RP Current Trends In Agriculture And Environmental Sciences
Vol. 5, No. 1 (January – March 2026) pp. 8–12
e-ISSN: 2583-6293

Cite this article: R. Soni, S. Sharma, M. Rao, Quantifying biomass potential of Soybean residues: Agro-ecological sustainability pathways in the Malwa Plateau, *RP Cur. Tr. Agri. Env. Sci*. **4** (2025) 8–12.

Original Research Article

Quantifying biomass potential of Soybean residues: Agro-ecological sustainability pathways in the Malwa Plateau

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ARTICLE HISTORY
Received: 10 April 2026
Revised: 27 May 2026
Accepted: 27 May 2026
Published online: 17 June 2026

KEYWORDS
Soybean residue; Biomass; Agro-ecological sustainability; Malwa Plateau; Renewable energy.

ABSTRACT
This study evaluates the bioenergy potential of soybean agricultural residues in the Malwa Plateau, Madhya Pradesh. By quantifying residue availability and examining energy conversion pathways, the research highlights sustainable strategies for integrating bioenergy into agro-ecological systems. The findings indicate that soybean residues can significantly contribute to renewable energy generation, reduce the environmental impacts associated with residue burning, and enhance rural energy security. Crop residues represent a sustainable and readily available feedstock for bioenergy production. The total gross crop residue potential in the Malwa region is estimated at 3.41 million tonnes per year, of which a substantial proportion is available as surplus for energy applications. Among the districts, Dhar generates approximately 0.40 million tonnes per year of gross crop residues and 0.138 million tonnes per year of surplus residues, making it a leading contributor. Other districts, including Indore, Ujjain, Mandsaur, Neemuch, Rajgarh, Ratlam, Sehore, Shajapur, and Dewas, produce surplus crop residues in the range of 0.11–0.13 million tonnes per year.The utilization of crop residues for bioenergy generation presents a viable and sustainable alternative to fossil fuels. It can help reduce greenhouse gas emissions, mitigate climate change, and address the challenges of open-field residue burning. Additionally, it offers socio-economic benefits by creating income and employment opportunities for small and marginal farmers.

1. Introduction

India's energy sector faces significant challenges due to population growth, economic and industrial expansion, and improving living standards. Despite having one of the fastest-growing economies in the world, dozens of millions of its residents still lack access to basic energy. According to reports, in order to meet the fundamental energy needs of its inhabitants, power generation capacity, including all captive plants, must rise from the existing capacity of approximately 183 GW to over 800 GW by 2031–2032 [1]. From a historical perspective, Kumar and Jain [2] found that between 1970–71 and 2006–07, India's consumption of coal went from 71.2 MT to 462.7 MT, crude-petroleum increased from 18.4 MT to 146.5 MT, and the India's domestic energy reserves are insufficient to meet demand, and as a result, the nation is mostly dependent on oil imports. For example, just 34 MT of crude oil were produced domestically in 2008–09 compared to 161 MT of crude oil used [3]. Almost 80% of crude oil is imported into India. In a similar vein, LPG and coal are imported to satisfy domestic demand. The majority of India's coal production is used to generate energy, with coal-fired power plants accounting for over 54% of all electricity generation. Other energy sources, such as massive hydro and nuclear power projects, are beset with issues and are subject to harsh environmental criticism. As a result, the nation's energy supply and demand are seriously out of balance.

With rising living standards, demand for electricity has also surpassed availability. Nearly every sector—industrial, commercial, institutional, and residential—is now dependent on diesel or furnace oil due to the limited supply of electricity. Large-scale kerosene consumption has been caused by inadequate rural electricity supplies. In India, almost 78 million people mostly rely on kerosene for lighting [4].

India has been forced to look for renewable and sustainable energy sources because of growing energy demand, a lack of conventional fuel options, oil geopolitics, and environmental concerns. The primary areas of renewable energy development in India have been determined to be biomass, solar, wind, and small hydro. The nation's combined grid-connected power potential from small hydropower, wind, and biomass is predicted to be more than 87 GW. In a similar vein, solar potential falls between 20 and 30 MW/km2 Hiloidhari*et. al*, (2014) In India, biomass resources is more widely available than other renewable sources. Acknowledging the potential of bioenergy production, India's Ministry of New and Renewable Energy (MNRE) has launched a number of biomass initiatives with promising results.

While access to LPG and electricity has improved in India over the past few decades, biomass usage as a traditional fuel has increased concurrently and now accounts for the majority of fuel used by rural households. According to Bhattacharya 26% of Indian rural households use agricultural residue or animal wastes for cooking, whereas 64% rely on firewood. Additionally, nearly 30% of urban households cook using conventional energy.

The benefits of contemporary biomass conversion technologies—such as combustion, pyrolysis, gasification, fermentation, and anaerobic digestion—are utilized in the generation of heat and power, liquid and gaseous transportation fuel, cooking biogas, and more. In rural India, biomass energy has enormous promise for contemporary applications, particularly in the lighting and cooking industries. Balachandra made a number of arguments in favor of modern biomass energy adoption, particularly for rural India: (i) India's biomass resources have a high potential to produce a sufficient amount of modern energy; (ii) advanced biomass energy technologies for decentralized utilization in rural areas have almost reached commercialization;

A total of 288 biomass power and cogeneration projects with a combined capacity of 2665 MW have been erected nationwide to supply power to the grid, according to the MNRE (Ministry of New and Renewable Energy, GOI). In India, sugarcane bagasse, rice husk, straw, cotton stalk, coconut shells, soy husk, coffee waste, jute wastes, groundnut shells, sawdust, and other biomass feedstock are frequently used to generate electricity. Numerous biomasses have been studied for the production of bioenergy, including loose biomass like rice husk cashew nut shell areca nut and sugarcane residue as well as woody biomass. The nation has also commissioned kilowatt-scale decentralized biomass power generation at the village level [10].

Because it provides necessary services that boost economic activity and enhance quality of life, energy is a crucial component of economic growth. Energy is also essential to the expansion of the world economy. Global economic development is impacted by fluctuations in energy prices, especially in developing countries that import fossil fuels. About 10% of all international trade is made up of fuel sources, with primary goods making up more than 50% (The World Bank, 2021). Fuel accounts for at least 70% of the total exports from a number of countries (IMF, 2021).

2. Literature review

The transition towards sustainable energy systems has accelerated research on biomass as a renewable and environmentally friendly energy source. Among various renewable options, biomass derived from agricultural residues has gained significant attention due to its abundance, renewability, and potential to reduce dependence on fossil fuels. In the Indian context, biomass plays a significant role in the energy mix, especially in rural areas where it contributes substantially to decentralized energy needs. Studies indicate that India generates nearly 500 million tonnes of biomass annually, highlighting its vast potential for bioenergy production [1].

Agricultural crop residues constitute a major portion of this biomass resource. Residues from cereals, oilseeds, and horticultural crops, including soybean husk, are produced in large quantities across different agro-climatic regions. Research estimates that India generates approximately 696 million tonnes of crop residues annually, of which a considerable fraction is available as surplus for bioenergy applications [2]. However, improper management practices such as open-field burning lead to environmental pollution and greenhouse gas emissions [4].

Various thermochemical and biochemical conversion technologies have been developed for biomass utilization. Processes such as combustion, gasification, pyrolysis, and anaerobic digestion enable efficient energy recovery from agricultural residues. These technologies not only enhance energy efficiency but also reduce environmental impacts [1, 5].

3. Methodology

3.1 Study area

The Malwa Plateau Zone of Madhya Pradesh, which includes the districts of Ujjain, Rajgarh, Dewas, Dhar, Mandsaur, Ratlam, Shajapur (Agar-Malwa), Indore, and Neemuch, covers 48.94 percent of the state's geographical area under soybean cultivation. This study looks at the growth of soybean area, production, and productivity during the study period.

Crop statistics of India, available from the Ministry of Agriculture (MoA), Govt. of India is a major data source for estimation of crop residue biomass availability [20]. The MoA has adopted a reliable and scientifically robust procedure to derive relatively precise estimation of crop production, cropping area, and yield. Average crop statistics of five years (2018-19 to 2022-23) are used in order to minimize yearly fluctuation in crop statistics.

Year-to-year variations are minimized by averaging cropped area and yield. Crop residue gross. The following formula is used to determine potential on a dry weight basis [20]. According to Singh et al. (2003), the Residue-to-Product Ratio (RPR) method was used to determine the annual gross potential of agricultural biomass. The estimation is based on the following formula:

$$(CR)_I = (RPR)_i \times (PrC)_i$$

where

$(CR)_i$ = Agricultural biomass of the *i*-th crop (tonnes),

$(RPR)_i$ = Residue-to-Product Ratio for the *i*-th crop (dry mass basis), and

$(PrC)_I$ = Crop production of the *i*-th crop (tones).

4. Observations

Table-1: District-wise Soybean residue and bioenergy potential in the Malwa Plateau.

S. No.	District	Area (Ha)	Production (T)	Yield (T/Ha)	Gross CR (T)	Surplus CR (T)
1	Dewas	386,425	346,732	0.90	381,000	130,000
2	Dhar	352,416	368,510	1.06	405,000	138,000
3	Indore	320,052	352,951	1.13	388,000	132,000
4	Mandsaur	317,146	323,173	1.04	355,000	121,000
5	Neemuch	285,627	284,109	0.98	313,000	106,000
6	Rajgarh	304,563	289,433	0.95	318,000	108,000
7	Ratlam	302,805	283,170	0.93	311,000	106,000
8	Sehore	305,092	282,162	0.92	309,000	106,000
9	Shajapur	303,195	277,116	0.91	305,000	104,000
10	Ujjain	320,550	293,658	0.91	323,000	110,000
11	Malwa Plateau	3,197,872	3,101,012	0.97	3,411,000	1,160,000

CR*Crop residues; T*Ton Ha*hectare

The table shows district-level data for Madhya Pradesh's Malwa Plateau region, including area (hectares), production (tonnes), yield (tonnes per hectare), gross crop residue (CR), and surplus crop residue for each of the ten main districts as well as the region as a whole.

With an average yield of 0.97 t/ha, the Malwa Plateau's total cultivated area is 3,197,872 hectares, yielding 3,101,012 tonnes.Significant biomass availability is shown by the region's 3,411,000 tonnes of gross crop residue, of which 1,160,000 tonnes are surplus.

At the district level, Dhar has the largest production (368,510 T) and one of the highest yields (1.06 t/ha). Indore has the highest yield (1.13 t/ha) while having a relatively planted area.

Dewas' output is quite low (0.90T/Ha) while having the highest agricultural area (386,425 hectares). Shajapur and Sehore have relatively lower yields (~0.91–0.92 t/ha).

Crop residue production is highest in Dhar (405,000 T) and Indore (388,000 T).

Surplus residue is most readily available in Dhar (138,000 T), followed by Indore (132,000 T) and Dewas (130,000 T).The yield varies substantially (0.90–1.13 t/ha), indicating changes in:. A larger agricultural area does not always translate into more yields. For example: Dewas has the largest area, but its yield is lower.

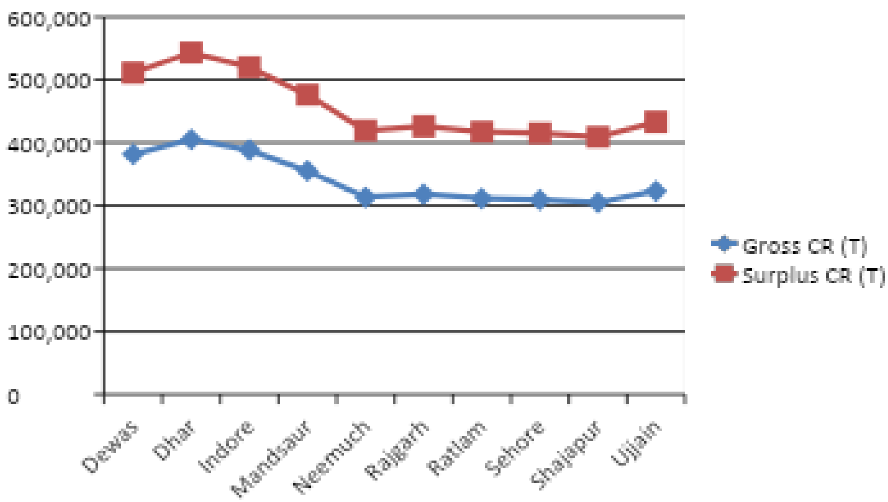

Figure 1: Comparative graphical analysis of gross and surplus crop residues across districts of the Malwa region using five-year average data.

The graph shows how the principal districts of the Malwa Plateau—Dewas, Dhar, Indore, Mandsaur, Neemuch, Rajgarh, Ratlam, Sehore, Shajapur, and Ujjain—generate different amounts of soybean crop residue. The red line shows surplus crop residue (CR) that might be used for bioenergy, whereas the blue line shows gross crop residue (CR).From Dewas to Neemuch, both gross and excess residues gradually decrease before stabilizing in the remaining districts. Due to their greater planting fields and better yields (0.9–1.06 T/Ha), Dewas and Dhar have the largest residue generation. Districts with lesser production scales, such as Shajapur and Neemuch, exhibit comparatively lower residual volumes. With a combined gross crop residue contribution of 3.41 million tonnes and a surplus of 1.16 million tonnes, the Malwa Plateau shows significant potential for biomass-based energy conversion. Opportunities for decentralized bioenergy systems are highlighted by the steady surplus across areas. Using these leftovers can promote agro-ecological sustainability, enhance soil health, and lessen open-field burning.

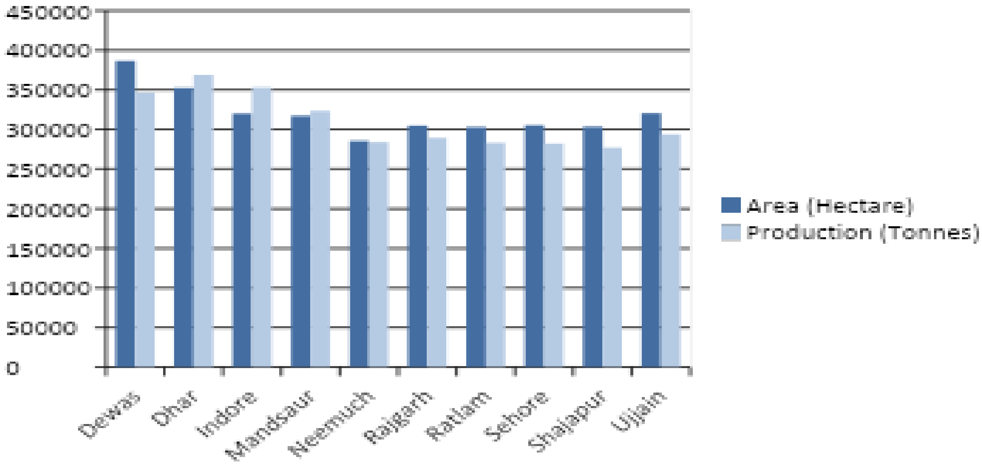

Figure 2: Relationship between cultivated area and soybean production across districts of the Malwa region (five-year average).

Based on five-year average data, the image shows a comparative graphical representation of soybean production (tonnes) and cultivated area (hectares) across the main districts of the Malwa region. Variations in area and production between districts like Dewas, Dhar, Indore, Mandsaur, Neemuch, Rajgarh, Ratlam, Sehore, Shajapur, and Ujjain are well depicted in the bar chart.

The largest cultivated area is found in Dewas, closely followed by Dhar and Ujjain, demonstrating the importance of soybean farming in these districts. Dhar and Indore, however, fare well in terms of production, indicating comparatively greater levels of productivity. Despite having a smaller area, Indore in particular has increased production, which is indicative of improved yield efficiency.

The graph shows that productivity (yield) is just as important to production as cultivated area. Higher production efficiency is attained in districts like Dhar and Indore, which may be related to better input management, irrigation systems, and farming practices.

On the other hand, regions like Dewas, which have bigger farmed acreage but comparatively lower productivity, show potential for yield enhancement through improved agronomic techniques and technology interventions.

5. Results

According to data from the Directorate of Economics and Statistics, Madhya Pradesh, the total area under cultivation in the district during the period 2018–2019 to 2022–2023 was approximately 3.19 Million hectare and soybean production 3.10 million tonnes. The gross crop residues generated over this period was estimated at 3.41 million tones. Within this total, surplus crop residues from soybean husk accounted for around 1.16 million tones, representing nearly 34% of the overall residue volume.

6. Conclusions

The present study estimated crop residue biomass and subsequently bioenergy potential of Soybean crop residues from 10 District for all the Madhya Pradesh. The Region 3.41 Mt gross residue annually, of which 1.16 (34% of gross) available as surplus. Dhar district produces the highest amount of surplus residue in the Malwa region (0.13 MT). Ten district *viz*. Dewas, Indore, Shajapur, Ujjain, Ratlam, Mandsaur, Rajgarh, Sehore, Neemuch. According to the data, some districts, including Indore and Dhar, do better than others in terms of efficiency and residue generation, even if the Malwa Plateau maintains a moderate average productivity. The large amount of excess crop waste shows great potential for sustainable biomass use, which might help renewable energy projects and lessen the negative effects of residue burning on the environment.

Authors' contributions

All authors contributed equally to the conception, design, experimental work, data analysis, interpretation of results, and preparation of the manuscript. All authors reviewed and approved the final version of the manuscript for publication.

Conflicts of interest

The author declares no conflict of interest.

Funding

This research received no external funding.

Data availability

All relevant data and supporting information are included in the article, thus there is no need to consult external sources for more information.

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