPV)			Employment Generation				Income Generation				Electrical Generation from SPV	Coal Avoidance from SPV
	Agriculture	SPV	Total	Agriculture Vegetable and Flowers	Agriculture Medicinal	SPV	Total	Agriculture Vegetable and Flowers	Agriculture Medicinal	SPV	Total		
Conservative rate (per literature)	15 ton/yr/ha	1040 ton/yr/ha		0.03 person/ha	1 person/ha	4 person/ha		$10{,}000 \times 10^6$ INR/yr/ha	40,000 INR/yr/ha	3.36×10^6 INR/yr/ha		1.4 GWh/yr/ha	400 tons/yr/ha
Type 1	39,458	2,330,623	2,370,081	53	877	5,261	6,138	18	35	4,419	4,454	1,841	1,473,080
Type 2	11,784	696,021	707,805	16	262	1,571	1,833	5	10	1,320	1330	550	439,923
Type 3	250,260	1.5E+07	2E+07	334	5,561	33,368	38,929	111	222	28,029	28,252	11,679	9,343,040
Type 4	5,505,720	3.3E+08	3E+08	7,341	122,349	734,096	856,445	2,447	4,894	616,641	621,535	256,934	2.1E+08
Total	5.807 10^6 tons/yr	343.013 10^6 tons/yr	348.820 10^6 tons/yr	7,743 persons	129,049 persons	774,296 persons	903,346 persons	2,581 10^6 INR/yr	5,162 10^6 INR/yr	650,409 10^6 INR/yr	655,571 10^6 INR/yr	27.100 GWh/yr	217 10^6 tons/yr

Figure 3. Satellite Image showing ash pond of KTPS, Koderma, JH. (Source: Google Earth)

Figure 4. Different vegetables grown using Fly ash as a part of ongoing study

different ratios in the soil up to 100% ash in some cases (Figure 4). The results have been quite encouraging with some of the vegetables showing positive trend in the ongoing study.

CONCLUSION AND WAY FORWARD

In the context of India's ongoing efforts to phase down coal and transition towards a more sustainable and decarbonized energy sector, the integration of agrivoltaics with coal ash utilization offers a promising pathway. This approach not only optimizes the use of barren and coal-ash covered lands but also addresses multiple challenges such as renewable energy generation, agricultural productivity, employment generation, and carbon dioxide sequestration.

Conclusion

The proposed model of using coal ash as a soil amendment or replacement in agrivoltaics systems has demonstrated potential for transforming unproductive land into valuable agricultural zones while simultaneously contributing to India's renewable energy and net zero targets. By applying this model across different land categories, India

Table 3. Estimated Impact of Agrivoltaics in India

	Unit	Year	Effect	Value	Percentage	Years Required
GHG Emission (CO_2 equivalent)	MT/year	2020	-349	3201	10.9%	9.2
Employment Generation	Persons/year	2023	903,346	593,729,164	0.2%	657.3
Income Generation	Million INR/year	2023	655,571	1,202,652,165	0.1%	1834.5
Electricity Generation	GWh/year	2023-2024	27	1176	2.3%	43.4
Coal Consumption for Electricity Generation	Million tons/year	2023-2024	-217	788	27.5%	3.6

could significantly reduce its dependence on coal, increase green energy production, and support rural economies through job creation and increased agricultural output as shown in Table 3.

The results from this study indicate that agrivoltaics, combined with the use of coal ash, can contribute to the reduction of CO_2 emissions, enhance energy security, and provide substantial socio-economic benefits. The estimated outcomes—such as generating 27 GWh of electricity, abating 349 million tons of CO_2 annually, and creating over 0.9 million jobs—underscore the importance of large-scale adoption of this model as shown in Table 3. Thus, for example, GHG Emission in 2020 @3201 MT/year would become net zero within 10 years because of emission abatement of @349 MT/year through agrivoltaics. Furthermore, this approach aligns with India's commitment to achieving net zero by 2070 and could play a critical role in meeting this ambitious goal.

Way Forward

To realize the full potential of agrivoltaics on coal ash-covered lands, a multi-faceted strategy is required. The following steps are recommended:

1. Policy Support and Incentives

- The government should develop policies that incentivize the use of coal ash in agrivoltaics, including subsidies for farmers and companies that invest in such projects. Earlier studies in European Union suggested use of 1% of the utilized agricultural area (UAA) to over with SPV [20].
- Regulatory frameworks must be established to ensure the safe and effective use of coal ash in agriculture, addressing any environmental and health concerns.

2. Research and Development

- Further research is needed to optimize the use of coal ash in different soil types and climates, ensuring that it supports sustainable crop growth without adverse effects.
- Innovations in agrivoltaic technologies, such as adjustable solar panels and automated irrigation systems, should be explored to enhance the efficiency of land use.

3. Capacity Building and Training

- Farmers and local communities should be trained in agrivoltaic farming techniques and the safe handling of coal ash.

- Partnerships between research institutions, industry, and government bodies could facilitate knowledge transfer and the adoption of best practices.

4. Pilot Projects and Scaling

- Initial pilot projects should be expanded to demonstrate the viability of agrivoltaics on a larger scale, with a focus on replicability across different regions of India.
- Scaling up these projects will require coordinated efforts between stakeholders, including public and private sector investments.

5. Monitoring and Evaluation

- Continuous monitoring of the environmental and socio-economic impacts of agrivoltaics projects is crucial to ensure sustainability and address any emerging challenges.
- Evaluation mechanisms should be established to assess the long-term benefits of these projects and to make data-driven adjustments to strategies.

By implementing these steps, India can leverage its abundant barren lands and coal ash deposits to create a sustainable and resilient agricultural system that complements its renewable energy ambitions. The successful integration of agrivoltaics into India's energy and agricultural landscapes could serve as a model for other countries facing similar challenges, contributing to global efforts to combat climate change and achieve sustainable development.

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